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Multi-layer network monitoring and analysis

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Abstract

Passive network monitoring offers the possibility of gathering a wealth of data about the traffic traversing the network and the communicating processes generating that traffic. Significant advantages include the non-intrusive nature of data capture and the range and diversity of the traffic and driving applications which may be observed. Conversely there are also associated practical difficulties which have restricted the usefulness of the technique: increasing network bandwidths can challenge the capacity of monitors to keep pace with passing traffic without data loss, and the bulk of data recorded may become unmanageable.

Much research based upon passive monitoring has in consequence been limited to that using a sub-set of the data potentially available, typically TCP/IP packet headers gathered using Tcpdump or similar monitoring tools. The bulk of data collected is thereby minimised, and with the possible exception of packet filtering, the monitor's available processing power is available for the task of collection and storage. As the data available for analysis is drawn from only a small section of the network protocol stack, detailed study is largely confined to the associated functionality and dynamics in isolation from activity at other levels. Such lack of context severely restricts examination of the interaction between protocols which may in turn lead to inaccurate or erroneous conclusions.

The work described in this dissertation attempts to address some of these limitations. A new passive monitoring architecture — Nprobe — is presented, based upon 'off the shelf' components and which, by using clusters of probes, is scalable to keep pace with current high bandwidth networks without data loss. Monitored packets are fully captured, but are subject to the minimum processing in real time needed to identify and associate data of interest across the target set of protocols. Only this data is extracted and stored. The data reduction ratio thus achieved allows examination of a wider range of encapsulated protocols without straining the probe's storage capacity.

Full analysis of the data harvested from the network is performed off-line. The activity of interest within each protocol is examined and is integrated across the range of protocols, allowing their interaction to be studied. The activity at higher levels informs study of the lower levels, and that at lower levels infers detail of the higher. A technique for dynamically modelling TCP connections is presented, which, by using data from both the transport and higher levels of the protocol stack, differentiates between the effects of network and end-process activity.

The balance of the dissertation presents a study of Web traffic using Nprobe. Data collected from the IP, TCP, HTTP and HTML levels of the stack is integrated to identify the patterns of network activity involved in downloading whole Web pages: by using the links contained in HTML documents observed by the monitor, together with data extracted from the HTML headers of downloaded contained objects, the set of TCP connections used, and the way in which browsers use them, are studied as a whole. An analysis of the degree and distribution of delay is presented and contributes to the understanding of performance as perceived by the user. The effects of packet loss on whole page download times are examined, particularly those losses occurring early in the lifetime of connections before reliable estimations of round trip times are established. The implications of such early packet losses for pages downloads using persistent connections are also examined by simulations using the detailed data available.

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Very special love and thanks goes to my wife, Jenny, whose continual encouragement and support has underpinned all of my efforts. She has taken on a vastly disproportionate share of our domestic and child-care tasks, despite her own work, and has endured much undeserved neglect to allow me to concentrate on my work. My love and a big thank-you also go to Charlie and Sam who have seen very much less of their daddy than they have deserved, and to Jo and Luke, 'my boys', with whom I have recently sunk fewer pints than I should.

Finally, the rôle of an unlikely player deserves note. In the early 1980's I was unwillingly conscripted into the ranks of Maggie's army — the hundreds of thousands made unemployed in one of the cruelest and most regressive pieces of social engineering ever to be inflicted upon this country. For many it spelled unemployment for the remainder of their working lives. With time on my hands I embarked upon an Open University degree, the first step on a path which lead to the Computer Laboratory, the Diploma in Computer Science, and eventually to the writing of this dissertation — I was one of the fortunate ones.

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List of Acronyms

AMP	Active Measurement Project (NLANR)
ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
BLT	Bi-Layer Tracing
vBNS	Very High Performance Backbone Network Service
BPF	Berkeley Packet Filter
C	The C Programming Language
CAIDA	Cooperative Association for Internet Data Analysis
CDN	Content Distribution Network
CGI	Common Gateway Interface
CPA	Critical Path Analysis
CPU	Central Processing Unit
CWND	Congestion WiNDow (TCP)
DAG	Directed Acyclic Graph
DAU	Data Association Unit (Nprobe)
DNS	Domain Name Service
DRR	Data Reduction Ratio
ECN	Explicit Congestion Notification
FDDI	Fiber Distributed Data Interface
FTP	File Transfer Protocol
Gbps	Gigabits per second
GPS	Global Positioning System

HPC	High Performance Connection (Networks)
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IAB	Instantaneous ACK Bandwidth (TCP)
ICMP	Internet Control Message Protocol
IGMP	Internet Group Management Protocol
I/O	Input/Output
IP	Internet Protocol
IPMON	IP MONitoring Project (Sprintlabs)
IPSE	Internet Protocol Scanning Engine
ISP	Internet Service Provider
IW	Initial Window (TCP)
SuperJANET	United Kingdom Joint Academic NETwork
LAN	Local Area Network
LLC	Logical Link Control
MAC	Media Access Control
MBps	Megabytes per second
Mbps	Megabits per second
MIB	Management Information Base
MSS	Maximum Segment Size (TCP)
NAI	Network Analysis Infrastructure
NDA	Non Disclosure Agreement
NFS	Network Filing System
NIC	Network Interface Card
NIMI	National Internet Measurement Infrastructure (NLANR)
NLANR	National Laboratory for Applied Network Research
OCx	Optical Carrier level x
PC	Personal Computer
PCI	Peripheral Component Interconnect

PDT	Payload Delivery Time (TCP)
PMA	Passive Measurement and Analysis (NLANR)
POP	Point of Presence
QOS	Quality of Service
RAID	Redundant Array of Inexpensive Disks
RFC	Request for Comment
RLP	Radio Link Protocol
RTSP	Real Time Streaming Protocol
RTT	Round Trip Time
pRTT	*partial* Round Trip Time
SACK	Selective ACKnowledgement (TCP)
SMTP	Simple Mail Transfer Protocol
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical NETwork
SSTHRESH	Slow-Start THRESHold (TCP)
SSU	State Storage Unit (Nprobe)
SWIG	Simplified Wrapper and Interface Generator
TCP	Transmission Control Protocol
UCCS	University of Cambridge Computing Service
UDP	User Datagram Protocol
URI	Uniform Resource Indicator
URL	Uniform Resource Locator
WAN	Wide Area Network
WAWM	Wide Area Web Measurement Project
WWW	World Wide Web

Chapter 1

Introduction

Computer networks in general, whether serving the local, medium or wide area, and in particular, the globally spanning aggregation known as the Internet (henceforth referred to simply as *the network*) remain in a period of unprecedented and exponential growth. This growth is not only in terms of the number of communicating hosts, links and switching or routing nodes; but also encompasses new technologies and modes of use, new demands and expectations by users, and new protocols to support and integrate the functioning of the whole.

Heavy demands are made by new overlaying technologies (e.g. streamed audio and video) which carry with them additional requirements for timely delivery and guaranteed loss rates — the concept of Quality of Service (QOS) becomes significant; the growth of distributed computing makes new demands in terms of reliability. Sheer growth in the size of the network and volume of traffic carried places strain on the existing infrastructure and drives new physical technologies, routing paradigms and management mechanisms.

Within this context the ability to observe the dynamic functioning of the network becomes critical. The complexity of interlocking components at both physical and abstract levels has outstripped our capacity to properly understand how they inter-operate, or to exactly predict the outcome of changes to existing, or the introduction of new, components.

1.1 Introduction

The thesis of this dissertation may be summarised thus: observation of the network and the study of its functioning have relied upon tools which, largely for practical reasons, are of limited capability. Research relying upon these tools may in consequence be restricted in its scope or accuracy, or even determined, by the bounded set of data which they can make available. New tools and techniques are needed which, by providing a richer set of data, will contribute to enhanced understanding of application performance and the system as a whole, its constituent components, and in particular the interaction of the sub-systems represented by the network protocol stack.

The hypothesis follows that such improved tools are feasible, and is tested by the design and implementation of a new monitoring architecture — *Nprobe* — which is then used in two case studies which would not have been possible without such a tool.

1.2 Motivation

This section outlines the motivation underlying passive network monitoring and the development of more capable tools by which it can be carried out. The following sections (1.3 and 1.4) introduce the desirability of monitoring a wider range of protocols and suggest the attributes desirable in a monitor which would have this capability.

1.2.1 The Value of Network Monitoring

The term *network monitoring* describes a range of techniques by which it is sought to observe and quantify exactly what is happening in the network, both on the microcosmic and macrocosmic time scales. Data gathered using these techniques provides an essential input towards:

- Performance tuning: identifying and reducing bottlenecks, balancing resource use, improving QOS and optimising global performance.
- Troubleshooting: identifying, diagnosing and rectifying faults.
- Planning: predicting the scale and nature of necessary additional resources.
- Development and design of new technologies: Understanding of current operations and trends motivates and directs the development of new technologies.
- Characterisation of activity to provide data for modelling and simulation in design and research.
- Understanding and controlling complexity: to understand the interaction between components of the network and to confirm that functioning, innovation, and new technologies perform as predicted and required. The introduction of persistent HTTP connections, for instance, was found in some cases to reduce overall performance [Heidemann97a].
- Identification and correction of pathological behaviour.

1.2.2 Passive and Active Monitoring

The mechanisms employed to gather data from the network are classified as *passive* or *active*, although both may be used in conjunction.

1.2.2.1 Passive Monitoring

Passively monitored data is collected from some element of a network in a non-intrusive manner. Data may be directly gathered from links — on-line monitoring — using probes[1] (e.g. `tcpdump`) to observe passing traffic, or from attached hosts (usually routers/switches or servers, e.g. `netflow` [Cisco-Netflow], Hypertext Transfer Protocol (HTTP) server logs). In the first case the data may be collected in raw form (i.e. the unmodified total or part content of passing packets) or may be summarised (e.g. as protocol packet headers). All or a statistical sample of the traffic may be monitored. In the second case the data is most commonly a summary of some aspect of the network traffic seen, or server activity (e.g. traffic flows [`netflow`], Web objects served, or proportion of cache hits).

Data thus collected is typically stored for later analysis, but may be the subject of real-time analysis, or forwarded to collection/analysis servers for further processing.

The strength of passive monitoring is that no intrusion is made into the traffic/events being monitored, and further — in the case of on-line monitoring by probes attached to a network attached directly to network links — that the entire set of data concerning the network's traffic and functioning is potentially available. The weakness, particularly as network bandwidths and the volume of traffic carried increase, is that it becomes difficult to keep up with the passing traffic (in the processing power required both to collect the data and to carry out any contemporaneous processing) and that the volume of data collected becomes unmanageable.

1.2.2.2 Active Monitoring

Active network monitoring, on the other hand, is usually concerned with investigating some aspect of the network's performance or functioning by means of observing the effects of injecting traffic into the network. Injected traffic takes the form appropriate to the subject of investigation (e.g. Internet Control Message Protocol (ICMP) ping packets to establish reachability, HTTP requests to monitor server response times).

The data gathered is largely pertinent only to the subject of investigation, and may be discarded at the time of collection, or may be stored for global analysis. Specificity of injected traffic and results may limit the further usefulness of the data gathered. There is always the risk that the injected traffic, being obtrusive, may in itself colour results or that incorrect or inappropriate framing may produce misleading data.

1.2.3 Challenges in Passive Monitoring

When considering passive monitoring, issues of maximising potential information yield and minimising data loss arise.

[1] Here and elsewhere in this dissertation the term *probe* is used to describe a data capture software system, and the computer on which it runs, connected to a network for monitoring purposes.

1.2.3.1 How and Where to Monitor

As the majority of data pertinent to a network's functioning and instantaneous state originate from, and are as a result of, the traffic traversing the network, it follows that the traffic itself is the richest source of data — and from that data, information of interest. At best data obtained from sources such as server logs or Management Information Bases (MIBs) can only be summaries; of events internal to a particular machine, of network events or traffic visible to the machine, or of events or state communicated by others. Such summaries are likely to be specific to a particular purpose, or of a limited subset of the data originally available. It follows that there are cogent arguments for conducting passive monitoring on-line (i.e. by using a probe machine to observe and examine all packets traversing the network(s) to which it is attached; the technique usually referred to as *packet monitoring*) rather than by observing or collecting state held by others.

This is, of course, exactly the way in which hosts such as routers build repositories of data (e.g. `NetFlow`), but there are crucial differences. Modern routers or switches are specialised machines, often able to handle high bandwidths by carrying out critical functions in hardware, and optimised for this purpose. Those core functions, moreover, are likely to be concerned primarily (or totally) with processing packets at a specific level in the protocol stack. The range of data collected by these machines is therefore generally limited, relatively inflexible in type and scope, and largely (although not always exclusively) specific to the protocol level of the machine's core function. The potential richness of information contained in the available data is largely lost.

Care must be taken when deciding the placement of on-line network probes, and the effects of placement upon the data gathered given due weight. Ideally probes should be attached to links where the greatest and widest sample of traffic is carried, where packets travelling in both directions between servers and clients are visible, and where routeing variations have minimal impact. A great deal may be learned, however, through selective placement (e.g. attachment to links accessing specific sites can illustrate the usage patterns of particular communities, attachment adjacent to modem banks or server farms may produce informative comparisons).

1.2.3.2 Avoiding Data Loss

As previously mentioned, constantly increasing bandwidths and traffic volumes make considerable demands of the mechanisms designed to collect, process and store monitored traffic. Leland and Wilson [Leland91] describe a relatively complex mechanism[2] employed at the start of the last decade to collect packet arrival times and lengths on a 10 Megabits per second (Mbps) ethernet segment, and which provided the data upon which at least two seminal papers were based [Leland94] [Paxson95]. In the intervening 13 years network link bandwidths have increased by up to three orders of magnitude; the increase in processor speeds, memory and storage capacities has tended to lag behind.

The core functionality of any on-line monitoring probe is to passively capture the traffic arriving at its interface to the monitored network, and to process and store data contained

[2] See Section 2.8.1 on page 39.

in or derived from that traffic. The utility of the monitoring is constrained by the processing power of the probe and its ability to store the desired data; if arrivals from the network over-run either capacity packets will be dropped and data lost. To process data arriving at rates of tens or hundreds of Mbps (or, increasingly, Gigabits per second (Gbps)) consumes considerable computational resources. To store the traffic traversing a fully utilised 10 Gbps link in one direction verbatim would, for instance, generate over 4.5 Terabytes of data per hour requiring an on-disc bandwidth in excess of 1,250 Megabytes per second (MBps).

It is useful to establish some terminology at this point, where *data* refers to the data which it is desired to capture from the network, and which may be a verbatim copy of all or part of packet contents, or may be an abstract of the partial content of interest:

Data *drop*: arbitrary data lost in an uncontrolled manner because the probe has been overwhelmed by arrivals (e.g. packet loss due to network input buffer over-run) or exhaustion of probe storage capacity

Data *loss*: failure to fully capture and store required data

Data *discard*: selective data rejection, either because it is not required or in order to limit the demands on the probe and hence avoid data drop (but not necessarily data loss)

Data *extraction*: identification, capture and storage of the required sub-set of the total data; implies data discard

Data *abstraction*: data extraction of a summary or semantic element from some part of the whole data as opposed to a verbatim copy of packet content

Data *association*: the aggregation of all data forming a logically associated sub-set within and *across* protocol and packet boundaries

Data *reduction*: reduction of the total volume of data to be stored through a process of data extraction

Data *reduction ratio*: the ratio of the volume of stored data to observed traffic volume after data reduction

In designing mechanisms for passive network monitoring the optimal degree of data reduction must be sought: too little and storage requirements become excessive both in volume and bandwidth, too much and the computational cost of data extraction may make it impossible to keep up with the monitored traffic.

Traditional monitoring tools (e.g. `tcpdump`[3]) impose a coarse-grained data extraction policy. Discard based upon packet filtering to select a desired sub-set of traffic operates at the resolution of whole packets, while further data selection is limited to capture of the first N octets of all accepted packets — hence potentially storing a considerable amount of unwanted content. There is no mechanism for *abstraction* of required data from packet content. The available processor resources are largely consumed in making two copies of the data between kernel

[3] Unless otherwise stated reference to `tcpdump` is to its use as a data-capture system rather than in its role as a packet content summary tool.

and user memory, one to read packet contents from the packet filter, and one for output to disc.

The consequence of such limited data extraction capability is that data capture has been largely restricted to the opening octets (e.g. Media Access Control (MAC), Internet Protocol (IP) and Transmission Control Protocol (TCP) headers) of a limited range packets representing a traffic class of interest. It follows that research based purely upon on-line monitoring has also been largely restricted to that which can be carried out using this sub-set of the data.

1.3 Multi-Protocol Monitoring and Analysis

Almost all passive on-line monitoring systems, and the research based upon the data which they collect, take as a minimum data set the IP and TCP headers contained in the captured packets. However, in the context of this dissertation the term *multi-protocol monitoring* is reserved for systems which harvest data from a wider span of the network protocol stack, particularly from levels at and above the *transport* level.

1.3.1 Interrelationship and Interaction of Protocols

The design of the network protocol stack seeks to achieve independence of each level of the stack from those above and below it, and to allow multiplexing of protocols at any level on to one or more protocols at the lower level. However functional and dynamic independence is not a reality — the demands made upon lower level protocols by those above will vary according to the purpose and behaviour of the user protocol or application. Contrast the differing demands made upon the infrastructure by TCP and the User Datagram Protocol (UDP); while both may seek to maximise throughput, TCP is adaptive to congestion, UDP is not. Both File Transfer Protocol (FTP) and HTTP traffic use TCP as a transport layer protocol, but make widely differing demands of it (and hence the underlying network); one attempts to maximise throughput in (usually) one continuous burst, the other will more often produce many bursts of activity as the Web browser opens pages containing graphic images — typically by opening multiple TCP connections to fetch those objects.

If network monitoring is to help us achieve a true understanding of the phenomena observed, analysis of behaviour at all levels and the interaction between them is desirable. The content of a Web object, for instance, may do much to illustrate the traffic following it across the network. For the reasons explained above past work has tended to concentrate data collection and analysis within a small set of protocols in isolation, albeit in a specific context. It is necessary to broaden this approach so that a greater range of data from multiple protocol levels is gathered and integrated, with obvious implications for data extraction and reduction which may now demand that a certain amount of the integration is performed *on the fly*.

New protocols, supporting existing or (more commonly) new traffic types (e.g. streamed media), are supported at lower levels by existing protocols whose original design never envisaged the demands now made of them. In such a circumstance it may be difficult to predict the possible interaction of protocols, which may be sufficiently complex that undesirable side effects are introduced, or the required functionality is not fully achieved. Monitoring methods must be developed which are capable of observing and correctly interpreting such phenomena.

1.3.2 Widening the Definition of a Flow

Much work has been done on the analysis of flows across the Internet; most commonly defined as all traffic passing between two host/port pairs without becoming quiescent for more than some specified time-out period. A richer understanding may perhaps be achieved by widening this definition into a hierarchy of flows, with all traffic flowing in the network at its head. Sub-flows (which need not necessarily be disjunct) may then be more flexibly defined (e.g. traffic between two networks, traffic providing a particular service, traffic carrying a particular payload type, traffic from a single host to a particular network flowing across a particular link, and so on).

While flow data collected in terms of host/port/protocol may be used to identify flows defined upon some subset of the tuple (e.g. network/network flows or flows of a particular service type) the flows so defined are themselves necessarily super-sets of those flows which can be defined by those tuples. Hence if certain aspects of network behaviour, or traffic types are to be studied in terms of flows, through the mechanism of monitoring, it may again be necessary to gather a more comprehensive data set as the traffic is observed. This also implies that packet contents beyond the network and transport protocol level headers must be examined. The transmission of real-time video and audio presents an example: streamed traffic may pass between end points on two hosts where the ports used are not well-known addresses, subsequent to negotiation during a set-up phase which uses a connection established using a known address. Without observing and interpreting the higher level protocol content of packets during the set-up period the existence of such a flow may be observed, but at best its nature can only be (perhaps incorrectly) inferred. Similarly the dynamics of passing IP multicast traffic may be better understood if data can be gathered from the relevant Internet Group Management Protocol (IGMP) packets; and of World Wide Web traffic if causal contents contained in earlier Web objects are identified. Many flows may only be fully identifiable and understandable if information is gathered from a range of relevant protocols.

1.4 Towards a More Capable Monitor

Section 1.2 has discussed factors motivating packet monitoring, some of the practical difficulties which may limit the usefulness of the technique, and the shortcomings of traditional packet monitoring software. Section 1.3 presents an argument for extending the capabilities of packet monitoring systems, particularly in order to capture a wider set of data across the span of the protocol stack.

It is unlikely, despite constant increases in the power of available processors, that probes based upon the prevailing current model of data capture will be able to provide the required functionality. A new generation of packet monitoring probe is therefore called for, in which the following attributes are desirable:

Optimal Data Reduction Ratio: Data storage requirements should be minimised by achieving the highest Data Reduction Ratio (DRR) compatible with the avoidance of information loss.

Efficiency: Processor cycles expended in *housekeeping* tasks such as packet and data copying should be minimised in order to free computational resources as far as possible for data extraction. Any memory copies should be of the *reduced* data.

Scalability: Emerging network bandwidths are likely to fatally challenge the capabilities of even costly purpose designed probes, and it is, in any case, desirable that probes should be based upon relatively inexpensive *commodity* hardware so that the widest range of placements and most representative data samples are available. Nevertheless it is desirable that monitoring facilities should be capable of keeping pace with high bandwidth links without data loss — probes should be *scalable* to meet bandwidth demands.

Fine-grained data extraction: To minimise storage requirements without data loss.

Data abstraction: To further minimise storage requirements where core data is less bulky than the corresponding packet content (e.g. textual HTTP header field contents may often be recorded more concisely as numeric codes).

Coarse-grained data discard: While fine-grained data extraction or abstraction are necessary (and imply a fine-grained data discard) they may be computationally expensive; the probe should also be capable of coarse-grained discard of unwanted data.

Statefulness: Simple data extraction, for instance of IP addresses or UDP/TCP port numbers, can be carried out on a per-packet basis with each packet treated as a discrete entity. At higher levels of the protocol stack, data extraction may require knowledge of previous packet contents; data of interest may span packet boundaries or may be semantically indeterminable without earlier context, and stream-oriented data may require reassembly or re-ordering (e.g. TCP re-transmissions). Data association may also be determined by earlier context. The probe must maintain sufficient state for the duration of a defined flow or logical data unit to enable accurate extraction and association of data in such circumstances.

Accurate time-stamping: Individual packets should ideally be associated with a time stamp which is attached *as they arrive at the probe* in order to avoid inaccuracies. Time stamps should be both as accurate as possible, and of an appropriate resolution which, as a minimum, reflects the serialisation time of packets at the bandwidth of the network(s) monitored.

Dynamic flow identification: Identification of flows based upon static 5-tuples of end-point IP addresses, TCP/UDP port numbers and transport level protocol is likely to be inadequate as an increasing number of services are sourced at dynamically assigned server ports or hosts. Probes used to capture data from such flows will require the capability to understand and track dynamic allocations.

Flexibility and modularity: A simple packet monitor exercising data capture through verbatim copying of packet content requires little or no knowledge of the arrangement, syntax or semantics of the data captured (although the user may need such knowledge, in order to define the packet octet range of interest). Capabilities such as fine-grained data extraction and statefulness imply that the probe must possess such knowledge and will in consequence be very much more complex. Such capabilities also imply that functionality will be closely tied to specific monitoring tasks and the data requirements of the particular study being undertaken — the *one-size-fits-all* probe model is no longer appropriate. It would be impractical to design a new and complex system for each new task; specificity must be accomplished through a degree of flexibility which allows functionality to be *tailored* as necessary. A design is suggested which provides an infrastructure of basic functionality, but which facilitates the addition of task-specific data extraction modules.

1.5 Aims

The work described in this dissertation concerns the development of a generic framework for data collection and analysis which can be tailored to specific research tasks. The aim was the design and implementation of a packet monitor possessing the desirable attributes described in Section 1.4 and which addresses the challenges posed in Sections 1.2.3.2 and 1.3.

The harvesting of data from the network is, of course, only the first step in a process which must proceed to a later analysis of the gathered data. Although study and content-specific analysis will be similar, however the data was collected, the logged data itself will reflect the task-specific *tailoring* of the collection process, and will be more complex in structure than the verbatim packet copy of a simple probe due to the intervening processes of data extraction and abstraction. The attributes of *flexibility* and *modularity* in the probe, as discussed in Section 1.4, must be reflected in the analysis software. In order to avoid the undesirable task of writing all parts of the analysis code from scratch for each individual study, an additional stage must be introduced into the post-collection processing of the data which understands the task-specific logging format and presents data in a canonical form. A second aim of the work has therefore been to develop a further generic framework for the retrieval and presentation of data from monitor logs.

The scope for research based upon use of such a powerful new monitoring system is enormous; a third and final aim of the work has been to conduct two studies as examples illustrating the potential of the new tools, but which would not have been possible without them.

1.6 Structure of the Dissertation

The following chapter of this dissertation describes the historical background to this work, and places it in the context of related research.

The remainder of the body of the dissertation falls broadly into two parts. In the first part

Chapter 3 describes the design and implementation of the `Nprobe` architecture and Chapter 4 introduces the framework for post-collection analysis of the logs collected. Chapter 5 goes on to describe a technique for modelling TCP connection activity based upon the protocol-spanning data provided.

The second part presents two studies based upon data collected using `Nprobe`. Chapter 6 describes the estimation of Web server latencies, Chapter 7 introduces the observation and reconstruction of Web page downloads, and in Chapter 8 this foundation is extended to examine causes of download delay with particular emphasis on delays originating from packet loss during the early stages of a TCP connection's lifetime.

Finally Chapter 9 reviews the work contained in previous chapters and draws a number of conclusions. The original contribution of the dissertation is assessed and areas for further work suggested.

Chapter 2

Background and Related Work

A considerable body of research based upon network monitoring has been established and to present a comprehensive review would be impracticable. This chapter therefore describes only some historically significant contributions and current work particularly related to the research described in this dissertation.

It is convenient to divide the work described into approximately functional (although not necessarily disjoint) categories:

2.1 Data Collection Tools and Probes

No survey of passive network monitoring tools would be complete without mention of the ubiquitous `tcpdump` [Jacobson89] which, with its variants, remains the staple collection tool for much post-collection analysis based research. Despite its high copy overheads and inability to keep pace with high arrival rates, its packet filtering capacity and familiarity are attractive to many projects. This familiarity also makes `tcpdump` a useful base-line to which other systems can be compared.

Packet capture is provided by the `libpcap` [McCanne89] library which also provides routines for verbatim binary dumping of packet contents to file[1], for reading back dumped files, and a platform-independent interface to a *packet filter*.

A coarse-grained data discard facility is provided by the packet filter — normally the Berkeley Packet Filter (BPF) [McCanne93] which incorporates a highly efficient and flexible stack-based content-matching capability allowing packets to be accepted on the basis of a very wide range of criteria. The packet filter may be implemented in user space, but is more often incorporated into the kernel for reasons of efficiency. Both the BPF and `libpcap` are widely used in other data capture tools.

[1] A defined 'capture length' of the first N bytes is usually dumped rather than the entire packet content; each packet is prepended with a short header record containing a time stamp, details of packet length, etc.

`Tcpdump` provides facilities for both packet capture and the textual summarization of packets. The latter role implies some syntactic and semantic understanding of the range of protocols handled, and hence a degree of data extraction — this is limited, however, to content presentation and no data reduction (other than partial packet capture) is applied to dumped content. Although both facilities may be used simultaneously the computational cost of presentation — not to mention the limitations of the human eye and brain — makes use in this way infeasible in monitoring all but the most sparse traffic. `Tcpdump` is therefore most commonly used as a data capture tool, the logs generated being interpreted and analysed by other software, or in presenting the content of previously gathered logs[2].

The AT&T **Packetscope** [Anerousis97] has provided the packet capture facility for a number of research projects. Built upon hardware consisting of dedicated DEC Alpha workstations equipped with raid discs and tape robots it is capable of collecting very large traces. Software is based upon `tcpdump` but with the kernel enhancements to optimise the network interface/-packet filter data path suggested by Mogul and Ramakrishnan [Mogul97b]. The ability to keep pace with 45 Mbps T3 and 100 Mbps Fiber Distributed Data Interface (FDDI) links with packet loss levels of less than 0.3%, while collecting contents up to and including HTTP protocol headers, has been reported by Feldmann [Feldmann00].

Further traces of HTTP request and response header fields collected using the PacketScope have been used to drive simulations [Caceres98] demonstrating the deleterious effects of cookies and aborted connections on cache performance.

The Cooperative Association for Internet Data Analysis (CAIDA) are responsible for continuing development of one of the most ambitious families of data collection tools — **OCx-Mon** [Apisdorf96]. **OC3Mon**, **OC12Mon** and **OC48Mon** probes, designed to keep pace with OC-3, OC-12[3] and OC-48 fibre-carried traffic at bit arrival rates of 155Mbps, 622Mbps and 2.5Gbps respectively, collected via a passive optical tap, have been widely deployed. 'Off the shelf' components are used in this Personal Computer (PC)-based architecture which uses precise arrival time-stamping provided by the network interface card, and custom firmware driving the card's on-board processor. Initially only the first cell of each AAL5-based IP datagram was passed by the interface (allowing for collection of IP headers and — in the absence of any IP option fields — TCP or UDP headers). No data extraction or association is carried out and no data reduction beyond selection of the leading proportion of packets to be collected.

The OCxMon family of probes have now been subsumed into the CAIDA **Coral Reef** [Keys01] project. Coral Reef provides a package of libraries, device drivers, and applications for the collection and analysis of network data. Packet capture is provided through the OCxMon family or more conventional Network Interface Cards (NICs) via `libpcap`; packet filtering (e.g. the BPF) may be incorporated.

The **IP MONitoring Project (IPMON)** monitor [Fraleigh01a], developed by Sprint ATL,

[2] Some analysis software uses `tcpdump` to extract data (possibly selected by a user-level invocation of the packet filter) and uses the textual output thus generated as its own input (e.g. TCP-Reduce [TCP-Reduce]).

[3] OC3Mon and OC12Mon were originally designed for the capture of Asynchronous Transfer Mode (ATM) traffic, but the range of network interfaces now employed has extended to additional technologies (e.g. 100 Mbps and 1 Gbps Ethernet).

is designed to keep pace with line speeds on up to OC-48 links. Only the first 48 bytes of each packet are stored, on a verbatim basis. The system is distinguished particularly by its use of Global Positioning System (GPS) receivers to very accurately synchronise time-stamps amongst distributed probes, and data taps from the network links using optical splitters and DAG Synchronous Optical NETwork (SONET) Network Interface Cards [DAG-Over].

2.2 Wide-Deployment Systems

Several projects deploy sets of probes monitoring traffic at selected points and whose output can be integrated in order to capture a more comprehensive picture of network traffic than can be obtained from a single monitoring point.

The National Laboratory for Applied Network Research (NLANR) Network Analysis Infrastructure (NAI) [NLANR98] project seeks to 'gather more insight and knowledge of the inner workings of the Internet' through the Passive Measurement and Analysis (PMA) [NLANR02] and Active Measurement Project (AMP) [NLANR] projects. Monitoring points are scattered amongst the High Performance Connection (HPC), Very High Performance Backbone Network Service (vBNS), and Internet2/Abilene high performance networks. Results, as raw traces, or at various levels of integration and abstraction, are publicly available.

The PMA project relies on a set of over 21 OC3 and OC12-based probes to passively monitor traffic passing over the target networks. The traces collected are post-processed, anonymized and collected in a central data repository. A set of trace selection and analysis tools are provided.

The AMP project uses over 100 active monitors which periodically inject traffic into the network to measure Round Trip Time (RTT), packet loss, topology, and throughput across all monitored sites.

Sprint ATL deploy 32 IPMON monitors at Point of Presences (POPs) and public peering points on their IP backbone networks. The very large data samples collected are used primarily for workload and link-utilisation characterisation, construction of traffic matrices, and TCP performance and delay studies [Fraleigh01b].

Possibly the most widely deployed passive monitoring system is to be found in Cisco routers and switches, which are equipped with a flow data collection mechanism, `Netflow` [Cisco-Netflow], which collects network and transport protocol layer data for each packet handled, together with routing information and first and last packet time stamps for each identified flow. Expired flow data is exported for storage/analysis by UDP datagram to enabled hosts running Cisco's own `FlowCollector` [Cisco-Netflow] software or other systems such as CAIDA's `cflowd` Traffic Flow Analysis Tool [CAIDA-cflowd]. Much work has been done using data collected by `Netflow` but is limited in its scope by the data set.

`Netflow`-collected information formed part of the input data for a study by Feldmann *et al.* [Feldmann01] which derived a model of traffic demands in support of traffic engineering and debugging.

While Netflow is a powerful and voluminous source of data, the limited data set provided severely restricts the scope of studies using it; its employment may also detract from router performance and, in conditions of high load, the proportion of data loss can be extremely high. It is noted in [Feldmann01] that up to 90% of collected data was lost due to limited bandwidth to the collection server.

Mention should also be made of the Simple Network Management Protocol (SNMP) [Stallings98], the most widely used network management protocol. Routers maintain a MIB of data pertinent to each link interface (e.g. packets and bytes received and transmitted or dropped, and transmission errors) collected by an agent. Most routers support SNMP and implement both public and vendor-specific MIBs. Data is retrieved by management stations via UDP.

2.3 System Management and Data Repositories

The employment of multiple probes capturing common or complementary data implies that techniques and systems must be developed for the transfer, storage and management of potentially very large volumes of data; and for secure remote management of remote probes[4]. Data *repositories* or *warehouses* are required which provide selection and retrieval facilities and implement data audit trails.

Several systems have been proposed and implemented. The data repository and management systems employed by Sprint ATL are described in [Fraleigh01b] and [Moon01]. Research at AT&T makes use of the facilities provided by the **WorldNet** Data Warehouse.

The NLANR National Internet Measurement Infrastructure (NIMI) project [Paxson00] [Paxson98], based upon Paxson's **Network Probe Daemon** [Paxson97b], uses servers deployed throughout the Internet to generate *active probes* which compute metrics such as bandwidth, packet delay and loss. This sophisticated and comprehensive framework is independent of the actual measuring tools used by the probes and will use the services of as many probes as are required for the metric measured and the desired level of accuracy. In common with all active techniques it suffers from the problem of capacity to generate only a small number of metrics at a time.

2.4 Monitoring at Ten Gigabits per Second and Faster

Advances in network technology dictate the need to monitor at continually higher line speeds. Probes keeping pace with OC-3 and OC-12 carried traffic are now commonplace and those capable of monitoring at OC-48 arrival rates are being deployed (e.g. Coral Reef and IPMON). The design of probes capable of monitoring higher speed networks is the subject of continuing research and development and becomes more feasible with increases in input/output bus bandwidths and the availability of the corresponding NICs. As NICs become more capable,

[4] Even *single* probes are usually, of course, likely to require remote management.

additional functionality can be incorporated to the advantage of monitoring systems: higher bandwidths dictate the need for more accurate and finer-grained time-stamps attached to packets at arrival times and many NICs now provide this functionality; some NICs supported by the OCxMon family, for instance, are migrating a sub-set of the packet filter into the card's firmware.

The current challenge is the development of probes with the capacity to pace network bandwidths of an order of 10 Gbps (e.g. OC-192 and 10 Gigabit Ethernet technologies). The NLANR **OC192Mon** project [OC192Mon] (with support from Sprint ATL) is currently testing a monitor capable of collecting IP header traces at such arrival rates.

Monitoring requirements, especially as distributed probe systems are deployed, and the bandwidths monitored increase, may call for functionality not normally found in NICs, and hence purpose designed cards. The University of Waikato (New Zealand) Dag research group have developed the **DAG** series of NICs [DAG-Cards] which incorporate accurate time-stamps synchronised using GPS receivers and can interface with OC-x or Ethernet carried traffic. The cards are equipped with large field-programmable gate arrays and ARM processors which allow for on-board processing (e.g. packet filtering or data compression). DAG3 Cards are designed to keep pace with OC-3 and OC-12 line speeds, and DAG4 cards with OC-48; both are used in PMA, IPMON and Coral Reef. DAG6 Cards, designed to match OC-192 and 10 Gigabit Ethernet speeds form the packet capture element of the OC192Mon project.

An approach to keeping pace with higher bandwidth networks by using monitoring clusters is described by Mao *et al.* [Mao01]. In contrast to the `Nprobe` method of striping packets across multiple processors/monitors (described in Section 3.3.2 on page 54) the authors describe a system in which a switch is used to direct packets to clustered monitors. Algorithms for monitor allocation and probe failure recovery are discussed.

Iannaccone *et al.* [Iannaccone01] describe some of the issues raised in monitoring very high speed links; some of the proposed techniques (e.g. flow-based header compression flow termination) had already at the time been incorporated in the *Nprobe* design.

2.5 Integrated and Multi-Protocol Approaches

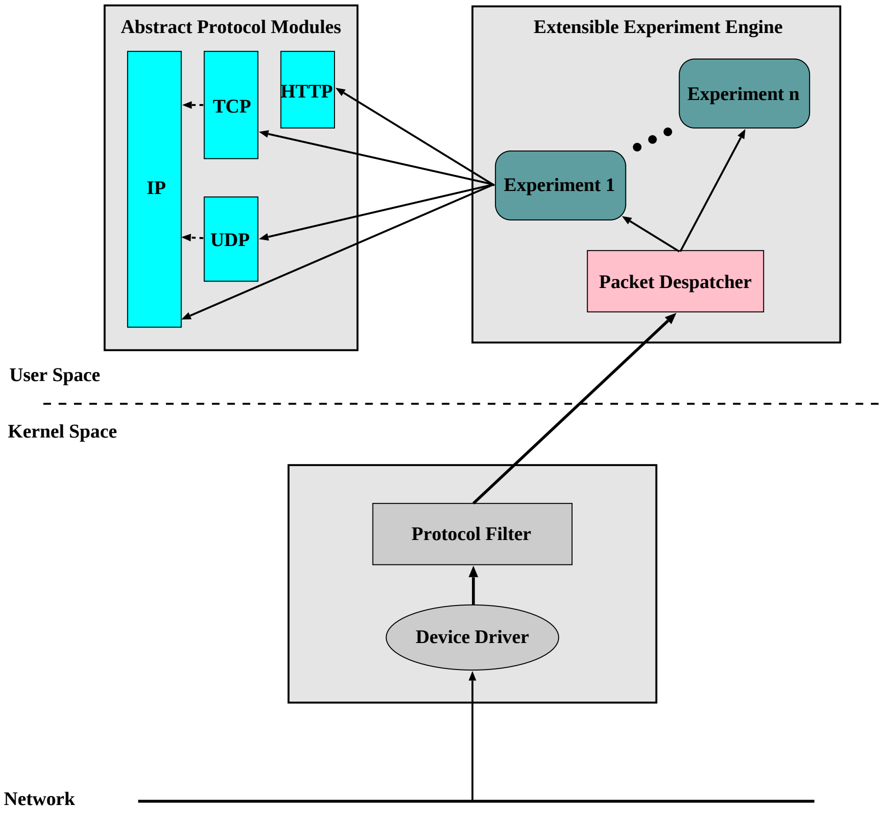
This section describes work employing a *multi-protocol* or *stateful* approach to probe design.

Malan and Jahanian [Malan98b] describe a sophisticated and flexible probe architecture — **Windmill** — designed to reconstruct application level protocols and relate them to the underlying network protocols. The architecture features a dynamically generated protocol filter, abstract analysis modules corresponding to network protocols, and an extensible experiment engine as shown in Figure 2.1.

The extensible experiment engine provides an interface allowing a remote probe administrator to dynamically load, modify and remove experiments without interrupting the continuity of probe operation. Results may be stored to disc and later retrieved through the interface or sent to a remote destination in real time using a custom data dissemination service [Malan98a].

The *Windmill Packet Filter* runs in the kernel for efficiency and is dynamically recompiled as experiments are added or removed. The packet filter passes packets identified by the experiments' *subscriptions* to a dispatcher which in turn passes them to the appropriate subscribing experiment(s). An experiment draws on the services of one or more *abstract protocol modules* to extract data specific to the protocol. The modules maintain and manage any state associated with the target protocol and also ensure that processing is not duplicated by overlapping experiments. A per-packet reference count is maintained which allows each packet to be freed once seen by all interested experiments.

Experiments have been carried out to investigate the correlation between network utilisation and routeing instability noted by Labovitz [Labovitz98], and to demonstrate real-time data reduction by collecting user-level statistics for traffic originating in the Upper Atmospheric Research Collaboratory, a data access system to over 40 instruments. The latter study also illustrated Windmill's ability to trigger external *active* measurements defined by the experiments in progress.

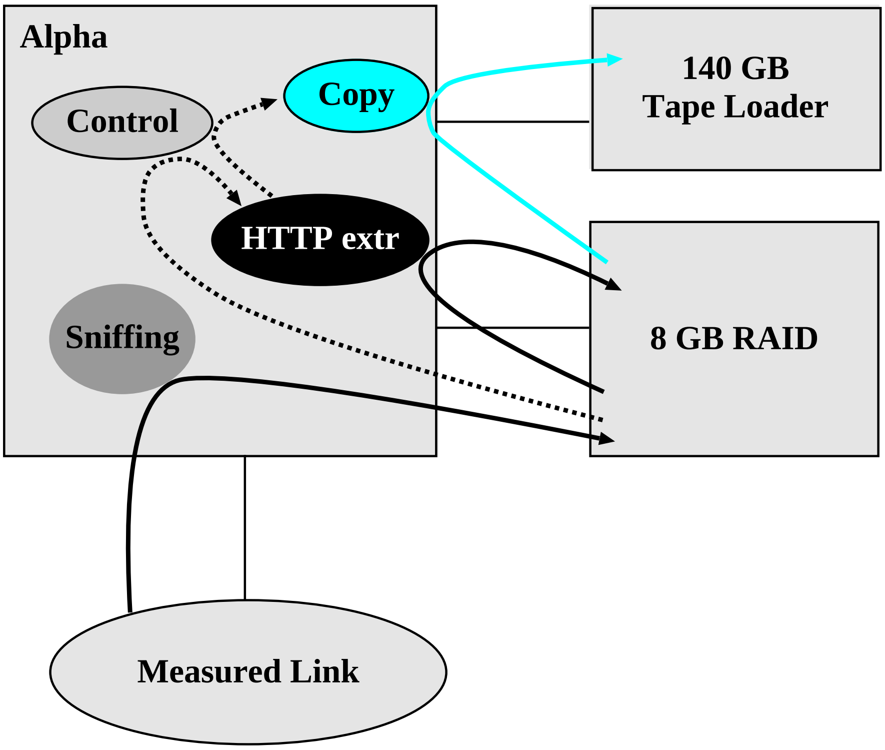


Note: Reproduced from *An Extensible Probe Architecture for Network Protocol Performance Measurement* [Malan98b] pp. 217 ©1998 ACM, Inc. Included here by permission.

Figure 2.1: **The Windmill probe architecture**

At lower levels of the protocol stack Ludwig *et al.* [Ludwig99] have conducted a study of the interaction between TCP and the Radio Link Protocol (RLP) [ETSI95] using `tcpdump` to collect TCP headers and their own `rlpdump` tool to extract data from an instrumented RLP protocol implementation. The two sets of data were associated during post-processing using the purpose designed `multitracer` tool.

Anja Feldmann describes use of the **Bi-Layer Tracing (BLT)** tool [Feldmann00] to extract full TCP and HTTP level packet traces [Feldmann98c][Feldmann98a] via packet monitoring based upon the packetscope. The tool's functionality is decomposed into four pipelined tasks: packet *sniffing* which captures selected traffic via the packet filter, writes it to file and anonymizes IP addresses; a Perl script controlling the pipeline and tape writing; HTTP header extraction software that produces time-stamps for relevant TCP and HTTP events, extracts the full contents of HTTP request/response headers, summarises the data part of transactions (e.g. body lengths) and creates logs of full packet headers; and off-line association of HTTP requests and responses. Control flow in BLT is shown in Figure 2.2.



Note: Reproduced from *BLT: Bi-Layer Tracing of HTTP and TCP/IP* [Feldmann00] with the kind permission of the author.

Figure 2.2: **Control flow of the BLT tool HTTP header extraction software**

Data extraction is performed under control of the Perl script once a sufficient number of packets have been received, and saved to reconstruct each HTTP transaction[5]. The extracted data is saved as three log files containing packet headers, unidirectional IP flow information, and HTTP/TCP data (e.g. events, timings and raw HTTP text).

A series of studies have been undertaken using BLT: the benefits of compression and delta encoding for Web cache updates are examined by Mogul *et al.* [Mogul97a], the frequency

[5] This step is actually staged due to the large number of packets that may be involved.

of resource requests, their distribution and how often they change are investigated by the same authors in [Douglis97]; the processor and switch overheads for transferring HTTP traffic through flow-switched networks are assessed by Feldmann, Rexford and Caceres in a further study [Feldmann98d]. BLT-produced data sets were used by Feldmann *et al.* [Feldmann98b] to reason about traffic invariants in scaling phenomena. Other work includes that on the performance of Web proxy caching [Feldmann99][Krishnamurthy97].

One of the earliest architectures designed with a capability for 'on the fly' data extraction is the Internet Protocol Scanning Engine (IPSE) [Internet Security96] developed by the Internet Security, Applications, Authentication and Cryptography Group, Computer Science Division, at the University of California, Berkeley. This packet-filter based architecture incorporated a set of protocol specific modules which processed incoming packets at the protocol level (e.g. TCP stream reassembly) before passing them upwards to experiment-specific modules. An HTTP specific module was used by Gribble and Brewer [Gribble97] to extract and record IP, TCP and HTTP header data in a client-side study of Web users on the Berkeley Home IP Service.

This section closes with mention of another probe design, **HTTPDUMP** [Wooster96] which, although extracting data only from the HTTP contents of packets into the *common log* format [Consortium95], is stateful in order to associate per-transaction data. Packets are extracted from the network via a packet filter into a FIFO queue from which a user-level thread reads and stores content in a cell-based array. Data is extracted, under the control of a dispatcher thread, on a *thread per transaction* basis on to disc. The designers themselves were disappointed with performance.

2.6 Flows to Unknown Ports

Identifying traffic within flows of interest will usually be based upon the *well-known* port at the server. In the case of some traffic types, the server will not communicate via such a well-known port, and port allocation may be dynamic; the Real Time Streaming Protocol (RTSP) [Schulzrinne98], the dominant control protocol for streaming content on the Internet, for example, defines a negotiation between client and server during which the characteristics of the streamed content, including server port, are determined. In such cases a probe is required to extract pertinent information (i.e. server port number) seen during the negotiation phase and to capture packets accordingly.

The `mmdump` monitor [van der Merwe00] is designed to have this capacity. Based upon `tcpdump` this system passes RTSP protocol packet contents to a parsing module which extracts the port numbers to be used for the streamed content, the packet filter then being dynamically modified to accept the flow so defined. Modules understanding the set-up phase used by the Session Initiation Protocol (SIP) [Handley99] and the H.323 conferencing control protocol [ITU-T96] are also incorporated into the tool. While monitoring, the probe initially accepts traffic on the well-known ports used by the monitored protocols. As set-up traffic is parsed (and saved) and streams added to the packet filter set, the streaming packets are also dumped to file. Further data extraction and association is performed during a second, off-line, pass of the saved data through `mmdump`.

2.7 Measurement Accuracy

Issues of accuracy in measurement are discussed by Cleary *et al.* [Cleary00] and Belenki and Tafvelin [Belenki00] with particular emphasis on time-stamp accuracy and precision. The emphasis of the first of these works is on the use of purpose-designed NICs for monitoring use (the DAG cards described in Section 2.4), while the second describes techniques for the analytical removal of error.

Pásztor and Veitch [Pásztor02] describe a software solution to providing timestamps with 1 ns resolution and low access overheads for PC-based monitoring applications.

2.8 Studies Based upon Passively Monitored Data

As an introduction to this section the comment in the preamble to this chapter, concerning the sheer bulk of research and publication in the network monitoring field, is reiterated.

Much past work has centred upon characterisation of network traffic, usually based upon one particular, or a combination of, protocols. Currently the greatest volume identified by protocol is World Wide Web (WWW) traffic transferred using the HTTP protocol [Fielding99]. With the growth in individual connections to the Internet there is little reason to think that this will change in the foreseeable future, and consequently this area receives particular attention.

2.8.1 A Brief Mention of some Seminal Studies

Perhaps the best known early bulk data collection was made by Leland and Wilson [Leland91] at Bellcore in 1989. A single board computer (SBC) with on-board Ethernet interface captured and time-stamped packets, the first 60 bytes of which were then stored in a dedicated buffer. The SBC was in turn connected to the internal bus of a Sun workstation which, when the buffer was full, copied its contents to disc. A lower-priority process then spooled the collected data from disc to tape. An interval timer board, also interfaced to the workstation's bus, provided accurate relative time stamps. Three seminal papers were based upon the traces of Local Area Network (LAN) and Wide Area Network (WAN) traffic gathered: on the nature and time-scale of network congestion [Fowler91]; and on the properties of self-similarity found in the traces [Leland94] and [Paxson95][6]. The self-similar nature of network traffic is a topic which has preoccupied many researchers ever since.

Another early bulk data collection was made by Crowcroft and Wakeman [Wakeman92] who monitored all traffic between University College London and the Unites States for a period of five hours. Data from IP and TCP/UDP headers were saved using `tcpdump` and a set of detailed traffic characterisations produced by analysing the (ASCII) traces using AWK scripts. The statistics generated included packet size, connection duration, and number of packets per connection distributions — both global and broken down by protocol; Domain

[6] Data from a wider selection of traces was also used in this study.

Name Service (DNS) response latencies; inter-packet delays and inter-packet gaps (in packets and time). It is interesting to note that, at the time (March 1991), the authors report that FTP and Simple Mail Transfer Protocol (SMTP) accounted for 79% of all traffic seen.

In 1990 the growing power of workstations prompted Jeffrey Mogul to present a paper [Mogul90] describing their use as passive monitors as an alternative to dedicated hardware. The principles of using workstations for this purpose, underlying issues, and some principles of post-collection analysis were discussed. The same author investigated the phenomenon of TCP *ACK compression* in TCP connections in [Mogul92]. It was shown, using passively collected traces of TCP/IP headers, that `ACK` compression could be automatically identified using techniques to compute instantaneous `ACK` bandwidths, and that a correlation existed between `ACK` compression and packet loss.

Vern Paxson is another investigator who has based several well known studies on passively-collected traces, of which three are mentioned here. In [Paxson94] 2.5 million TCP connections from 14 traces of wide-area traffic are used to derive analytic models describing the random variables associated with common application protocols and a methodology presented for comparing the effectiveness of the models with empirical models such as `tcplib` [Danzig91].

A study described in [Paxson99] used data derived from *passive* measurement of 20,000 TCP bulk transfers to observe and characterise a range of network pathologies and TCP behaviours. Measurements were taken using the **NPD** measurement framework [Paxson97b] at *both* end-points in recognition of asymmetry between forward and return Internet paths. The same data was used in a further study with Mark Allman [Allman99b] which evaluated the effectiveness of a number of *retransmission timeout estimation* algorithms and investigated an improved receiver-side bandwidth estimation algorithm.

2.8.2 Studies of World Wide Web Traffic and Performance

Improvements to overcome the shortcomings in HTTP/1.0 were suggested by Mogul and Padmanabhan [Padmanabhan95] and the initial design of HTTP/1.1 persistent connections informed by simulation studies driven by data sets derived from Web server logs [Mogul95][7].

Traffic to and from the official Web server of the 1996 Atlanta Olympic Games was observed by Balakrishnan *et al.* [Balakrishnan98] who took TCP header traces from the FDDI ring feeding the servers, which were additionally instrumented to notify the tracing machine of retransmitted packets. The traces were post-analysed to examine the dynamics of the connections used, and to suggest improvements that might be made to transport-level protocols. Deficiencies were found in the existing TCP loss recovery techniques (almost 50% of losses requiring a coarse timeout for recovery), receivers' advertised windows were found to contribute a bottleneck, and the correlation between `ACK` compression and packet loss was confirmed. It was discovered that multiple parallel HTTP connections were more aggressive users of the network than single connections, current use of Selective ACKnowledgements (SACKs) avoided only a small proportion of timeouts, and parallel connections with small outstanding windows suffered a disproportionate share of loss. Proposed improvements to single connections' loss

[7] This work is described more fully in Section 7.2 on page 160.

recovery mechanism using *right edge* recovery (prompting duplicate `ACKS` by sending a segment with a *high* sequence number), and to multiple connections' loss recovery by integrating congestion control/recovery across the set of connections, were simulated and found to be beneficial.

Bruce Mah determined a set of several Web retrieval characteristics using solely `tcpdump`-collected traces of TCP/IP headers in order to establish an empirical model of HTTP network traffic for further use in simulation studies [Mah97]. Grouping of individual components into Web pages depended upon a set of heuristics. Factors such as request/reply lengths, document size, consecutive document retrievals and server popularity were quantified.

Mark Allman [Allman00] used a combination of passively-collected header traces and Web server logs to characterise downloads from a single server over a period of one and a half years, and to extend this work to investigate the TCP-level activity of the connections used. The findings note increasing use of the TCP SACK option, the detrimental effects of small advertised windows, that larger values of Congestion WiNDow (CWND) would be beneficial and that the use of persistent TCP/HTTP connections appeared to be *declining.*

An investigation of Web traffic by Donelson Smith *et al.* [Smith01] using OC3Mon and OC12Mon-gathered traces of TCP/IP headers from a campus network, and further similar traces from the NLANR repository, established a number of characterisations of the traffic and the patterns of TCP usage by HTTP.

The **Wide Area Web Measurement Project (WAWM)** [Barford99a][Barford99b] combines the collection and analysis of packet traces with active measurement techniques to study the effects of varying load on Web servers. A server, established for the purpose of the experiments, was subject to a variable load generated by the Scalable URL Reference Generator (SURGE) [Barford01] on both local and distant clients.

A similar, but extended, combination of active and passive components was used to drive a further study [Barford00] using varying loads, but employing *critical path analysis* (CPA) techniques to identify and quantify the time elements constituting object download times.

Web object download times were deconstructed into server address resolution, TCP connection establishment, server latency and object download times by Habib and Abrahams [Habib00] using the `keynote` measurement tools [Keynote98] and artificially generated loads. Olshefski *et al.* [Olshefski02] describe `Certes` (CliEnt response Time Estimated by the Server), a server-based mechanism which combines connection drop, acceptance and completion rates with packet-level measurements to measure response times experienced by the client. The effects of combining Certes with web server control mechanisms and listen queue management to improve quality of service are discussed.

Several studies based upon combined TCP and HTTP data gathered using the Packetscope (BLT) have been referred to in Section 2.5.

2.9 Summary

This chapter has attempted to distill a ‘snapshot’ of the current state of passive monitor design together with some historical background and indication of how trends towards the monitoring of higher network bandwidths are to be accommodated. It will be noted that few of the probe architectures presently implemented possess all, or even a majority of, the desirable attributes described in Section 1.4.

A broad division exists between architectures intended to keep pace with high bandwidths (OCxMon, IPMON), which essentially only capture a verbatim copy of packet headers up to the TCP level and are not stateful, and those with more capable data extraction features (Windmill, IPSE and Packetscope (as BLT)). HTTPDUMP suffers from poor performance and is, essentially, only a single-protocol monitor, while `mmdump`, which supports dynamic flow identification does not (except in this limited sense) implement data extraction.

The Packetscope (BLT) is built upon a complex data flow and control structure, with fragmented logging, which is likely to inhibit its generality in terms of multi-protocol monitoring of a range of higher level protocols. The majority part of data association is postponed until the post-processing stage, hence rendering trace logs less concise than might otherwise be the case[8]. Data extraction is largely coarse-grained, HTTP headers, for instance, being copied verbatim. Although it is reported as keeping pace with FDDI link speeds of 100Mbps it is surmised that the complexity of the architecture may inhibit its use to monitor at substantially higher network bandwidths.

Both Windmill and IPSE implement finer-grained data extraction, but both designs predate currently common bandwidths, and it is not known how well they would perform, or how easily the designs might be adapted, in the present context.

Some relevant research using data obtained through passive monitoring are briefly described in Section 2.8.2. These studies may be characterised into those observing real traffic [Mah97], ([Balakrishnan98], and [Smith01]); and those based upon artificially generated traffic ([Barford99a], [Barford00], and [Habib00]).

In the context of Chapters 7 and 8 of this dissertation there is a critical distinction between those studies based solely upon data garnered from the traffic’s TCP and IP headers ([Balakrishnan98], [Mah97], [Allman00], [Smith01], and [Habib00]); and those where the base data contained elements drawn from activity at the HTTP level ([Allman00], [Barford99a], [Barford00], and [Feldmann00]). In the case of the latter category, the studies based upon BLT-gathered data are unique in that the HTTP-level data was extracted from monitored packets — in all other cases the higher-level protocol information originated from server logs (Allman) or from specially instrumented servers.

All of the work mentioned relates TCP and HTTP-level activity with the exception of that by Mah [Mah97] and to a greater-or-lesser extent derives some characterisation of Web traffic. With the, again, notable exception of the BLT studies, associations between TCP and HTTP-

[8] The BLT architecture is designed as in part to deliberately disassociate stored data in order to address concerns of privacy and security.

level activity have to be largely[9] *inferred* from the lower-level protocol activity using knowledge of the operational semantics of HTTP; thus a data-carrying TCP segment transmitted by a browser client can be assumed to carry a HTTP request, and the following data-carrying segments from the server to carry a reply; a pause in activity may imply that an entire page has been downloaded and further activity following this 'think-time' that a fresh page has been requested[10]. The extent to which such reliance upon inference may affect the accuracy of results is discussed further in Section 7.3.1 on page 162.

[9] In the case of studies collecting only TCP and IP header data, of course, *entirely.*

[10] Mah [Mah97] demonstrates the effect of differing assumed *think-times.*

Chapter 3

The Nprobe Architecture

The increasing power of relatively inexpensive PCs in terms of processor frequency, bus bandwidth, memory, and disc capacity makes feasible the design of a relatively inexpensive yet more capable on-line monitoring system than currently available; one utilizing standard hardware, device drivers, and operating systems, but sufficiently nimble to keep up with the potential bandwidth usage of contemporary network link technologies.

Such a system should be capable of capturing all packets traversing the network(s) to which it is attached with minimal or no loss. It should be sufficiently powerful to process and analyse protocol header fields at all levels together with some simple examination of packet content — the capacity for data reduction at a speed matching its input from the network, and should have attached storage media with access bandwidth and capacity sufficient to store generated data without loss and for trace periods of a macrocosmic scale.

This chapter describes the implementation of the `Nprobe` monitoring system and the *on-line* packet processing performed in order to extract and store data of interest. The later *off-line* processing of the stored data is described in Chapter 4.

3.1 Design Goals

The design and implementation of the `Nprobe` monitor have been based upon a set of general requirements which dictate that it should:

- possess the desirable characteristics introduced in Section 1.4 on page 27.
- be based upon an *off the shelf* PC machine architecture with sufficient expansion slots to accommodate several network interface cards
- incorporate multiple processors of the highest commonly available frequency for maximum processing power

- run the Linux operating system — although it is desirable to use standard operating system components and device drivers, the availability of the Linux source code makes some relatively minor but necessary modifications possible
- be equipped with high capacity Redundant Array of Inexpensive Disks (RAID) storage
- minimize the overhead of copies to and from user and kernel space while performing Input/Output (I/O) by using the kernel's memory mapping facility
- be non-invasive of the attached network(s)
- collect packets arriving at network interface(s) but not process them in the device drivers, minimizing modification to the drivers
- perform all packet processing in user-level processes, hence maintaining flexibility
- employ a modular architecture for user-level packet processing software

3.2 Design Overview

Figure 3.1 illustrates the principal components and arrangement of the `Nprobe` architecture.

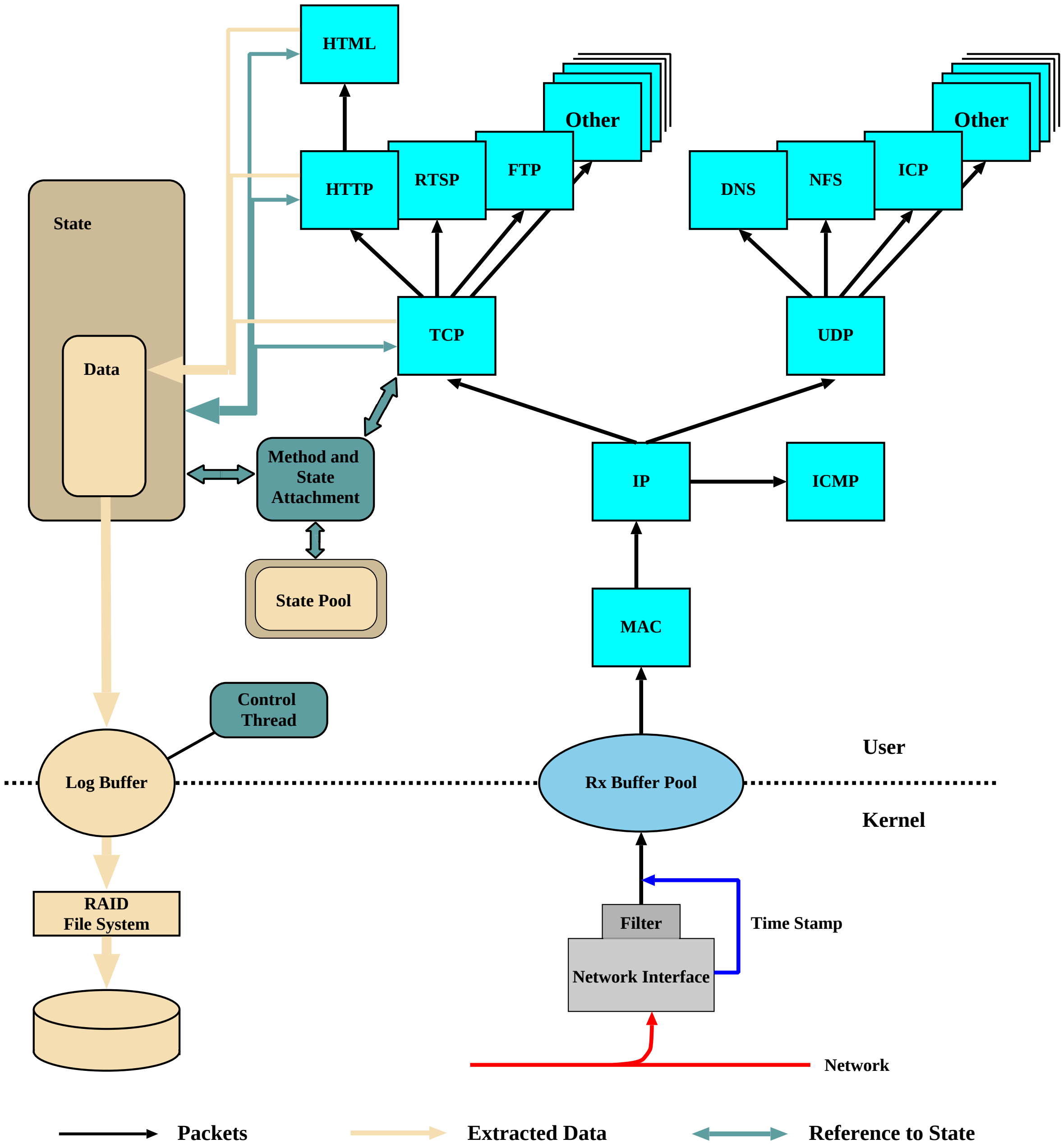
3.2.1 Principal Components

`Nprobe` functionality encompasses three stages: packet *capture*, packet *processing*, and *data storage*. Buffering between the stages accommodates burstiness in packet arrivals, and variations in packet processing and data storage rates.

Packets arriving from the network are presented to a simple filter implemented in the NIC's firmware; those passing the filter are time-stamped and transferred into a kernel memory receive buffer pool without any further processing.

A probe will have one or more receive buffer pools, each associated with one user-level *Nprobe process* and mapped into its address space. `Nprobe` processes present packets held in the receive buffer pool to a series of protocol-based modules which extract the required data from each packet *in place*; each packet is processed in turn in its entirety (except as noted in Section 3.3.3.4 on page 59), and its containing buffer marked as free for re-use by the network interface driver. Data extraction will normally be dependent on the context provided by the processing of preceding packets; this context is held as state which is attached to each packet as it is processed. Extracted data is temporarily stored as part of the attached state.

When the last packet of an associated series has been processed all of the extracted data held in state is copied into an output log buffer from where, once sufficient data has been accumulated, it is written to a trace file on disc.



Note: For the sake of clarity only one Nprobe process is illustrated, and data extraction and state reference are shown only from the TCP, HTTP, and HTML protocol modules.

Figure 3.1: **The principal components of Nprobe showing packet and data flows**

3.2.2 Rationale

The Nprobe design rationale is presented in Section 3.2.2.1 and develops the two intimately related themes of *data* flow through the system and *control*; a third, and equally significant theme — that of *state* emerges as a consequence.

Several monitoring architectures are briefly described in Chapter 2; in Section 3.2.2.2 on page 50 the Nprobe design rationale is developed further by comparison with the most similar systems described in Section 2.5 on page 35.

3.2.2.1 Data Flow and Control

The central task of a passive on-line monitoring system is to transform an afferent flow of data contained in packets captured from the network into stored output consisting of only the required data. This task will be partitioned into functional components which must be coordinated. In a sophisticated system which performs data extraction, reduction, and association, the control of interaction between these components may become complex. Subject only to physical constraints of bus and I/O bandwidth, the system's capacity to keep pace with packet arrivals will depend upon the maximum possible proportion of Central Processing Unit (CPU) resources being available to the system's central task, and to this task being executed as efficiently as possible. Any control function should therefore absorb the minimum possible number of CPU cycles and should not introduce inefficiency into packet processing; separate control processes requiring frequent context switches are, for instance, undesirable.

In the Nprobe design control is as far as possible *data driven* (e.g. packets are passed from one protocol processing module to another according to their content): the packet processing loop is driven by the presence of packets in the receive buffer pool, data copy from state to log buffer is triggered by the processing of the final packet of an associated sequence). No control processes are introduced (with one exception — the infrequently called file management thread described in Section 3.3.4 on page 68) and control derives from data processing, hence adding only a minimal overhead.

Any monitoring system must accommodate the *bursty* nature of packet arrivals, the widely varying workload involved in the processing of individual packets, and the variable rate at which saved data is generated — at the very least *buffering* will be required between these three fundamental stages in the flow of data through the system. The desirability of packet processing in user-level processes to maximize flexibility, and of avoiding such processing in device drivers so as to minimize modification, has been stated as a design goal; to these can now be added the desirability of minimizing any packet processing as part of network interrupt handling — such processing may compromise the buffering of bursty arrivals and contribute to the risk of packet loss at the network interface. Arriving packets are therefore simply placed in a receive buffer pool by the interface; the pool is as large as is possible with regard to overall memory size in order to accommodate bursty arrival rates and variable processing demands.

Monitors based upon the tcpdump model incur a considerable *data copy* overhead as arriving packets placed in the kernel's receive buffers must be copied into user memory space for processing. Nprobe avoids this penalty by using the kernel's memory-mapping facility to map the receive buffer pool directly into the user-level packet processing process(es)' address space. All data extraction and other processing is carried out on the packets *in place*.

At the very high arrival rates to be expected when monitoring contemporary networks, even a relatively large receive buffer pool would be exhausted if required to hold incoming packets for any more than a minimal period. The Nprobe design therefore calls for all packets to be processed, as far as is possible, in their entirety as soon as possible after arrival and the buffer so freed returned to the pool of buffers available to receive new incoming packets. This principle is, of course, violated by the necessity to hold out of order packets when reconstructing stream oriented flows (e.g. as explained in Section 3.3.3.4 on page 59). That some packets must inevitably be held strengthens, rather than negates, the necessity that the remainder be dealt with promptly.

The immediate processing of packets has two important implications. Firstly, while the data contained within packets which is pertinent to lower level protocols (e.g. TCP and IP headers) forms discrete, per-packet, quanta and may be extracted as such, higher-level protocol data may well conform to both syntactic and semantic units which span packets; the processing of discrete packets must therefore be carried out in the context of the additional state needed to 'bridge' processing across packet boundaries, and the processing itself is made rather more complex. Secondly, however, control flow is simplified. Packets are simply passed upwards by the processing modules representing the ascending levels of the protocol stack as determined by the packet type and contents and the data requirements of the study being conducted.

The desirability of *statefulness* was introduced in Section 1.2 in the context of enabling packet-spanning data extraction and association from contents at higher protocol levels, and reinforced earlier in this section in the context of bridging packet boundaries during processing. Even when the data collected requires no context external to the containing packet (e.g. TCP or IP headers), there are good reasons for maintaining data association across logical flows as, for example, explained in Section 3.3.3.4. The existence of state requires a determination of the *granularity* with which it is held, which in turn follows from an identification of the most efficient Data Association Unit (DAU)[1]. A larger DAU may assist in achieving a high data reduction ratio (as less data is required to be stored solely to later associate data), but may make unacceptable demands on memory, or be unfeasibly expensive to compute on the fly. A smaller unit may be cheaper to compute, make less demand on available memory (as it is likely to be completed and dumped to disc after fewer packets have been seen, its lifetime will be shorter and less units of state will therefore be concurrently held), but may be more expensive to maintain and to save (e.g. several smaller units would be more expensive to initialize or to transfer into output buffers than fewer, larger, ones).

In the case of the Nprobe design this decision was informed by two, happily complementary, factors: it was anticipated that most studies would be based upon particular traffic types (i.e. services as identified by TCP or UDP port numbers), and that the association of packets

[1] A DAU is defined as the sequence or set of packets from which logically or semantically associated data is aggregated.

(and hence of the data extracted from them) by the five-tuple of the two host IP addresses, port numbers and the IP header protocol field is a relatively cheap operation. The normal DAU was therefore chosen to coincide with the naturally self-suggesting unit of the TCP or UDP connection; and it is at this granularity that state is initialized and associated with the packets processed; and data associated, stored, and dumped to disc. The choice of DAU also determines the point at which packets are associated with the state providing the context within which they are processed, and it will be consequently seen in Figure 3.1 on page 47 that attachment of state to packets is carried out at the level of the transport level protocol processing modules. Once state has been attached to a packet, additional, protocol-specific state, may be further attached to the basic unit as the packet is passed to higher-level modules. Throughout the remainder of this dissertation the set of packets contributing to a DAU are referred to as a *flow*.

As data is extracted from packets, it is stored as part of the associated state and upon termination of the flow is copied into a log buffer in memory. The log buffer is configured as a *memory mapped* file, hence is written asynchronously to disc by the operating system — the only data copy required therefore is that of the *reduced* data from state to buffer.

3.2.2.2 Comparison with other probe architectures

The maximum duration of an `Nprobe` monitoring run is determined by the available disc capacity — both the `Packetscope (BLT)` and Windmill are designed to collect very long, continuous, traces: BLT through utilizing tape storage and `Windmill` by exporting data during collection. The first of these solutions to the problem presented by finite and limited disc capacity when collecting very long traces, was not considered for incorporation into the `Nprobe` design on grounds of expense, and because the overheads associated with copying to tape would violate the underlying aim of producing a ‘lean and mean’ design where the maximum possible resources are devoted to packet capture and data extraction. The option of exporting data while the monitor was live was also similarly discounted on grounds of avoiding additional CPU and I/O bandwidth overhead, and because, in the anticipation that probe placements would normally be such as to preclude the provision of dedicated data download links, downloading large volumes of data while monitoring would carry the risk of perturbing the monitored traffic. The provision of dedicated links would, alternatively, limit probe deployment options. It is thought that the provision of disc capacity sufficient to record 24 hour traces (and hence any diurnal traffic cycles) is likely to cater adequately for the majority of studies; only a very few connections remain alive beyond this time scale, and longer periodic variations in traffic can be catered for by repeated traces.

`Nprobe`, Windmill and BLT all incorporate a packet filter in some form, although differing in purpose and implementation. Both Windmill and BLT implement coarse-grained data discard through packet filtering: the former accepting only HTTP traffic selected by port number and the latter the selection of traffic dynamically subscribed to by the currently running experiments. In both cases, the packet filter operates on packets which have been accepted from the attached link and placed into the probe's receive buffers. The `Nprobe` filter is relatively simple and serves a different purpose — to support *scalability* as described in Section 3.3.2 on page 54; it is implemented in the NIC's firmware with the result that unwanted packets are rejected without being transferred into receive buffers, hence avoiding unnecessary load on the probe's Peripheral Component Interconnect (PCI) bus.

The BLT control flow, shown diagrammatically in Figure 2.2 on page 37, implements pipelining between the packet sniffing, data extraction, and (two stage) writing to log through the mechanism of files used as buffers between the stages of the pipeline. HTTP data extraction is only carried out after a set number of packets have been accumulated. Computational overhead is introduced by the number of data copies introduced into the long data path and by the need to manage the stages of the pipeline; the accumulation of packets prior to data extraction would incur a considerable memory penalty if they were not buffered on disc, but this in itself must introduce a bottleneck and tend to slow operation. This mechanism contrasts significantly with the minimal control overhead, buffering arrangements and fast packet turnover of the Nprobe design.

Flexibility and the capacity to load and unload different experiments while continuously monitoring also lead to a relatively complex data and control flow in the Windmill architecture, as shown in Figure 2.1 on page 36. This represents a very different approach to the tailoring of the probe to suit the data requirements of varying studies than that employed in Nprobe. The Windmill packet filter accepts the super-set of all packets required by subscribing experiments, which are then submitted to the experiment(s) by a packet dispatcher. The various experiments draw upon the services of a series of abstract protocol modules which are called recursively to extract the required data from each packet. The protocol modules maintain any state that must be maintained across packet boundaries. Because Nprobe is not designed for continuous operation, flexibility can be achieved through the addition or modification and recompilation of the various user-level processing modules, and it is suggested that this approach can lead to an equal or greater functionality (as described in Section 3.3.3.1 on page 55) without the additional complexity of the Windmill design. The ability to gather data concurrently for a range of experiments is provided by provision of a suite of appropriate processing methods which form part of state, control flow thereby being determined by packet content rather than external mechanisms.

3.3 Implementation

Nprobe remains under continuing development but at the time of writing (April 2003) the major infrastructure has been implemented together with modules processing common link-level (MAC), IP, TCP, UDP, DNS, HTTP and Hypertext Markup Language (HTML) protocols. Embryonic modules relevant to ICMP, FTP, RTSP, and NFS have also been partially developed. The Nprobe implementation is coded entirely in the C language.

3.3.1 Packet Capture

The receiving interface places incoming packets into a receive buffer pool in the normal way, this pool is considerably larger, however, than that normally employed in order to buffer between bursty arrivals and variable packet processing demands at higher levels. All packet processing is carried out by user-level processes, to which the buffer pool is made visible by mapping the buffer pool memory into the processes' memory space using the standard kernel memory mapping mechanism. In this way no copy overhead is incurred in making packet contents available to the analysis processes. Packet handling as part of interrupt processing thus remains minimal and is primarily concerned with buffer management and with standard device control functions.

3.3.1.1 Network connection

`Nprobe` connection to the target physical network will depend upon the technology of the network: in the case of shared media types (e.g. 10 Mbps Ethernet, FDDI) it is sufficient to connect in the normal way and to operate the interface in promiscuous mode; in the case of non-shared media it is necessary to tap directly into links or to make use of the *port monitoring* facility provided by switches — although care must be taken to select links or switches which will maximize the visibility of traffic. In some instances it may be necessary to employ multiple taps drawing traffic from several links into a range of interfaces.

`Nprobe` machines have to date monitored fibre-optic carried ATM traffic via a passive optical splitter placed into the link(s) of interest[2] and 1 Gbps ethernet networks via port monitoring.

3.3.1.2 Operating System and Driver Modifications[3]

`Nprobe` runs over the Gnu Linux operating system with minimal modification, principally to circumvent minor shortcomings in the memory management and mapping code. Other small patches have been required to improve the behaviour of the asynchronous `msync()` system call used in writing data log files to disc (see Section 3.3.4 on page 68).

Minor modifications are required to the standard interface drivers — the mechanism by which buffers are marked as containing valid data by the driver during interrupt processing, and then freed by the receiving process for re-use must now encompass interaction between kernel and user space processes. The firmware of the most commonly used NICs has also been modified to provide the high-resolution time stamps described in Section 3.3.1.3 and packet filtering functionality described in Section 3.3.2 on page 54.

3.3.1.3 Packet arrival time-stamping

The modified NIC firmware prepends each accepted packet with an accurate arrival time stamp generated by a clock on the card. In this way inaccuracies due to latency between

[2] Care must be taken when using optical splitters because of the signal attenuation caused by the splitter; it is envisaged that suitable links will be identified as those between switches within switching centres, rather than long haul links, so this should not be found to be a problem in practice.

[3] The work described in this Section (3.3.1.2) has been carried out by Dr. Ian Pratt and Dr Steven Hand of the Computer Laboratory Systems Research Group. Dr. Pratt is responsible for modifications to the network interface drivers and NIC firmware and Dr. Hand has contributed the file system patches.

arrivals and packet processing (whether in the device driver or in user-level processing) are avoided.

Table 3.1: **Serialization delays for a range of packet payload sizes including allowance for MAC, IP and TCP/UDP headers.**

Payload octets	Serialization delay in μs for bandwidths of:				
	10 Mbps	100 Mbps	155 Mbps	1 Gbps	10 Gbps
0	41.600	4.160	2.684	0.416	0.042
512	451.200	45.120	29.110	4.512	0.451
1024	860.800	86.080	55.535	8.608	0.861
1460	1209.600	120.960	78.039	12.096	1.210
2048	1680.000	168.000	108.387	16.800	1.680
4096	3318.400	331.840	214.090	33.184	3.318
8192	6595.200	659.520	425.497	65.952	6.595
16384	13148.800	1314.880	848.310	131.488	13.149

The clock provided by the NICs currently used by Nprobe provides timing with an accuracy and precision of approximately 1 μs but does not run at exactly 1 MHz, and is vulnerable to drift with variations in temperature. As packets are processed the NIC-generated time stamps are periodically compared with the system clock; the current NIC clock frequency is calculated from the elapsed time of both, and its current offset (NIC clock ticks are relative to an arbitrary base) from real-time noted. As packets are drawn from the receive buffer pool, these two parameters are used to calculate an accurate real-time arrival stamp for each. The periodic comparison between NIC-generated time stamps and the system clock is based upon a small number of repeated readings of both in order to identify and eliminate inaccuracies which may arise as a result of intervening interrupt handling.

Time stamps generated in this way will have a relative accuracy of one or two microseconds, and an absolute accuracy determined by the accuracy of the system clock — typically within 1 millisecond, using the Network Time Protocol [Mills92]. Reference to Table 3.1 will show that a relative accuracy of 1 μs is not precise enough to accurately measure the serialization times of back-to-back packets at network bandwidths of 1 Gbps and above, but is of the same order as the serialization times of minimum-size packets at bandwidths of 100 Mbps or small (512 octet) packets at bandwidths of 1 Gbps.

3.3.1.4 Tcpdump-collected Traces

Nprobe processes can, as an alternative to drawing packets from the receive buffer pool, read them from a tcpdump-format trace file. This facility was initially provided for developmental purposes so that *frozen* samples of network activity could be processed multiple times, but it is also useful to have the ability to apply Nprobe's data extraction and analysis capabilities to traces collected using tcpdump (although, of course, the limitations of tcpdump will still apply).

The ability to read packets from `tcpdump`-style traces is also used in investigating data processing failures as explained in Section 3.3.6 on page 72.

3.3.2 Scalability

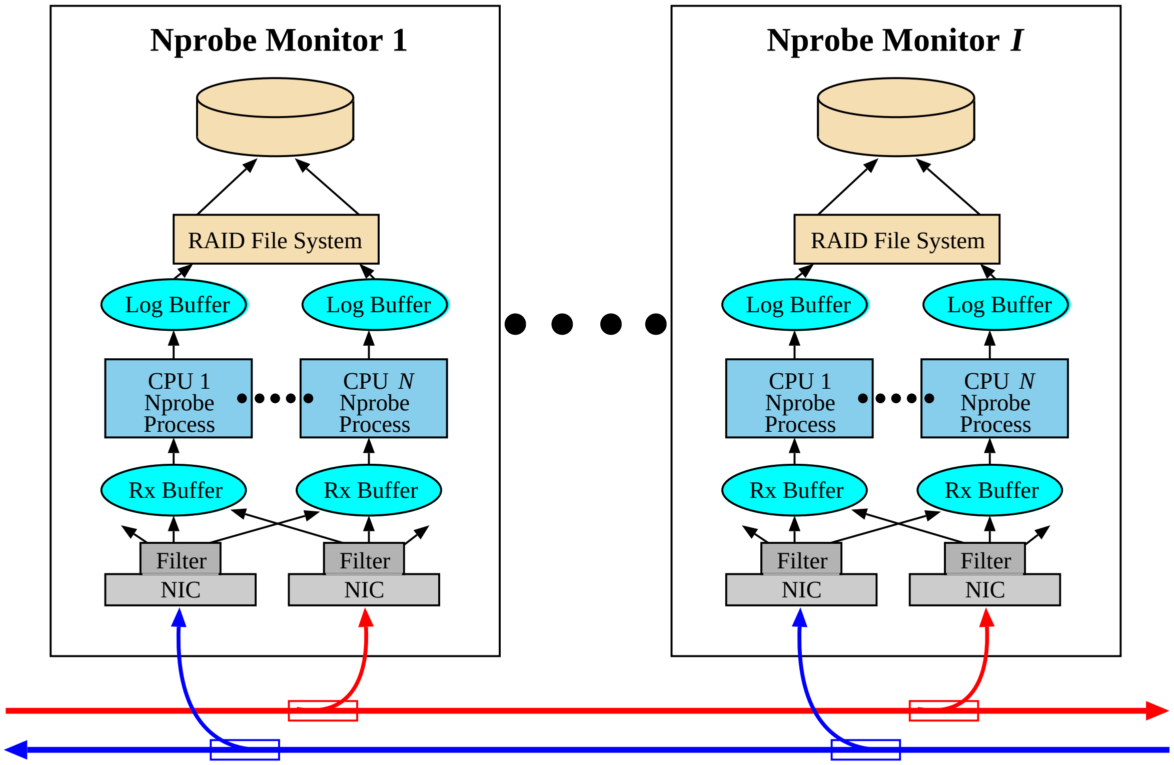
It must be recognised that a probe's ability to keep pace with packet arrivals will be over-run at some point as the need arises to monitor higher bandwidth links or link utilisation increases; however efficiently the probe's software processes incoming packets, the available processor cycles are finite and physical limitations exist in terms of memory access time and I/O or bus bandwidth and contention. Even costly and dedicated purpose-designed hardware will eventually hit hard limits, but these will be lower in the case of probes built upon commodity PCs.

`Nprobe`'s scalability is based upon the *striping* of packets across multiple `Nprobe` processes, possibly running on multiple probes; although the capacity of individual PC-based probes may be less than that of purpose hardware, their relatively low cost makes the employment of monitoring clusters an attractive proposition. Striping may, alternatively, be used as a form of coarse-grained data discard in order to collect a sample of the total network traffic by simply discarding a sub-set of the total stripes.

A simple filter, shown in Figure 3.2 on the facing page, is implemented in the firmware of each of the probe's NICs; accepted packets are transferred into the receive buffer pool associated with an individual `Nprobe` process, rejected packets are simply dropped, hence not placing load on the probe's PCI bus. The filter employs an N-valued hash based upon packets' XOR'd source and destination IP addresses — hence distributing traffic amongst N processes, each dealing with a specific aggregated bi-directional sub-set of the total. The number of processes employed will be determined by the power of the probe machines and the arrival bandwidth; if the number of processes required exceeds that available on a single machine then multiple probes, forming a monitoring *cluster* will be deployed. Where multi-processor probe machines are employed, one `Nprobe` process is run per processor (hence exploiting processor affinity — to exceed one process per processor would simply unnecessarily waste cycles in context switching).

3.3.3 On-Line Packet Processing and Data Extraction

Packets collected by `Nprobe` are processed *on the fly* by user-level `nprobe` processes which extract the required data from the contained protocol headers and payloads and save it for post-collection analysis. Each incoming packet is dealt with in its entirety and the containing buffer immediately returned for re-use by the input driver unless temporarily retained for TCP sequence ordering. Because data extraction also requires a partial analysis of packet content in order to associate data, on-line processing is henceforth referred to as *packet analysis*; to avoid confusion the later off-line analysis of collected data is referred to as *data analysis*.



Note: The simple NIC filter rejects packets which are to be processed by other probes in the cluster; accepted packets are placed in the buffer pool associated with the `Nprobe` process which will process them.

Figure 3.2: `Nprobe` **scalability**

3.3.3.1 Modularity and the Protocol Stack

The packet analysis software — *Wan*[4] — is implemented as a series of modules, providing flexibility and allowing monitoring and analysis functions to be composed and customised as required to meet the needs of single or multiple studies. Each module extracts protocol specific data, and where necessary demultiplexes packets to higher level protocol processing modules.

In general modules provide multiple, configurable, additive levels of data extraction which may be characterised in order of their increasing functionality to:

Simply count packets/bytes passed to the module: The base functionality which is provided by all modules.

Demultiplex packets according to content: Packets may be passed to the appropriate higher-

[4] The `Nprobe` on-line packet analysis code suite is collectively known as *Wan*. The name is not a well-known networking acronym — the software is named after a fictitious character, an orphan growing up surrounded by advanced alien technology which he regards as commonplace and knows how to use, but who has no understanding of the underlying principles.

level protocol module or not processed further.

Process data for presentation to higher-level protocol modules: Strip protocol headers and perform a minimal correctness check; more complex processing may be required — in the case of a TCP processing module, for instance, higher level protocol handling modules may require a properly reconstructed and ordered byte-stream.

Extract data specific to the protocol: The degree and nature of the data extracted may itself be configurable, or alternative modules supplied which are tailored to the exact needs of a particular study.

As explained in Sections 3.2.2.2 and 3.3.2 the NIC-based packet filter provides scalability rather than a coarse-grained packet discard function — the latter is distributed amongst the processing modules. Because the `Nprobe` architecture does not copy packets from kernel to user space, there is no longer a need to concentrate discard in a kernel-based filter to avoid copying packets which will later be discarded. By distributing packet discard amongst processing modules, where discard decisions can be based upon packet contents, considerable flexibility can be achieved, and both accepted and discarded packets can be accounted for. Whatever the specific study-based data being currently collected by `Nprobe` it is desirable that this is placed in the context of the traffic mix traversing the monitored network. By appropriately configuring modules the desired level of detail can be obtained; at each protocol stack level demultiplexing may either pass packets to the appropriate higher-level module where they will be accounted for (and possibly processed further) or alternatively simply account for them as the default 'other' type.

3.3.3.2 State and Data Management and Format

The concept of a *data association unit* (DAU) was introduced in Section 3.2.2.1 and may be defined as a sequence of packets having semantic or functional continuity at one or more levels of the protocol stack, and from which data is extracted, aggregated and associated. For the reasons described in Section 3.2.2.1 the DAU normally employed is that of the TCP or UDP[5] connection. It is clear that both the state necessary to extract and associate data across packet boundaries, and the extracted data itself, will refer to the same DAU and that the two can therefore be stored and managed together, extracted data forming part of the state associated with a DAU during its lifetime. The storage allocation unit for state is henceforth referred to as a State Storage Unit (SSU). Each current DAU will have a corresponding State Storage Unit (SSU) held in the probe's memory.

Lines 1 – 9 of Fragment 3.1 show the (partial) C structure forming the repository of basic TCP or UDP connection data. Lines 11 – 18 define the state associating the packets of these DAUs and illustrate how the data is encapsulated within the outer SSU structure at Line 15. In this way state and data are identified for attachment to packets, initialised and managed as a single unit, and data can be transferred efficiently as a single continuous block of memory. Complex data and state associations may require several levels of nested structures.

[5] UDP is, of course, not connection oriented as is TCP , but a UDP connection can now be defined as the sequence of packets which together form a DAU .

The continual birth and death of DAUs gives rise to a very high turnover of associated SSUs. Rather than constantly allocate and free memory it is more efficient[6] to create a pool of the various SSU structures when the monitor is activated, and for SSUs to be drawn from it as required. The pool is organised as a stack so as to maximise locality of reference.

Flexibility in the degree and type of data collected from packets, tailored to the specific requirements of a particular study (or set thereof), is reflected in the requirement for a similar degree of flexibility in the content and format of the SSUs employed. State and data vary with studies' requirements within a specific protocol and the composition of data extraction functions as packets are passed from one module to another will determine a parallel composition of SSU components. Additionally, even for the same composition of data extraction functions/SSU components, the nature and extent of data may vary significantly (e.g. an HTTP/TCP connection may carry one or many HTTP transactions, the HTTP header fields present in each may vary, and the types of object returned for each may vary).

The choice of TCP or UDP connection as the normal DAU determines that an SSU is associated with a packet as it is passed to the corresponding transport-level protocol processing module. As new DAUs are encountered a new SSU is drawn from the pool and entered into a hash list based upon IP addresses and port numbers[7]; as succeeding packets are processed the appropriate SSU can therefore be efficiently located.

The content and format of a SSU for each `Wan` module are defined by the module itself and reflect the data that will be extracted by it; by linking module-level SSUs these become sub-components of the SSU corresponding to a specific DAU and the composition of module-level extraction functions can be accommodated; repetitive data extraction (e.g. multiple HTTP transactions over one TCP connection) is accommodated by chaining the SSUs associated with a particular module. Figure 3.3 on page 59 illustrates the arrangement of a generalised SSU . Because the monitor may see traffic travelling in only one direction, state and data are divided into meta state/data applying to the DAU as a whole and two directional sub-units, each pertaining to a unidirectional flow. The directional sub-units need not be symmetrical.

The size of data fields within an SSU may be statically or dynamically determined. Numeric or abstracted data will be stored in numerical data types of known size, but a mechanism for the storage of variable-sized data (normally alphanumeric strings or sequences, e.g. the alphanumeric Uniform Resource Locator (URL) field of an HTTP request header) is also required. The demands of efficient packet processing preclude an exact memory allocation for each data instance and a trade-off therefore has to be made between allocating sufficient space to accommodate unusually large requirements and making unduly heavy demands upon the available memory. In the case of such data a count of length is kept and used to ensure that only the data (as opposed to the size of statically allocated buffers) is logged.

Code Fragment 3.2 illustrates the way in which variable-length data is stored. The `http_trans` structure forms the top-level SSU for HTTP transactions, and the nested `http_trans_cinf` structure is the request data repository. The URL length field `reqlen` at Line 5 forms part of

[6] Profiling of the `Wan` code during early development showed that up to 40% of processor cycles were being consumed in allocation and deallocation of memory for SSUs.

[7] The hashing strategy used is actually two-stage, based first upon IP addresses and then port numbers. The option to associate multiple connections as a single flow is thereby provided.

```
struct flow_inner
{
  unsigned int state;              /* State and disposal flags
      */
  unsigned short srcport, dstport; /* NBO */
  unsigned int srcaddr, dstaddr;   /* NBO */
  us_clock_t first_arr_tm;         /* absolute us */
  unsigned int last_arr_tm;        /* relative us */
  unsigned char serv_type;
};

struct flow_common
{
  list_t hlist;                    /* hash list links */
  list_t conn_timeo_q;             /* connection time out queue
      */
  struct flow_inner inner;         /* Data */
  unsigned char type;              /* eg. TCP, UDP */
  ...
};
```

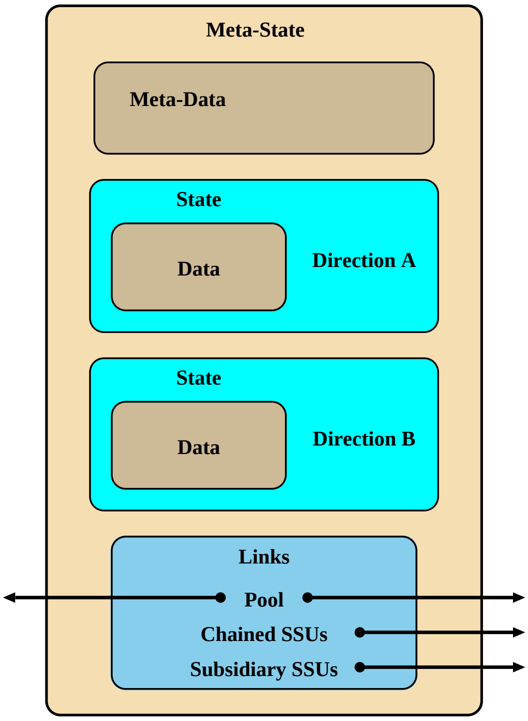
Fragment 3.1: **Encapsulation of extracted data. The `flow_inner` structure holds the data which will be logged, the outer `flow_common` structure contains the state required to associate packets belonging to the same DAU.**

the extracted *data* — and will hence be saved with it — but the URL string itself at Line 12 is kept as part of the enclosing *state*. As the string part is of variable length it will have to be transferred and stored as a discrete data item under the control of the known length; it would be wasteful of log file and disc space to write out the entire (usually sparsely populated) **`http_reqstr`** array.

Timing data is central to many studies, and as described in Section 3.3.1.3, packet time stamps are provided with a precision of 1 μs. Time stamps recorded in a 32 bit unsigned integer would overflow/wrap-round in a period of a little over one hour. Such wrap-rounds can normally be inferred, but to remove possible ambiguity in the case of events temporally separated by periods exceeding the wrap-round period, significant time stamps (e.g. TCP connection open times) are recorded as 64 bit quantities in epoch time. To ensure conciseness in the data stored the majority of timings are recorded as 32 bit offsets from such significant event times (time-out mechanisms will normally preclude the possibility of wrap-round ambiguities in such cases).

3.3.3.3 IP Processing

The IP module performs header check-sums, checks header correctness and maintains basic network-usage statistics. IP headers and any options are stripped and packets, differentiated



Note: Link fields allow composition of units associated with the protocols from which data is to be extracted and chaining of multiple instances or queue membership (e.g. the SSU pool or timeout queues). State and data may be further nested to an arbitrary depth to meet the data extraction and storage requirements of individual modules.

Figure 3.3: **Generalised SSU arrangement**

by transport-level protocol, are dispatched to the appropriate module (e.g. ICMP, UDP, TCP).

As it is anticipated that `Nprobe` will normally be monitoring non-local traffic, datagram reassembly functionality is not provided, but could be added if required. In this case the facility to time-out incomplete datagrams (similar to that described in Section 3.3.3.4 in respect of missing TCP segments) would be necessary.

3.3.3.4 TCP Processing

Because the modules corresponding to transport-level network protocols are the normal locus of state attachment, and because data collection will normally be determined by service type (determined by port numbers), the TCP module is designed to allow considerable flexibility in the way it processes packets, in the way in which it dispatches packets to higher-level protocol modules, and in its coarse-grained discard functionality.

Packets arriving at the module are associated with a SSU as explained in Section 3.3.3.2. The presence of the `SYN` flag in the TCP header will denote a new connection and cause a new TCP SSU to be drawn from the state pool and entered into the SSU hash list, subsequent packets

```
struct http_trans_cinf
{
  unsigned int reqstart_us;      /* us relative */
  unsigned int reqend_us;        /* do */
  http_reqstr_len_t reqlen;      /* length of request string */
  ...
};

struct http_trans
{
  struct http_trans *next;       /* next in chain */
  char http_reqstr[HTTP_REQSTR_LEN]; /* URL requested */
  unsigned char method;          /* request method */
  struct http_trans_cinf cinf;   /* request-specific data */
  ...
};
```

Fragment 3.2: **Recording variable-length data. The `http_trans_cinf` structure contains a count of the number of characters held in the `http_reqstr` array of the `http_trans` structure.**

belonging to the connection will find the associated SSU by reference to this list[8].

Part of the TCP module's function is to pass packets on to higher-level protocol processing modules in the case of protocols or services of interest. Rather than demultiplex each packet individually the module to which a packet is passed is determined by the attached SSU . As the first packet of a connection is encountered, and an SSU allocated, the server port number is used to determine the service carried by the connection and to allocate a method suite which will form part of the state associated with the connection and will be used in any processing of the connection's packets. The method suite is provided by the higher-level module(s) and comprises functions:

`xx_open`: Called when the connection opens

`xx_segment`: To process data segments carried by the connection

`xx_synch`: Which attempts recovery over missing data segments

`xx_close`: Called at connection close

`xx_dump`: To transfer extracted data to the output buffer

[8] The TCP module may be configured to accept only connections where at least one `SYN` packet of the three-way connection establishment phase is seen, or all connections. In the former case packets belonging to connections where the `SYN` is not seen will be discarded; in the latter case the first packet seen of any connection will result in the allocation of an SSU. The distinction is likely to arise only in the case of connections already in progress when the probe is activated, or seen as a result of routeing changes.

Method suites are accompanied by a flag-set, also provided by the appropriate higher-level module, which controls the packet processing carried out at the TCP level, primarily whether the delivery of a coherent, ordered, byte stream is required, whether packets should be checksummed and whether packet header information should be recorded.

Two alternative default method suites are provided by the TCP module: the first simply accounts for all connections and packets not providing a service of interest as an aggregate of 'other' packets and octets, the second maintains similar counts but on a per-connection basis for each connection seen.

If TCP-level activity is of interest the significant header fields (e.g. sequence and acknowledgement numbers, segment size, window advertisement, and flags) of each packet are logged. Flow-based compression is used; because packets are associated repeated fields such as addresses and port numbers do not need to be saved for each. As connections are opened each is assigned a unique 32 bit identifier and this, the addresses, port numbers, and time logged. Any further data associated with this connection, for instance the main dump of extracted data, is identified by reference to this unique identifier. Per-packet header data is accumulated as part of the connection's data and dumped to log with it on the close of the connection. Because each connection may comprise a potentially very large number of packets it would be infeasible to pre-allocate sufficient memory to meet all cases; the normal TCP SSU therefore buffers data pertaining only to 32 packet headers. In the case of longer connections, the header data is periodically written to the output buffer in blocks of this size, identified by the connection identifier. For conciseness each block of header data carries a 32 bit time offset from the connection opening, and each packet records a further time offset from this.

Data collected for every connection processed will include a set of significant event timings (e.g. that of `SYN`s, `FIN`s or `RST`s, first and last data segments in each direction); a count of TCP and payload octets, and of total and data segments; a count of missing, duplicated and out of order packets and octets; and connection Maximum Segment Size (MSS) and window-scale options.

Packets from which higher-level data is to be extracted will normally be subject to IP check sum verification before being passed for further processing. Malformed or corrupted packets may break processing code or incorrect data may be extracted; it is assumed that such packets will also be rejected by the receiving host and therefore retransmitted and seen again by the probe.

The TCP headers of incoming packets presented to the module are checked for correctness, and stripped from packets being passed to other modules. Any TCP option fields are examined and MSS notifications and window scale factor options extracted. Other options are not currently recorded as data, but may be noted as points of interest as explained in Section 3.3.6 on page 72. The flags field of each header is examined, and the current connection status held in state; a greatly simplified TCP *state machine* detects connection closure either through the normal 4-way handshake or the presence of the `RST` flag.

Care must be taken that SSUs associated with the inevitably arising unclosed connections do not exhaust the probe's memory; such connections may result from `FIN` or `RST` segments unseen due to packet loss, routing changes, or crashing or misbehaving hosts. A timeout mechanism is employed to detect and deactivate quiescent connections. The question of whether a static or adaptive timeout should be used is discussed by Christophe Diot *et al.* [Iannaccone01], based upon work by K.C.Claffy *et al.* [Claffy93][Claffy95], who conclude that a 60 second timeout will correctly determine the termination of an adequate proportion of flows. A slightly different approach is employed in the `Nprobe` implementation: the memory allocation available for the storage of TCP SSUs is bounded and there is consequently no reason why connections should be timed out until all available SSUs have been utilised (i.e. it is the finite amount of available memory which determines how many currently live flows can be accommodated by the system, and hence dictates that timeouts must occur as a consequence of new flows arriving). In this way timeout periods are not static, but are dynamically determined by the level of network and probe activity, and may be made as long as possible so as to accommodate the maximum possible period of connection quiescence before forcing closure. A *minimum* timeout period now needs to be determined so as to detect over-early timeouts due to the capacity of the probe being over run. In practice, subject to a shorter timeout period determined by SSU availability, an upper timeout bound is imposed — as data is logged at connection closure an over-generous timeout period would lead to it appearing in the saved traces later than it should, with possibly unfortunate results when analysing partial traces.

All live TCP SSUs are placed upon a *timeout queue*; as each packet is processed its arrival time is noted and its SSU is moved to the tail of the queue which is consequently time ordered with the least recently active connection at the head. The last arrival time of the queue head is periodically examined to ascertain whether connection(s) should be timed out. The queue head SSU is recycled and the associated connection timed out if the pool of free TCP SSUs becomes exhausted.

All packets (other than those aggregated and accounted for as ‘other’) are examined in the context of the connection’s sequence space and counts maintained of out-of-order, duplicated or missing segments[9]. In the normal case of connections providing services of interest, where packets are passed to further modules, those modules expect to receive a complete and ordered byte stream corresponding to that delivered to a higher-level protocol in the receiving machine. The TCP module therefore performs the necessary reordering and coalescing required to deliver a coherent byte stream. In-sequence segments are delivered immediately using the segment processing function provided by the method suite associated with the connection, segments already seen are discarded or trimmed, and any segments preceded by a gap in the sequence space are held pending reordering and delivery — note that this is the one exception to the general rule of immediate packet processing and buffer return.

Each TCP SSU provides for a sequence-ordered priority queue in which any held segments are placed; as the great majority of segments placed into the queue will be received in order, and hence be appended at the rear, the cost of insertion is normally trivial. If packets are held on the queue any newly arriving in-sequence packets are checked against the sequence of the queue head; if the sequence void is filled all queued packets up to any further sequence gap are immediately removed from the queue, passed on for processing and the containing buffers

[9] These may not be the same as seen by endpoint hosts due to `Nprobe`’s placement at an arbitrary point between the two; segments can, for instance, be lost ‘downstream’ of the probe or routes changed and packets routed around it.

returned to the receive pool.

A timeout mechanism is also required for out of order segments held awaiting the arrival of missing segments (which may not be seen, in the same way as packets signifying connection closure can be lost to the probe). A more aggressive timeout policy is required however — each live connection only consumes one SSU but may require multiple out of order segments (and hence receive buffers) to be held — exhaustion of the receive buffer pool would result in disastrous packet drop and data loss. The segment at the head of a connection's held queue is therefore timed out if any of the following conditions apply:

- More than a set proportion of the entire receive buffer pool is consumed by held segments — in practice a proportion of 50% of the total number of buffers has been found to give satisfactory operation.
- An acknowledgement for any sequence number beyond the missing segment(s) is seen hence indicating that a retransmission is unlikely to be encountered.
- The number of segments held by the connection reaches a predetermined threshold — to guard against the possibility of long connections absorbing a disproportionate number of buffers.
- The connection as a whole is timed out.

When a timeout occurs the held segment(s) are presented to the appropriate method suite's `synch` function which may attempt to resynchronize its data extraction with the interrupted byte stream (e.g. the HTTP module's resynchronization function might look for byte sequences indicating the start of a fresh transaction, or simply jump a certain number of bytes if the sequence gap falls within the length of a known-size object). All subsequent held segments are then processed in the same way as if an arriving segment had filled the sequence void. In the case of timeouts due to overall connection timeout the synchronisation function may be repeatedly called if multiple sequence voids exist, until all segments have been processed. It should be noted that the arrival of a `RST`, or the `FIN` segments representing a full connection close do not trigger a timeout (which could then precede the arrival of retransmitted packets).

3.3.3.5 UDP Processing

The configuration and operation of the UDP module are very similar to those of the TCP module with the significant and obvious exception that connection-oriented functionality — the tracking of connection set-up and tear-down phases and byte-stream ordering — is not required.

Because there is no UDP mechanism corresponding to the closure of a TCP connection there is not the same convenient signification of when a flow has reached completion and data can be dumped, and state torn down. The timeout mechanism will ensure that all flows are eventually terminated from the probe's viewpoint, but this may lead to an undue consumption of UDP SSUs associated with flows completed, but awaiting timeout. It is expected that UDP flows of interest (i.e. those where state is attached, rather than those simply accounted for as 'other') will normally also be processed by higher-level protocol modules which will detect termination as determined by the protocol semantics (e.g. trivially, a DNS flow is terminated by the receipt of a response datagram).

3.3.3.6 HTTP Processing

The main function of the HTTP processing module is to parse HTTP request and response messages and to extract data from the lines and header fields of interest. The following are identified and processed:

Request-Lines: Method, requested URL and HTTP version are extracted.

Response status lines: Numeric response code and server HTTP version are extracted.

Header Fields: Currently recognised fields include:

- `Connection` (persistent or non-persistent connections are identified and persistence negotiations tracked.)
- `Content-Type` and `Content-Length`
- `Referer (sic)`
- `Transfer-Encoding`
- `TE and Trailer` (are trailer header fields acceptable, and if so are any present to be parsed?)
- `Host`
- `User-Agent`
- `Via`
- `Location`
- `Refresh`
- `Server`

The header field identification and data extraction infrastructure is implemented through a series of C macros in such a way that additional fields can be trivially added. It is planned to extend the current set of fields to include those pertaining to cache control, object freshness and lifetime and conditional requests.

The timing of significant events (e.g. the start and finish of request and response headers and bodies) is recorded.

Although the great majority of HTTP headers are usually wholly contained in a single TCP segment the possibility of fragmentation across several segments must be catered for where the sender implements a particularly aggressive transmission policy. Rather than construct a parsing mechanism which is able to recommence after the interruption represented by segment boundaries a less complex policy is followed: if header parsing detects a truncated header (i.e. the segment end is detected but the header remains incomplete) the header is copied into a temporary buffer which is linked to the HTTP SSU. Subsequent segments are appended to the buffer and the parse recommenced until the header is found to be complete. Although this mechanism is less elegant than designing a parsing mechanism capable of spanning segment boundaries it is used because the situation is sufficiently rare that the additional overhead in state maintenance and processing complexity that would be necessary, and that would necessarily apply to all transactions, would almost certainly be more expensive.

A TCP connection may carry multiple HTTP transactions if a *persistent* TCP connection is used. The module is therefore required to identify persistent (or potentially persistent) connections and process on this basis — the type of connection may determine how the end of any response body is signified. The default connection persistence type is determined from the client and server HTTP version numbers contained in the respective request and response lines and any dynamic persistence negotiation conducted through `Connection` header fields is tracked.

In the case of persistent connections carrying multiple transactions, the transaction boundaries may be inferred from activity at the TCP level (i.e. the end of each response is marked by the transmission of the next request), but this inference is not reliable due to the possibility of *pipelining* (i.e. successive requests are sent without waiting for the response to the previous request to be received) — boundaries must be identified using 'Content-Length' header fields or by tracking chunked encoding headers. As each transaction on a persistent connection is encountered a new HTTP SSU is drawn from the pool and chained to its predecessor — the SSU associated with the first transaction on a connection of either type will be linked to the connection's TCP SSU.

```
struct http_conn
  {
    /* multiple trans. on persistent connection - kept as SLL
         */
    http_trans_t *trans;    /* first transaction on list */
    http_trans_t *reqtrans; /* current request */
    http_trans_t *reptrans; /* current reply */
    http_conn_meta_t meta;
  };
```

Fragment 3.3: **Stepping through pipelined HTTP connections. The top-level HTTP SSU contains pointers to a chain of per-transaction HTTP SSUs and to those of the current request and response transactions. The `meta` field is a structure containing state and data pertaining to the connection as a whole.**

Because multiple transactions on a connection may be pipelined the request and response currently being processed may not be one and the same. Fragment 3.3 illustrates the mechanism which permits request and response processing to independently step through chained HTTP SSUs.

The combination of HTTP header parsing and location of the HTTP body end serve to delimit the message entity. Header and body lengths are recorded. In all cases a crc-based hash is used to *fingerprint* the entity; the fingerprint is stored and may be used in later analysis to identify the resource or to detect changes in its composition. No further processing is carried out on entity bodies, except in the case of HTML documents, which are passed to the HTML processing module.

3.3.3.7 HTML Processing

The primary function of the HTML module is to parse HTML documents and to extract and record any contained links — this data may be used during data analysis to aggregate the multiple transactions used to fetch a complete page. *Reference* links (i.e. those followed under user control) are distinguished from *in-line* links (i.e. those referencing document images, frames, style sheets etc.).

If pages are to be successfully reconstructed both links and additional information are required; the parser therefore passes through both the head and the body of the document and recognises:

Elements/Tags: Which may contain attributes with absolute or relative URL values. A non-exhaustive list includes:

`ANCHOR` `AREA` `BODY`
`FRAME` `IMG` `IFRAME`
`LINK` `MAP` `STYLE`

The attributes themselves: Which may take URL values, including:

`HREF` `BACKGROUND` `ACTION`
`USEMAP` `SRC` `CODE`
`CODEBASE` `OBJECT` `ARCHIVE`
`DATA`

Base Elements/Tags: Which may define the base of relative or relocated URLs (e.g. `BASE`) and the end of such base scopes.

META tags: Particularly `HTTP-EQUIV` elements and `REFRESH` directives together with the associated `CONTENT` and `URL` attributes. Such directives may cause repeated or periodic downloads of the same or other documents, or may be used as a redirection mechanism.

There is a significant probability that HTML documents will span several TCP segments, and the simple mechanism employed to parse fragmented HTTP headers is therefore inappropriate. Instead a ‘simple’ parser has been implemented which is capable of resuming a parse interrupted by segment boundaries. This mechanism implies both that the state of the interrupted parse must be recorded and that a linear, rather than a recursive, method be employed — a series of *templates* are provided which specify the tags and elements of interest and the relevant attributes. As the first part of an HTML document is passed to the module an HTML SSU is attached to the HTTP-level state; an interrupted parse records the current parse phase (e.g. a relevant element has been encountered and is being actively parsed, no element is currently encountered) and sufficient data to identify the element or attribute being parsed (normally by recording the currently active template). As subsequent segments are received the parser is therefore able to resume at the appropriate stage.

```
#define LINKS_BUFSZ (128*16)

/*
 * -6 allows for two record terminators plus (optional) time
 * stamp and preamble byte
 */
#define LINKS_BUFLEN (LINKS_BUFSZ - 6)
#define LINKS_MAX_BUFS 16     /* beware runaway parse */

struct links_buf
  {
      struct links_buf *next; /* chained in use or in pool */
      unsigned short nchars;  /* use - including delimiters
          */
      char buf[LINKS_BUFSZ];  /* the buffer itself */
  };

struct links
  {
    struct links_buf *chain;  /* first buffer in chain */
    struct links_buf *current;/* current buffer */
    char *buf;                /* where currently writing */
    unsigned char nbufs;      /* number currently chained */
    unsigned short nchars;    /* usage of current buffer */
    unsigned int totchars;    /* total o/a buffers */
  };
```

Fragment 3.4: **HTML links buffer and management structures.**

Because HTML document sizes, and the number of contained links, may vary considerably, it is, once again, infeasible to provide buffers sufficiently large to accommodate all of the data that may be extracted for all currently active documents. The HTML SSU therefore provides for a basic buffer to which others can be chained as necessary. Fragment 3.4 illustrates the buffer and buffer management structures employed. As parsing proceeds the current buffer is populated with a continuous series of records, each consisting of:

- One byte of record-type identifier denoting the record (and link) type
- The record itself, which may be:
  - A null-terminated character sequence representing a URL

- A null-terminated character sequence representing a base URL (used in relative URL resolution)
- An end of base scope marker
- A four byte sequence representing a relative time stamp giving the arrival time of the segment containing the link (the time stamp applies to all following links until the next time stamp is encountered.)

When the end of the flow is reached and data dumped, the chained buffers are coalesced and prepended with a count of content length.

3.3.3.8 Dynamic Flow Recognition

Identifying traffic within flows of interest will usually be based upon the *well-known* port at the server as described in Section 3.3.3.4. However in the case of some services the server will not communicate via such a well-known port, or port allocation may be dynamic; the RTSP [Schulzrinne98] protocol, for example, defines a negotiation between client and server during which the server port is determined.

Services using a known port outside the well-known range are trivially catered for — the port number can simply be coded into the table of significant port numbers of interest in the normal way. Where services using negotiated port numbers are to be investigated it is anticipated that a module with knowledge of the syntax of the negotiation protocol (which will be directed to a known port) will be deployed and will identify the port to be used. This port can then be entered into the table of ports of interest, and a suitable SSU inserted into the SSU hash table — as the base SSU will be a TCP or UDP SSU it will also discriminate packets based upon IP addresses so will not accept other, unrelated, traffic which may also be using the same port number.

3.3.4 Data Output

Sections 3.2.1 and 3.2.2.1 introduce the need for buffering between the extraction of data and its storage on disc. The data generation rate will be variable due to bursty packet arrivals and variations in the computational expense of data extraction, and it is desirable to commit to disc efficiently in multiples of the block size. The relationship between stored data and output buffering is illustrated in Figure 3.1 on page 47.

As flows terminate, extracted data, held in state, is *dumped* into a log output buffer as a series of continuous records in the format to which they will be written to disc. The format must reflect the variable nature and format of the data collected and must therefore be *self-specifying*. Each record opens with a header containing a record *type*[10] identifier and an integer record length count: the type identifier is used, when retrieving data from disc, to

[10] Output record types are not confined to those recording extracted data — others may record interesting phenomena or probe-centric data as explained in Sections 3.3.6 on page 72 and 3.4 on page 73.

identify the data type and format of the DAU *meta data* block following the header; the length field is used during retrieval to step over unwanted records.

Dumping is triggered by the `close` function of the method suite provided by service-level protocol modules, which will invoke the services of the corresponding `dump` method. Where SSUs are linked, dump invocations will be chained to save all data from the various SSU subcomponents of the overall SSU. At least one chained dump call will normally be made — to the appropriate transport-level SSU associated with the service. Data dumping functionality must reside with the protocol processing modules as it is they who define and understand the protocol specific data storage format and any state denoting the nature and degree of the data extracted. The data held as part of any top-level SSU will contain a flags field denoting which data constituents have been extracted and consequently which nested data structures are to be dumped. In the case of the TCP module, for instance, connection *meta data* (shown in Figure 3.3 on page 59) will always be dumped and contains flags indicating which directional traffic has been seen; one or both *directional* sub-SSU state repositories will be dumped accordingly. When data is retrieved from trace files the same meta data fields will be used to indicate the format and presence of the saved data. Figure 3.4 illustrates how the dump format is controlled by the contents of state.

The output buffer is configured as a *memory mapped* file and is therefore written out to disc by the operating system's `piod` thread as blocks of data accumulate. The only memory copy involved in data output is therefore that of dumping data to the buffer. This copy is unavoidable as the unpredictable nature and extent of the data as it is extracted denies the possibility of formatting or reserving buffer space until the termination of each flow.

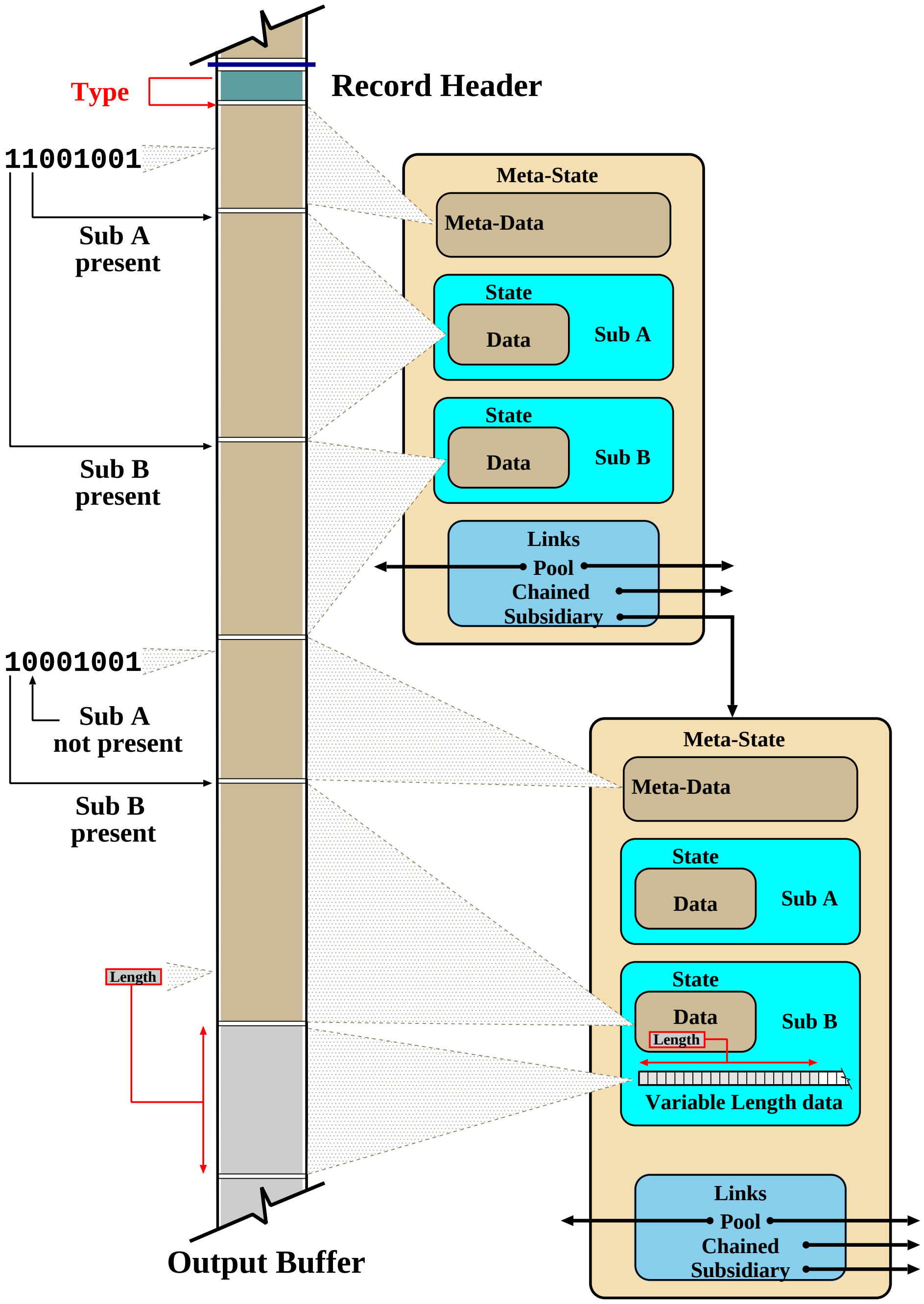
Even with the high data reduction ratio achieved by `Nprobe` very large trace files will be gathered which may exceed the maximum file size allowed by the system. Output is therefore divided amongst a succession of trace files, a file cycle being signalled when a predetermined number of bytes have been dumped. Although the memory mapped output file is configured for asynchronous operation, the unmapping of a completed file (which will cause it to be closed and the file cache buffers to be flushed) can cause the unmapping process to block for a short period. Because continuous processing of incoming packets is critical to avoid receive buffer pool exhaustion, each `Nprobe` process spawns a file management thread at probe start-up which manages file cycle operations. As this thread is called upon infrequently, the context switch overhead is acceptable.

3.3.5 Protocol Compliance and Robustness

When processing very large numbers of packets and flows it is inevitable that some will be encountered giving rise to *maverick* conditions:

Pathological conditions: Which may arise from poor protocol implementations, misbehaving or poorly configured hosts, malformed packets or protocol headers, corruption of packet contents, or other errors.

Protocol specification infringements due to erroneous implementations: Some Web browsers



Note: Each record is preceded by a header indicating the record *type*; the top-level SSU *meta data* indicates which sub-units of data are present, each sub-unit may also contain meta data indicating the presence of more deeply nested data. The meta data will also indicate which further chained or linked SSU data is present. Data units will indicate the presence and extent of any variable length data.

Figure 3.4: `Nprobe` **data dump format**

and Servers, as an example, terminate HTML header lines with a lone `<NL>` rather than the specified `<CR><NL>` sequence.

Flow interruptions: Missing packets which have been lost in the network or due to routeing changes).

Intentional protocol infringements: One family of Web browsers, for instance, does not conform to the standard TCP four-way handshake after receiving an HTTP object on a non-persistent connection — it simply transmits a `RST` segment. The TCP module must be capable of differentiating such behaviour from `RST` segments indicating pathological connection conditions.

Inconsistencies due to probe placement: Because the probe may be placed in an arbitrary position at any point between communicating hosts, normal protocol semantics may not fully apply. Multiple concurrent TCP connections, for instance, may appear to exist between the same two hosts *and same two port numbers* — a `RST` segment, for example, may be sent by one host followed by a `SYN` segment opening a new connection between the same two ports. Traffic belonging to the first connection may still be seen arriving from the other host. Such a case is compounded by hosts which do not correctly implement the selection of TCP Initial Sequence Numbers and reuse the sequence space of the original connection.

Content or behaviour which is correct but which is not understood by processing modules: The complexity inherent in network and end system dynamics, and component interactions, will give rise to situations that the probe is unable to dispose of correctly — to foresee every circumstance that will arise is infeasible.

In the case of a simple probe which copies packet content verbatim, the problems posed by such mavericks are deferred until post collection analysis of traces, but a data-extracting probe must be capable of handling any condition without interrupting normal operation, corrupting collected data, extracting erroneous data, or itself entering a pathological state — it must be *robust* in the face of whatever arrives[11] on the network.

Maverick conditions arising from pathological states or protocol compliance failures will normally be detected during packet processing as checksum failures, malformed packets or protocol headers, or breaches of protocol syntax or semantics. A distinction must be made between *incorrect* and *misleading* semantics: the former (e.g. pathological errors in TCP sequence numbering, contradictory HTML header fields) are detectable and action can be taken; the latter (e.g. incorrect HTML Last-Modified header fields, inaccurate HTML content) are not. The `Nprobe` implementation, in attempting to identify such conditions, is guided by consideration of how problematic packets or content would impact upon *the receiving host or application*; thus the former category may generate an error condition, the latter would probably also remain undetected by the recipient.

Detectable errors will result in one of the following outcomes:

[11] Or, conversely, sometimes, what does *not* arrive.

The condition is regarded as pathological: An error condition is generated and processing of the packet is dropped — detailed processing will not be carried out on any subsequent packets of the DAU.

The condition is not pathological, but further full processing of the DAU packets is impossible: For example a missing TCP segment over which a higher-level protocol module cannot resynchronize with the byte stream or an HTML header parse failure.

The error is fatal only to processing of the individual packet: If recovery is possible normal processing may resume with subsequent packets.

Disambiguation or toleration of probe position inconsistencies: Apparently concurrent TCP connections between the same host/port pairs, for instance, can largely be resolved by maintaining SSUs for each connection and assigning packets to a particular flow on the basis of sequence space feasibility; delays between seeing the final packet of an HTTP response and the first packet of a subsequent request on a persistent connection may make it impossible for the probe to tell whether or not pipelining is taking place — processing must proceed correctly without this knowledge.

The condition would probably be accepted by the receiving host: The probe must attempt to accommodate it (e.g. minor syntactic errors; the HTTP module can, for instance, parse header lines missing the `<CR>` part of the delimiter).

In all cases the SSU and corresponding data will be marked and the type of error recorded.

Considerable ingenuity has been invested in attempts to ensure that maverick conditions are detected and the correct action taken, particularly in the case of minor or recoverable errors. The law of diminishing returns, however, applies: some problems will be too computationally expensive to detect or recover from, and others will be too rare to reasonably accommodate. Where to set the cut-off point is subject to arbitrary decision, but the `Nprobe` implementation sets a target of successfully processing 99% of all incoming packets. Some semantic irregularities or inconsistencies may be detectable, and corrective action possible, during data processing when the absence of time constraints allows greater computational resources to be employed, and when data can be integrated and compared across DAU boundaries.

3.3.6 Error Handling, Identification of Phenomena of Interest and Feedback into the Design

In addition to the main trace files `Nprobe` outputs an *error log* to which offending packets are written in their entirety when error conditions are generated. This log file is formatted as a `tcpdump` trace file, but with the MAC/LLC header overwritten with an error code and some (error dependent) bytes of additional information; the interface type field of the `tcpdump` file header identifies the file as generated by `Nprobe`.

The `tcpdump` format was chosen as it allows examination of the error log files using `tcpdump`[12],

[12] A slightly modified `tcpdump` is used which is capable of interpreting and printing the data over-writing the LLC/MAC header.

and in particular because the packet filter can then be used to select packets for display or extraction by error type (possibly in combination with other criteria). As `Nprobe` can take packet input from `tcpdump` trace files (see Section 3.3.1.4), offending packets can be re-offered to the analysis process multiple times as an aid to module development or improvement. The error log output is managed by the file management thread and file cycling is synchronised with that of the trace files.

When error conditions arise resulting in the situation where further data extraction is not possible for the remainder of a flow it is still, nevertheless, desirable to track, and account for, any subsequent packet arrivals (e.g. the HTTP module provides for two types of *dummy* transaction SSU; these accumulate a count of packets and octets arriving after error conditions or sequence voids).

Conditions, or phenomena, of interest may arise during probe operation which it is desirable to record, but which do not form part of the data normally extracted: it may, as an example, be wished to count occurrences so as to determine whether extraction code should be enlarged to handle certain conditions, to identify unusual correlations between data, or to note minor syntax infringements. A C macro, which can be placed anywhere in a processing module, identifies the desired condition and causes a record of type `interesting` to be written to the normal log buffer; the record is textual and therefore provides a very flexible means of recording all associated data of interest.

A similar, macro-based, mechanism which parallels distributed coarse-grained data discard can also be placed anywhere in the processing modules to dump entire packets to the error log when interesting, as opposed to error, conditions are encountered. Traffic samples conforming to a flexible specification can thereby be gathered.

The mechanisms in this section provide both a means of examining and categorising the cause of error conditions, which can be utilised in the iterative design process, and a means of gathering sample data over a range of granularities for the development of new processing modules.

3.4 Trace and Monitoring Process Metadata

An operating probe will not only generate data extracted from the packets observed — data pertinent to traffic as a whole, and to the probe's own operation must be recorded; such trace and monitoring process *meta data* is gathered and dumped on a periodic[13] basis as a number of output record types which record for each period:

Operational error conditions: Principally the number of packets dropped due to receive buffer pool exhaustion or by the network interface[14]

[13] The period employed is arbitrary, involving a balance between computational/storage cost and granularity, but two seconds is currently employed. A summary of major data items is also presented at the console with a rather greater period.

[14] `Nprobe` is intended to operate with nil packet loss but rather than shut down the system if loss occurs it is

CPU and system usage: CPU cycles accounted to the `Nprobe` process, interrupts taken, context switches, page faults, I/O blocks, memory Resident Set Size, and number of page swaps as retrieved from the `/proc` pseudo-filesystem

Process receive buffer and SSU pool usage accounts: The number of buffers withdrawn and returned to the receive pool and the maximum number concurrently held, together with similar data pertaining to the SSU pool

Timeout accounting: The number and type of connection and reassembly timeouts, and the minimum timeout period necessitated by SSU pool availability

Traffic statistics: A count of total packets and octets received with categorisation of type and sub type(s) at the granularity and level of detail provided by the various protocol processing modules; the arrival bandwidths of major traffic classes

Output file usage: The total number of bytes and records or packets written to the trace and log files respectively, both overall and in respect of the current file cycle

Operational meta data: Which is saved at each file cycle and includes the file start and end times, `Wan` software version and configuration, hardware version and operational parameters of the monitoring run

Disposal summary: Saved on a per file basis giving a summarised total of the periodic data, the number and type of error conditions encountered and successful flow terminations, maximum and minimum values for the number of concurrent active flows of each type, and maximum and minimum arrival rates for the major traffic types

New probe deployments and shifting traffic patterns dictate that overall operating parameters (e.g. the relative proportions of the various SSU types held in the pool) have to be tuned; the availability of suitable meta data informs this process.

3.5 Hardware and Deployment

`Nprobe` was initially developed on a DEC Alpha 3100 workstation equipped with a four GB hard disc and network interface provided by a TurboChannel FDDI NIC fed from an optical tap in the University of Cambridge Computing Service (UCCS) internal FDDI ring.

Further development was carried out using the probes which have been deployed to date: dual Intel 500 MHz Pentium III machines with 64 GB software RAID discs. These probes have been fitted with Fore 200LE ATM and Alteon ACEnic 1 Gbps NIC cards and deployed to monitor traffic traversing the link between the UCCS and the United Kingdom Joint Academic NETwork (SuperJANET) and in the switching centre of a large commercial Internet Service Provider (ISP).

preferable to record loss rates periodically. Traces with unacceptable loss can be rejected. SSU pool exhaustion is regarded as a fatal error condition as it may result in massive data loss. The shutdown condition would be recorded.

A new generation of more powerful probe machines are being acquired (April 2003) based upon dual Intel Xeon 2.4 GHz processors with 4 GB of DDR EEC memory, each equipped with thirteen 200 GB RAID discs. A range of deployments across institutional and ISP locations is planned.

3.6 Probe Performance

Deployments to date have not strained the probe's capabilities — traffic rates of approximately 120 Mbps with HTTP content of 95 Mbps have been monitored continuously without packet loss, with the consumption of less than 20% of available processor cycles on a 500 MHz development machine, and achieving a data-reduction ratio of approximately 12:1. Calculation of capacity based upon off-line data extraction (i.e. running the monitoring software with input from `tcpdump` trace files) suggest that the software itself will keep pace with bandwidths of approximately 780 Mbps, using a single 2.4 GHz processor, when a small number[15] of concurrent connections are monitored.

Benchmarking tests have been carried out[16] using traffic generated by clusters of machines and concentrated via a common switch. The test load has encompassed a range of traffic mixes, packet sizes, and numbers of concurrent connections, and has also included the replay of real traffic multiplexed to the desired line rate by modifying host IP addresses. The results, described in [Moore03], suggest that any one of several factors may limit monitoring capacity.

The performance of the available Gigabit Ethernet cards varies, and unfortunately, their capacity to perform at nominal ratings over single packets does not, in general, extend to a sustained ability to deal with trains of small packets. The appropriate combination of NIC and motherboard are necessary to achieve optimal performance, as underlined in a study by Hughes-Jones *et. al.* [Hughes-Jones93]. PCI bus bandwidth can prove a bottleneck, and at high arrival rates interrupt handling becomes problematic. A high number of concurrent connections, and hence high state memory requirement, can cause the extraction software to become a limiting factor due to frequent processor cache misses. As other components of the system are tuned and optimised trace bandwidth onto disc will eventually become a further bottleneck.

Initial tests based upon a *single* data extraction process running on a 2.4 GHz processor suggested that live traffic loads of approximately 790 Mbps could be accommodated over a limited number of concurrent flows, the rate dropping to 280 Mbps when using replays of real traffic mixes. When all non-HTTP traffic was removed from these traces a sustainable monitoring rate of 189 Mbps was achieved. It should be noted, however, that these results were obtained using standard interface drivers and un-optimised extraction code with full debugging and 'safety' features enabled. Since they were performed, considerable improvements to capture rates have already been made, and there is confidence that full capture approaching 1 Gbps using a single probe will shortly be achieved — and will be exceeded using the emerging faster

[15] A small number of connections, in this context, meaning those whose state can be accommodated in the processor's L2 cache.

[16] The benchmarking work has been carried out by Euan Harris, Christian Kreibich and Dr. Andrew Moore of the Computer Laboratory Systems Research Group.

PCI bus technologies.

3.7 Security and Privacy

Because on-line monitoring can potentially examine and record the entire content of network traffic, regard must be paid to issues of the *privacy* of users and the *security* of content; to these should, perhaps, also be added the protection of researchers — consider the position of an investigator who unintentionally discovers illegal activity.

The accepted practice in addressing these issues is to *anonymize* IP addresses and to limit data capture to the lower, and essentially content free, levels of the protocol stack. The first of these mechanisms, it is argued, may provide an illusory security and may place considerable practical limitations on the useful information content of captured data; the second is, of course, in contradiction to one of the basic rationales underlying the `Nprobe` design.

It must be remembered that research based upon monitoring is only one of a growing number of legitimate activities which may potentially compromise security and privacy. Most network service providers, whether ISPs, private or public institutions, or other organisations, carry out some form of monitoring — for network or personnel management purposes. In the United Kingdom it has been proposed that ISPs should keep comprehensive records of users' e-mails and Web accesses which will be available, on demand and without legal scrutiny, to a wide range of central and local government agencies. The level of security, and respect for privacy, required in monitoring must be placed in the context of the many potential sources of 'leakage'.

Address anonymization may be classified by method into techniques which render the original address recoverable (i.e. employing symmetrical cryptosystems) or not (using one-way cryptographic functions), and further into those which are *prefix-preserving* (i.e. anonymized addresses based within the same network or sub-net will still be identifiable as such) or not. There are powerful arguments for both recoverable and prefix-preserving schemes: the proposed research may well require identification or aggregation of the original addresses (e.g. all of an ISP's dial-up customers, all traffic to a certain service); original IP addresses may be required in data analysis (e.g. reconstruction of Web page download activity may require DNS look-ups of addresses as explained in Section 7.5 on page 172). Whichever anonymization scheme is employed the level of security offered may be partially illusory: an IP address of 32 bits represents a relatively small search space, and with relatively little traffic analysis (if any is actually required at all) is very vulnerable to a *known text* style of attack. Although the designers of prefix-preserving schemes (e.g. Xu *et al.* [Xu01]) claim security comparable with non prefix-preserving methods it is inescapable that the discovery of one address will compromise others. If recoverable schemes are employed, security rests inevitably with the group in possession of the essential *key*.

Data gathered from higher protocol levels may similarly be anonymized through encryption, but will almost certainly have to be recoverable to be usable, and may be equally vulnerable to known text attack (consider commonly known and popular Web sites). Higher and lower-level data may also be combined to compromise security: the IP address of a Web server may, for instance, be anonymized but will possibly appear as a textual `Host` field in HTTP headers — if one is to be anonymized both must be, and also the requested URL — hence adding considerable, and perhaps unacceptable, computational overhead to data extraction. Anja Feldmann describes the BLT exercise [Feldmann00] as separating the data files containing anonymized IP addresses from those containing HTTP header fields, yet the two must be capable of combination, hence security rests, in effect, in the secure storage of data rather than the mechanism employed.

The essence of the matter rests with *access*; it is argued that any probe-gathered data, anonymized and encrypted or not, is to some extent vulnerable and security must rest primarily in restricting access to it. It is certainly to be hoped that researchers are possessed of no less integrity than others (ISP employees, for instance) with access to sensitive user information, and that their data storage facilities will be at least as secure. Technical security mechanisms must be considered as an adjunct to, rather than as a substitute for, the appropriate use of measures such as Non Disclosure Agreements (NDAs) and data security enforcement.

It may be that, when seeking probe placements, or permission to monitor, researchers feel the need to engage in a certain degree of technological over-kill in order to reassure providers and managers that the issues have been addressed, or to conform to the expectations of their peers. The experience of finding potential deployments for `Nprobe` monitors suggests strongly that the majority of service providers are happy to give access subject only to the appropriate NDAs.

`Nprobe` therefore relies upon access restriction as its primary mechanism ensuring privacy and security. The probes can only be activated by a very restricted group of root users, and data stored at the probe or elsewhere can only be accessed by a similarly restricted group. Access to remote probes is only possible using secure means (e.g. `ssh`) and data is downloaded in encrypted form using similar mechanisms (e.g. `scp`). Address and data anonymization (of, for instance, URLs) can be applied as data is collected if required, using recoverable techniques which may, additionally, provide for prefix preservation.

Addresses are anonymized in the case of traces made available in the public domain or in published results.

3.8 Summary

A unique passive on-line network monitoring architecture has been proposed, which embodies the desirable attributes introduced in Section 1.4 on page 27 of Chapter 1, and is subject to the design goals described in Section 3.1 on page 45. The design rationale employed is described in Section 3.2.2 on page 48 and developed with reference to the themes of *data flow*, *control* and *state*. The monitor would provide a more powerful and flexible tool than hitherto available for harvesting data from the network and would, consequently, enable studies which had previously not been possible.

The main body of this chapter describes the more detailed design and implementation of the monitor — `Nprobe`. The major infrastructure and protocol processing modules have been completed, and although design and development of the probe continue — it is part of the underlying design philosophy that it should be extensible — probes have been deployed and have operated satisfactorily. Traces have been gathered, some of which form the basis of the studies presented in Chapters 6 and 8 which demonstrate the utility of the system.

The success of the design and implementation of `Nprobe`, and the extent to which it has lived up to its ambitious goals may be judged, following the operation of prototype probes, by the forthcoming purchase of a series of more powerful and capable hardware platforms and the planning of their wider deployment.

Chapter 4

Post-Collection Analysis of Nprobe Traces

Chapter 3 has described the implementation of the `Nprobe` monitor and the generation of *trace files* containing data extracted from packets traversing the network. During data collection, packet contents are only analysed sufficiently to allow the correct interpretation of content during data extraction or abstraction, to aggregate data at the granularity of a Data Association Unit (DAU), and to allow flow-based compression. The transformation from data to information will require, at the very least, the retrieval of data from the format in which it is stored in the trace files and, in almost all cases its further *post-collection* association and analysis.

This chapter describes the mechanism of post-collection data analysis and a framework for its design and execution which reflects the unique nature of the traces gathered by `Nprobe`. The framework is introduced in Section 4.1; Sections 4.2 – 4.5 describe its components and the analysis process itself, and Section 4.6 illustrates how the toolkit that it provides is used to construct complex analysis processes. Section 4.7 considers how confidence may be attached to the results obtained, and in section 4.8 implementation issues arising from the use of Python are discussed.

4.1 A Generic Framework for Post-Collection Data Analysis

Analysis of `Nprobe`-gathered data presents challenges which differ both in scale and nature from those inherent in the analysis of more conventional probe traces. The format of the trace files is more complex and is likely to be extended or amended. The data itself is richer and more complex, and consequently the information which can be distilled from it will also be both more sophisticated and diverse. As a result a wider range of analysis *tasks*, or forms of analysis, may be called for to fully realise the information potential of the data.

The design of a data gathering system such as `Nprobe` must, therefore, be accompanied by an *analysis framework* which addresses these issues. Such a framework should recognise the differing demands of two broad phases in the analysis process:

- Analysis development: calling for an *analysis development environment* supporting fast assembly of analysis software from existing components, reasoning about the meaning and relationships of data items, iterative analysis algorithm design, comprehensive tracing during analysis execution, detailed examination of preliminary results, and a high level of code re-use
- Generation of results: where mature analysis code is run on complete traces and the emphasis is on summarising, selection, and the presentation of results

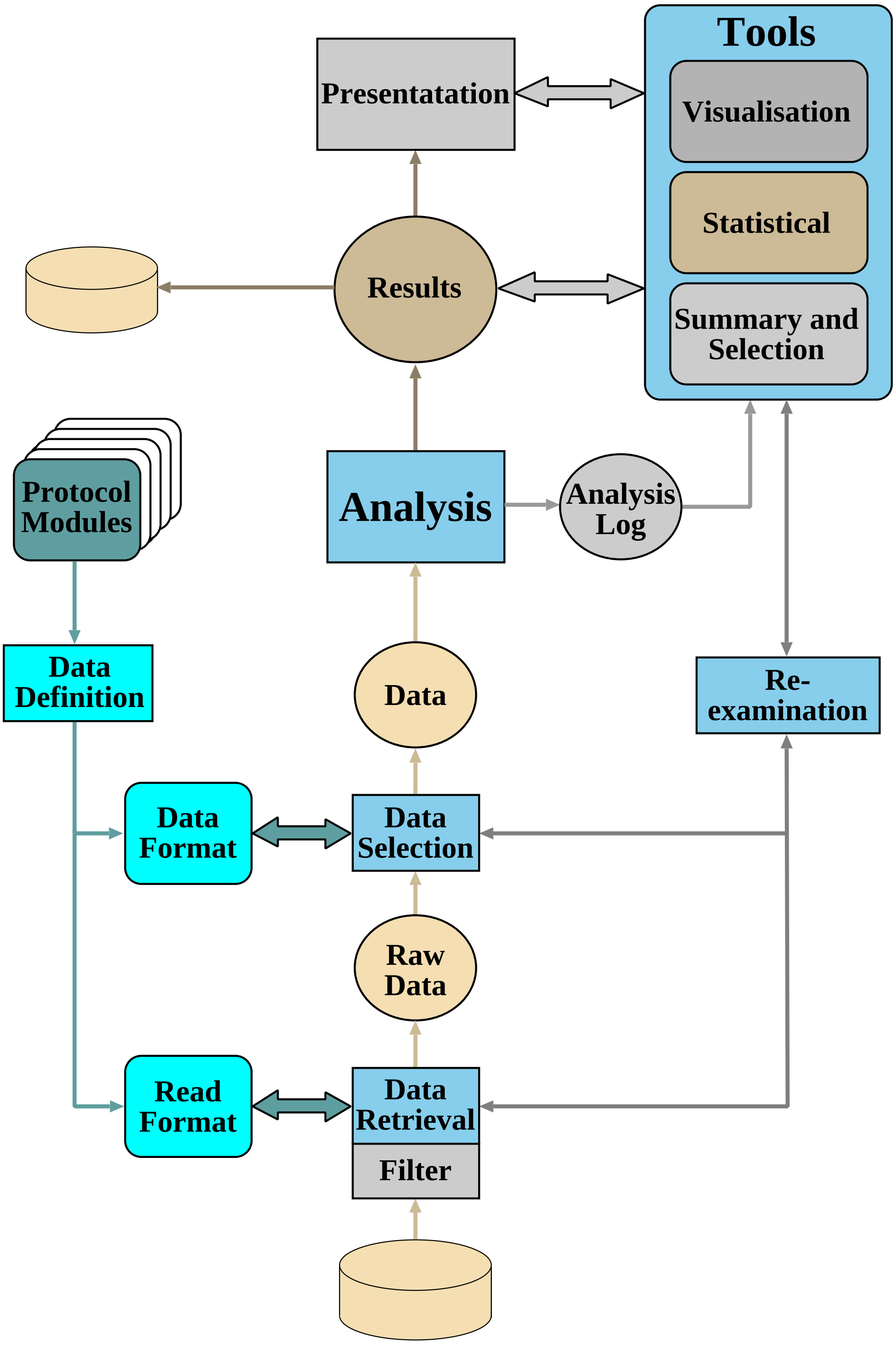
The principal components of the `Nprobe` data analysis framework and their relationship to each other are shown in simplified form in Figure 4.1.

The analysis framework and analysis tasks related to specific studies are implemented in Python [Python01][Lutz96]: its late binding, powerful high-level data types, object orientation, modular structure, and suitability for quick prototyping make it attractive for use in complex analysis tasks where there may be a considerable degree of code re-use. Section 4.8.1 on page 106 enlarges upon the suitability of an object-oriented language for writing data analysis software, and some of the difficulties inherent in the use of Python are discussed in Section 4.8.2.

4.1.1 Modularity and Task-Driven Design

Analysis design will be motivated in three ways:

- Identified tasks: where directed research requires specific, predefined, information.
- Suggested tasks: arising where analysis results indicate that additional information may be available, or that further phenomena of interest may be investigated. The scope of the data gathered by `Nprobe` makes it likely that, even when data has been gathered tailored specifically to the needs of an identified task, further, suggested, tasks will be generated during analysis, or that additional identified tasks may be based upon the same data set.
- Exploratory analysis: because `Nprobe`-gathered data is so rich, it will often contain values or correlations not envisaged when identifying the data to be collected, and which do not fall within the scope of suggested analysis tasks. Exploratory analysis may be particularly suggested when:
  - Traces contain *speculative* data (i.e. not identified in advance as required for a particular research goal, but gathered for the sake of completeness or its potential informational content).
  - *Archival* traces are gathered (e.g. for purposes of future research or time based comparison). Patterson *et al.* [Patterson01] identify the need to collect such traces which are, by their nature, entirely speculative.



Note: Individual protocol modules determine the disc format and the selection of the required data items. Analysis results may be selected, presented and saved under the control of summary and selection, statistical, and visualisation tools.

Figure 4.1: `Nprobe` **data analysis**

Even disparate analysis tasks will share some common functionality (e.g. the manipulation of trace files, selection and retrieval of data from trace files, the aggregation and presentation of results, and other utility functions), but rising to a very high degree in the case of suggested or additionally identified tasks. The decomposition of any analysis task will, in other words, identify many sub-components (both utility and analytic) which are shared with other tasks. A series of modules, or components, are required which can be reused and composed as necessary to meet the requirements of the current analysis task, new modules being added when necessary and enlarging the existing pool of components. Top-down analysis design will therefore become a matter of recursively decomposing a task until sub-tasks can be met from the set of standard or existing modules and any new components identified and implemented.

The analysis framework may therefore be regarded as providing a *toolkit* of utility and analysis components, which can be combined as required to meet the requirements of specific tasks with the minimum duplication of functionality and expenditure of time spent in the development of analysis software. The toolkit also contributes the analysis development environment.

Analysis framework or toolkit components may consist of Python modules, module-level functions, classes, or class methods, as determined by the functionality provided and the way that they will be used in conjunction with other components. At the highest level, analysis will be driven by a Python *script*, which will import and call upon the services of the required components. Simple analysis tasks may be implemented in a very few lines of code using only basic data retrieval components, but even comparatively complex tasks can be executed by a relatively short script which imports and uses the more sophisticated higher-level analysis and utility classes.

4.1.2 The Framework Components

The components of the data analysis framework fall into four categories:

A consistent data retrieval interface: Traces gathered using a monitoring system such as `tcpdump` consist of a series of verbatim extracts of packet content, each prepended with a header containing data such as arrival time stamp, packet length and capture length. Successive headers are read from the trace file, identifying the length of the following (possibly partial) packet to be read. Post collection analysis is presented with pertinent data from the header (e.g. time stamp and packet length) and as much of the verbatim packet contents as were captured. Before any analysis can proceed the required data must be extracted from packet contents.

In contrast, `Nprobe`-gathered traces contain data already extracted from packet contents during collection, but due to the variable degree, nature, and format of the data, retrieval from trace files is more complex, and the required subset of the total recorded data must be selected. Section 3.3.4 on page 68 explains how `Nprobe` trace files consist of a series of records with a self specifying format, and Figure 3.4 on page 70 illustrates the mechanism diagrammatically.

Differing studies may require the retrieval of a varying set of trace records from trace files, and of varying sets of data selected from those records. Because `Nprobe` is intended to be extensible, and to be flexible in its collection of data, new protocol modules may be added, or existing modules amended or extended. In order to avoid the need to rewrite analysis code from scratch in each case it is necessary to provide a uniform *data retrieval interface* for the recovery of data from trace files, and its selection in canonical form. The interface should, furthermore, as far as possible, be transparent to changes in trace file format, and allow the simple addition of new data record types.

The data retrieval interface is described in detail in Section 4.2 on the next page.

Data analysis components: The very simplest analysis may be implemented by the appropriate code contained within a script, but as explained in Section 4.1.1 and Section 4.8.1 on page 106 it will normally be preferable to implement analysis components as the methods of dedicated *analysis classes*. Sections 4.3.1 on page 87 and 4.3.2 on page 88 introduce *protocol analysis classes* providing analysis methods applicable to individual instances of protocol use and Section 4.3.3 on page 88 explains how *associative analysis classes* are used to aggregate and analyse data pertinent to several instances of a protocol's use and where data spans protocols.

As new analysis tasks are encountered new classes will be written, new methods added to existing classes, or existing classes will be sub-typed to modify their functionality. By implementing analysis functionality in this way the repertoire of components made available to the toolkit is continually enlarged.

Data conversion, analysis support, and general utilities: There are many low-level and utility functions shared by a range of components, together with functionality required to support analysis tasks independent of the nature of the task itself. Section 4.8.2 on page 106, for instance, describes how data conversion or manipulation is required in the case of some C data types not supported by Python, Section 4.3.5 on page 89 introduces the common support required to accumulate analysis results, and Section 4.3.6 on page 90 explains a method of storing data locations to enable partitioning of analysis tasks. It is convenient to make these and similar functionalities available as a set of utility components.

Tools for summarising, examining, selecting, and presenting results: The toolkit provides tools for summarising, examining, selecting, and presenting results. These tools, which are described in more detail in Section 4.4 on page 91, will be used primarily for the management of results when running mature analysis code, but when used during analysis development contribute primarily to the analysis development environment.

Tools for visualising trace file data and analysis results: The bulk and scope of trace file data call for tools which render the data and the relationships that it contains in a compact and readily comprehensible form. Visualisation provides a powerful aid to understanding and reasoning and is supported by the tools described in Section 4.5 on page 93.

Framework components are used to construct a *trace file reader*, which although not part of the framework is an essential accompanying utility. A Python script uses the data retrieval interface and textual presentation methods contributed by `Nprobe's` protocol modules to read a trace file and present its contents in human-readable form. Multiple trace files, representing the whole, or part of a monitoring run, may be specified as input, in which case the trace meta-data is aggregated appropriately. The reader permits rudimentary file navigation by applying a set of input filters, specified in the command line, which determine the record(s) to be displayed using one or more of the criteria: record type(s) or identifier; originating host(s); protocol(s), or connection identifier.

4.2 The Data Retrieval Interface

`Nprobe` trace files contain binary data as records in the self-specifying format described in Section 3.3.4 on page 68 and consist, in essence, of a series of dumped C structures. The content and format of these structures is, in turn, determined by the type definitions of the various `Nprobe` infrastructure and protocol-specific packet processing modules. An interface is required, therefore, between trace files and analysis code which performs not only the retrieval of data from disc, but its conversion to a form suitable for use in the Python analysis code. It would be possible to hand craft such a data retrieval interface, but this would be a time consuming task, and would not meet the requirement that the interface be transparent to minor changes or additions to the underlying C structures — even minor changes would require laborious re-writing of parts, or all, of the interface. The core of the required interface is therefore generated automatically by the Simplified Wrapper and Interface Generator (SWIG) [Beazley96], the operation of which is described in greater detail in Appendix A.

4.2.1 Data Retrieval Components

Data retrieval from trace files draws upon services provided by several Python modules:

A trace file manipulation module: Which exports a `get_files` function taking as its argument a list of one or more trace files[1], or a directory containing trace files, orders the files and checks for continuity, and aggregates monitoring and traffic meta-data. The meta-data and a list of open file objects are returned.

A flexible filter module: Containing an infrastructure which constructs a filter allowing selection of DAUs for analysis based upon arbitrarily complex predicates which may be composed and may span multiple protocols. Predicates are selected as an analysis process command line argument.

The SWIG-generated file interface module: Which defines the principal classes based upon the required `Nprobe` infrastructure and protocol module C data structure definitions:

A TraceFile class: Which provides trace file *navigation* methods (e.g. analogues of `fseek` and `ftell` file-positioning functions, step over the current record), record *selection* methods (e.g. to position the file pointer to read the next record encountered of

[1] It is explained in Section 3.3.4 on page 68 that, for all but the shortest monitoring runs, a series of trace files will be generated. Analysis may be based upon a single file of the series, all files, or a subset selected by appropriate use of shell wild-cards.

a specified type or group of types), file *reporting* methods (e.g. to provide textual summaries of file contents or monitor meta-data), record *retrieval* methods which build upon the record selection methods and DAU classes to return objects of those classes populated with data, and various other *utility* methods relating to manipulation of trace files as a whole.

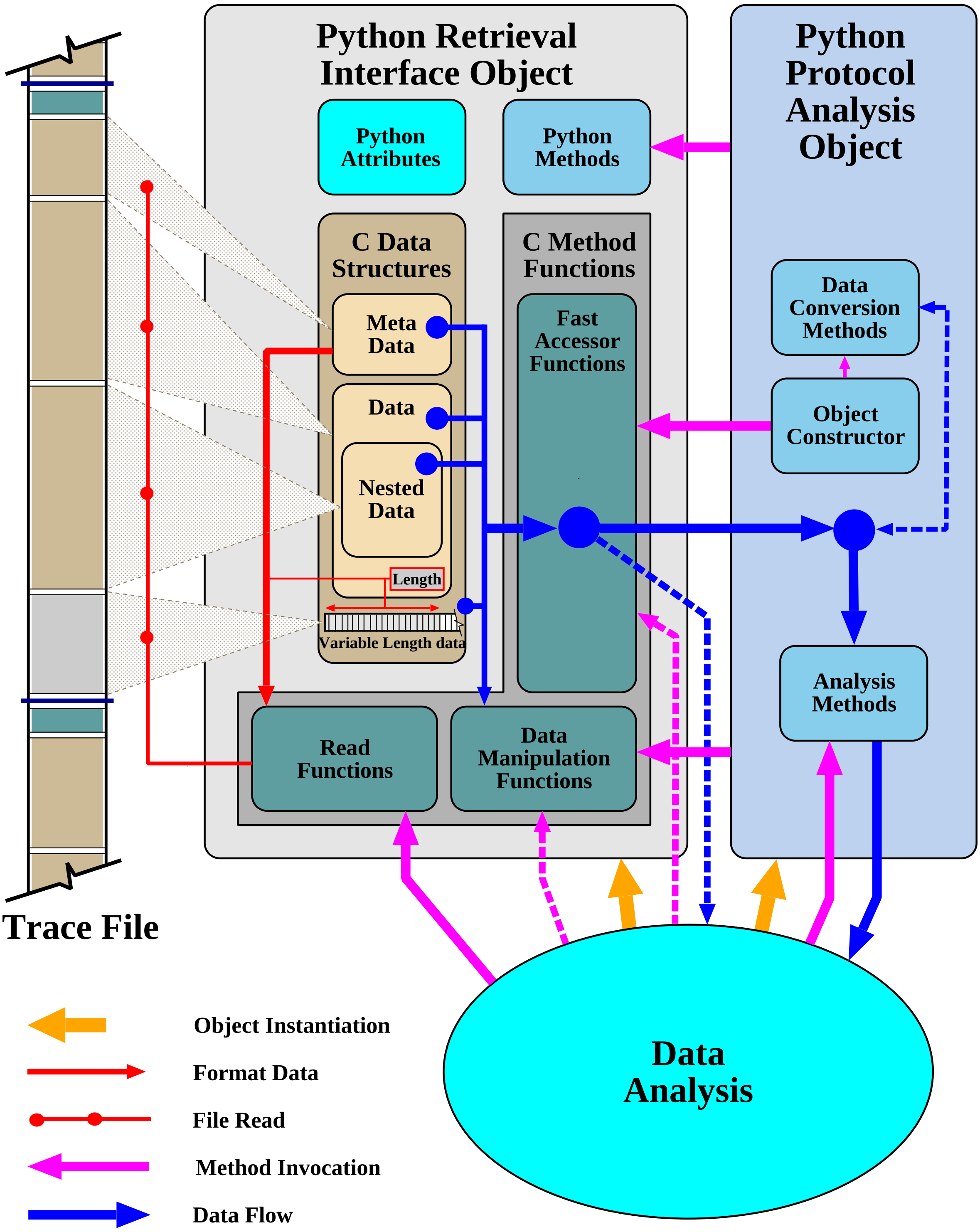
Data retrieval classes: Whose primary purpose is to provide a mechanism for reading formatted data from trace files and fast accessor functions to individual data fields.

Utility classes: In some instances data manipulation is required which is not readily accommodated as a method of one of the existing classes. In other cases classes needed for analysis purposes perform the majority of their data manipulation upon the C based structures underlying the basic retrieval classes. In these situations it is advantageous to define utility classes as a set of C structures and functions for which SWIG will generate a Python interface — access to data is hence more efficient, and manipulation can be carried out with minimal crossing of the C/Python interface. The list of *links*, for instance, contained in an HTML Web object are recorded in a buffer of type *char*, as explained in Section 3.3.3.7 on page 66, in which header type fields, textual strings and multi-byte integer values are serialised. The reconstruction of Web page downloads described in Chapter 7 makes use of a *Link* class; in order to populate objects of this class the buffer must be parsed and values of the correct *type* extracted — a trivial task to implement using C pointer manipulation and type coercion, but which would be complex, and less efficient in Python.

Module-level utility functions: Many utility functions required during analysis are `Nprobe` specific, are not provided by standard Python modules, are more efficiently invoked from C, or (where provided by Python) may be more conveniently accessed from the interface module. Such functions are provided as SWIG-generated module level Python functions by inclusion of the appropriate C prototypes and implementation code (which may be hooks into functions provided by standard libraries or elsewhere in the `Nprobe` code) in the SWIG interface definition file. Examples of such functions include byte-ordering utilities, textual representations of *abstracted* or *coded* data values, or name/address translations.

Class utility modules: It is convenient to provide utility modules which provide functions associating high and low level or related protocol-based classes, or instantiate and populate sets of classes. A `http_util` module, for instance, exports a function `get_conn_and_trans` which, given a file positioned at the start of a file record containing data appertaining to a TCP connection carrying HTTP transactions, will instantiate the appropriate TCP and HTTP transaction DAU retrieval classes, populate them with data from the trace file record and return the TCP object together with a list of the transaction objects.

As data retrieval from trace files involves a series of highly iterative operations, as much as possible of the data retrieval functionality is implemented in C. The data retrieval interface is illustrated in Figure 4.2.



Note: Data analysis code or objects instantiate an object of the appropriate SWIG-generated retrieval interface class and call its `read` method to populate it with data contained in the serialised record structures. Data may be selected from the retrieval object using its accessor methods, but the analysis code will normally instantiate a higher-level protocol object whose constructor will call the retrieval object's accessor methods and its own data conversion methods. The dashed method invocation and data flow lines indicate optional routes.

Figure 4.2: **Data retrieval from `Nprobe` trace file records**

4.2.2 Data Retrieval

The classes generated by SWIG do not store the values of data attributes in the normal Python internal representation, but in the defined C structures as part of the underlying C implementation of the class. The read functions provided by the `Nprobe` modules can therefore *populate* retrieval class objects with data from trace files simply and efficiently by reading a block of data from file into the corresponding structure. It is the function of the accessor methods to select individual data items from the C structures and return their Python representation.

Trace file objects' `get_next_rec` method provides the mechanism to sequentially locate trace file records of the required type(s). The records' header fields indicate the precise record type and hence the data retrieval class providing the appropriate `read` method. The first data to be read will be meta-data, part of which specifies which structures are present in the serialised record. Where nested or chained data is present, the process continues recursively until the entire record is read, and the retrieval class instance(s) fully populated with the data present.

Appendix B provides an example of the use of the data retrieval infrastructure to read `Nprobe` trace files during the analysis process. Code Example B.1 on page 205 demonstrates how the use of retrieval classes and standard utility functions enables analysis functions or scripts to retrieve data in a very few lines of code; Code Example B.2 on page 207 illustrates the function of retrieval classes in greater detail.

4.3 Data Analysis

Data analysis processes will call upon a range of components provided by the analysis framework, but as explained in Section 4.1.2 analysis functionality is provided primarily by a collection of analysis classes.

4.3.1 Protocol Analysis Classes

Although analysis code can access data using the retrieval classes' accessor functions, this is, in most cases, not the optimal mechanism:

- The same data item may be referenced several times, each occurrence requiring translation at the C/Python interface.
- Many data fields are of types not directly supported by Python (e.g. unsigned or long long integers as explained in Section 4.8.2 on page 106) and would require mapping on to a supported type for every reference.
- The majority of time stamps are relative; to adjust them to a common base on every reference would be inefficient.

These difficulties could, of course, be overcome by a single recovery of each data value using an accessor function, and its storage in the retrieval class as a Python data attribute after any necessary type or base conversions; the retrieval class would have to be equipped with a set of methods to provide the necessary conversions. This solution is not ideal: Section 4.8.2 on page 106 explains that memory capacity can be a problem when using Python to analyse large data sets, and this difficulty would be exacerbated by, in effect, storing each data item twice. Instead, a higher-level *protocol analysis* class analogous to each protocol specific State Storage Unit (SSU) of the DAU-based retrieval-level classes is defined in which the data values are stored after any conversion. Data retrieval can now be based upon the use of a single object of each retrieval class whose `read` method is repeatedly called for each new record; the object is passed as an argument to the protocol class constructor and its accessor functions invoked to select the required data during instantiation of the new object. All type and base conversions are now carried out in the higher-level class' constructor method, possibly calling other, dedicated, class methods. The reuse of a single retrieval object of each class carries additional benefits: repetitious creation of new objects is avoided, and the objects themselves can be instantiated fully equipped with all chained and linked subsidiary SSUs, storage, buffers for variable length data, and optional components (e.g. buffers for TCP packet header data, HTML links buffers, multiple HTTP transaction chains) rather than inefficiently and repeatedly allocate them on a per-record demand basis.

During simple data analysis where few data values are required, where repeated accesses to those values are few, or where the data requires no conversion, the use of higher-level objects is not required and data selection can simply use the retrieval class objects' accessor methods directly.

4.3.2 Discrete Protocol Analysis

Data analysis may be concerned with activity occurring at a single protocol level, or when relating activity at multiple protocol levels may still contain components drawn from a single level. Analysis of *discrete* protocols is carried out by analysis *methods* of the protocol analysis classes, each analysis task being implemented by a dedicated class method and operating on the class object's data attribute values.

As explained in Section 4.2.2 the protocol class objects are populated with data by invocation of the appropriate retrieval class' accessor methods, and at this initialisation stage any necessary type conversions are carried out. The semantic integrity of the data is also checked at this stage.

4.3.3 Protocol-Spanning Analysis — Associative Analysis Classes

Analysis will usually draw from data relating to activity at several levels of the protocol stack. Multi-protocol trace file data is already associated at the granularity of a DAU, and this will be reflected in the grouping of protocol class objects containing the retrieved data. There will also, however, be analysis tasks for which further integration or association of data is required (e.g. all of the TCP connections and transactions involved in the download of a Web page and DNS requests associated with the TCP connections to a Web server).

Such complex analysis requires mechanisms both to gather and integrate the more widely associated data, and to perform analysis on the large data composites which are collected. Analysis of this sort can be carried out by execution of an appropriately coded script, but it is likely that multiple forms of analysis will be carried out on the data composites, and either a specific script for each purpose, or a single and unduly complex script would be required. It is therefore preferable to define a further set of yet higher-level *associative analysis* classes which can be instantiated by a relatively simple script, which act as the aggregation locus for the set of protocol analysis objects of interest, and provide methods for each of the various analysis tasks. Where components of the analysis relate only to one protocol level, the associative analysis objects' methods can invoke the discrete protocol analysis methods of the protocol analysis class objects which they have gathered. Chapter 7 demonstrates how a *WebHost* analysis object gathers together all of the TCP-connection protocol objects relating to a single client with the the HTTP transactions that they carry, and how it provides methods which, for instance, reconstruct Web page downloads, identify causes of delay, and relate the pages downloaded to each other.

4.3.4 Analysis Classes as Toolkit Components

Analysis classes, by forming a locus in which data and analysis methods are associated, contribute analytical components to the toolkit which can be readily selected, combined, or modified. Specific analysis functionality is made available simply by instantiating an analysis object of the appropriate class and calling the class method required, encapsulation ensuring that objects may call upon each other's services without risk of undesirable side effects.

Where new analytical methods are required new classes may be called for, but existing classes will often provide the needed functionality by the addition of new methods or by the modification of their behaviour by sub-classing. The ease with which existing components can be modified ensures that a wide range of tasks can be constructed based upon a relatively small number of basic components.

4.3.5 Accumulation of Analysis Results

Data analysis will generate two categories of output: the analysis results, usually in statistical form, and a record of the analysis process itself; both require accumulation and collation as analysis proceeds through its input data. In accordance with the aim of establishing a generic analysis framework a further utility is provided — the *StatsCollector class.*

Different analysis tasks will generate results with widely varying characteristics and content, which will require similarly differing collation. There are, however, many items of functionality which will be common to all analysis, and the `StatsCollector` class is designed to make these readily available. The following, for example, are provided:

Logging methods: Used to create and manipulate logs of analysis activity. Entries in analysis logs might include *trace statements* recording activity, summaries of the input data or results, notes of data which are not amenable to interpretation by the analysis algorithms, or records of particular conditions or combinations found in the data.

Recording methods: A consistent syntax and format for log entries is provided by a set of recording methods.

Interface methods: Which provide a common interface to tools which summarise, select, or present results.

A consistent analysis control interface: Analysis tasks may proceed differently according to the task in hand; the way in which activity logs are collected may, for instance, vary between analysis intended purely to generate results and that being carried out in an analysis design environment.

The results collection and collation functionality specific to each analysis task are provided by using the mechanisms of sub-typing and inheritance to define task specific collector sub-classes. Such sub-classes may be defined with the required collection and collation methods, or may act as 'results repositories' for similar methods provided by analysis classes.

In their most sophisticated form objects of `StatsCollector` sub-classes control the analysis to be performed by calling the analysis methods of the protocol and associative analysis objects of interest to generate the data which they accumulate. At the completion of analysis the `StatsCollector's` *termination* method will invoke a *Summary* object (described in Section 4.4.1 on page 92) to summarise analysis activity and results.

4.3.6 Memory Constraints

Any analysis of large data sets may encounter difficulties due to the memory requirements of the analysis program exceeding the physical memory capacity of the machine upon which it is being executed; this problem is particularly evident when using Python as described in Section 4.8.2 on page 106. As analysis proceeds working space is needed which remains constant, but there will be an additional memory requirement proportionate to the size of the trace file being analysed due to:

- Accumulation of results
- Accumulation of data pending association or aggregation
- Retention of data which may be needed for further examination

Various strategies can be used to circumvent these difficulties, the analysis task usually determining which will be employed:

Partition of the analysis: The process of analysis may be partitioned in order to reduce memory demands. *Transverse* partitioning (i.e. analysing sub sets of a series of trace files or only partial files) is effective, but may be inappropriate where long-term trends or phenomena feature in the analysis. *Longitudinal* partitioning is often the technique of choice, but may suffer from the disadvantage of additional complexity, the introduction of additional passes through the data, or the need to accumulate data in order to control or identify the partitions.

Accumulation of results in temporary data files: The nature of the data collected by `Nprobe` will normally encourage analysis generating rich and voluminous results (consider complete data concerning the timing, causes and magnitude of packet loss delays for all of the Web page downloads and millions of supporting TCP connections contained in a large trace), and the results of several analysis tasks may be generated concurrently as described in Section 4.8.2 on page 106. The data which will be accumulated during analysis may therefore become very bulky, and will advantageously be stored in temporary files. In this case a further analysis pass, or a separate subordinate analysis program will be required to correlate and accumulate such *intermediate* results.

Concise representation of data held for association, aggregation, or further examination: Data will frequently be held for purposes of association or aggregation but not analysed further until that process is complete (e.g. associating all of the TCP connections and HTTP transactions originating from a particular client). As the data is not immediately required the analysis process need only collate it and store a reference to its location during a preliminary pass and proceed to full analysis during a second pass once association is complete — in effect producing a fine grained longitudinal partition of the data. A further utility class — *FileRec* — makes this possible. The class stores references to the data as a list of open file/offset pairs indicating where the data is to be found together with a type code indicating the type of analysis class relevant to further analysis. The `FileRec` class exports one primary method — `reconstruct` — which instantiates an analysis object of the appropriate type and uses the necessary retrieval classes to populate it with data. Code Example B.3 on page 209 illustrates the use of the `FileRec` class.

Strategies may also be determined by whether analysis is being conducted in its final form or in the analysis development environment. In the former case it is likely that full traces will be analysed, and greater use will be made of longitudinal partitions and the accumulation of results and analysis logs in temporary files. During analysis development shorter traces, or excerpts, will probably be processed, but the ready availability of results and the facility to re-examine the analysis of individual record are, by comparison, more desirable; greater use will therefore be made of `FileRec` objects.

4.4 Analysis Logs, Results and Presentation

Analysis processes produce a log summarising their activity and noting any points of interest encountered which the analysis designer wishes to be recorded. Processes will also generate results which may consist of many sets and subsets of data, which may be large and complex, and which may require examination and management. An interactive *analysis summary tool* presents log contents and results in a convenient form.

4.4.1 An Analysis Summary Tool

The analysis of large trace files will generate large logs recording and summarising analysis activity. Log entries are generated at the discretion of the analysis designer but at a minimum are likely to include data relevant to the analysis process (e.g. the count of file records processed, the number of DAUs encountered) and to record points of note arising during analysis (e.g. situations where analysis could not satisfactorily resolve the data presented or had to use heuristic rather than deterministic rules to interpret it, error conditions, or phenomena of particular interest). During analysis design many additional entries may be made identifying and quantifying situations or values requiring further attention.

The size of log files, and the wide variety of entries, would make it very difficult to identify and collate the information that they contain; support is therefore provided by the analysis summary tool. The tool collates, sorts, and summarises log entries; the summary is presented as a pane containing *top-level* summary entries which can be interactively selected and recursively expanded in detail, hence allowing for fast and comprehensive navigation of the log. Collation may be selected by *entry* (e.g. TCP connections with multiple `SYN` packets) or by *id* (e.g. by connection identifier, Web client address).

As explained in Section 4.3.5 the summary tool is normally invoked from the analysis process's `StatsCollector` object, which is also responsible, during invocation, for providing the tool with a *callback* function; log entries may be accompanied by *tags* identifying the data generating the entry, and which are passed by the tool as an argument to the callback. The callback will identify the type of entry and will re-analyse the data which generated it with full tracing enabled, possibly also invoking the appropriate visualisation tool[2]. Hence an audit trail is established allowing the originating raw data and its analysis to be examined in close detail.

The summary tool may also be used in 'stand alone' mode for the retrieval and examination of logs generated by past analysis processes. When used in this way the facility to examine the origin of entries is, of course, absent.

4.4.2 Summaries of Analysis Results

The analysis process's `StatsCollector` object may generate summaries of the analysis results and references to data sets which are appended to the log. The summary tool also collates, summarises and presents these entries in the same manner as normal log entries.

In the case of results entries, the callback functions provided by the `StatsCollector` will normally present data sets by invoking the *data plotter* tool or other visualisation tools appropriate to the granularity of the summary items. Because the callback is provided by the `StatsCollector`, the system allows for very flexible selection of the data or its subsets which are to be examined.

[2] Visualisation tools are described in Section 4.5 on the facing page .

4.5 Visualisation

Visualisation tools constitute an important element of the toolkit and provide support in the design and mature phases of analysis. They contribute significantly to the design environment, as described in Section 4.5.3, and in assessing informal indicators of confidence as described in Section 4.7.5.

4.5.1 The Data Plotter

The data plotter tool may be used as a stand-alone data plotter but is normally invoked from the summary tool in order to display selected data sets from analysis results. The tool is designed to make the manipulation, examination and comparison of data sets possible without reloading; and provides interactive support for raising, lowering, or blanking out individual sets and a zoom facility. Plotting styles can be varied as desired, and the data re-plotted as scatter plots, histograms, probability and cumulative density functions as appropriate to its type. Basic smoothing methods are also available.

The plotter acts as the principal data management tool allowing selected data sets (or sub sets) or their derivatives (e.g. distribution functions) to be saved or printed. The most significant difference between the plotter and other plotting programs is, however, its facility allowing the user to examine the derivation of data points. A callback and tag mechanism similar to that employed by the summary tool allows the user to select a set of data points and to examine the underlying raw data and the process of its (re-)analysis in close detail.

4.5.2 TCP Connection and Browser Activity Visualisation

The raw trace file data contributing to each datum generated during analysis are likely to be complex and bulky and to have complex relationships (consider the data associated with each packet of a TCP connection, the number of packets that may be sent on a single connection, the complications due to packet loss, and the number of connections that may be involved in a Web page download). The raw data, furthermore will be sparsely distributed amongst the other file contents. Although the trace file reader mentioned in Section 4.1.2 presents trace records in a convenient form, and provides rudimentary facilities for selecting associated data, it would be time consuming, and (in the case of large data associations) virtually impossible to fully assimilate and comprehend all items without assistance. The appropriate visualisation tools will present data in a compact and comprehensible way which assists in identifying the relationships that it represents.

Trace file data analysis is, however, concerned with the distillation of information from the raw data. Visualisation should, therefore, not only present the raw data but also, insofar as is possible the information generated by analysis and the relationships upon which it is based. The analysis framework visualisation tools are designed to meet this requirement.

4.5.2.1 The TCP Visualisation Tool

The TCP visualisation tool, illustrated in Figure 4.3, plots sequence numbers against time in a style similar to `Tcptrace` [Ostermann]. Data segments are shown as vertical arrows scaled to the data length carried, acknowledgements as points, the `ACK` high water drawn, and segments are annotated with any flags set. Other salient data (e.g. window advertisements) may also be shown.

The tool, however, has considerably greater functionality: Chapter 5 explains a technique for examining the dynamics of TCP connections, relating them to activity at higher levels of the stack and identifying application behaviour and connection characteristics. Where connections have been subject to this technique its inferences are also displayed: the relationship between TCP and application activity, causal relationships between packets, and congestion windows are, for instance shown; secondary plots of the number of packets in flight, inferred network round trip times, and application delays are also presented.

Figure 4.3 shows the tool's primary window displaying, as an example, the activity of a non-persistent TCP/HTTP connection. Although the figure contains a great deal of interesting detail comment on a few features illustrates the power of the visualisation:

A The solid purple line to the left of the segment arrows represents the server's congestion window as predicted by the connection model — the number of segments in each subsequent flight increasing as the window opens.

B Packet #13 is retransmitted (packet #18 — shown as a *red* arrow) at approximate time 540 ms.

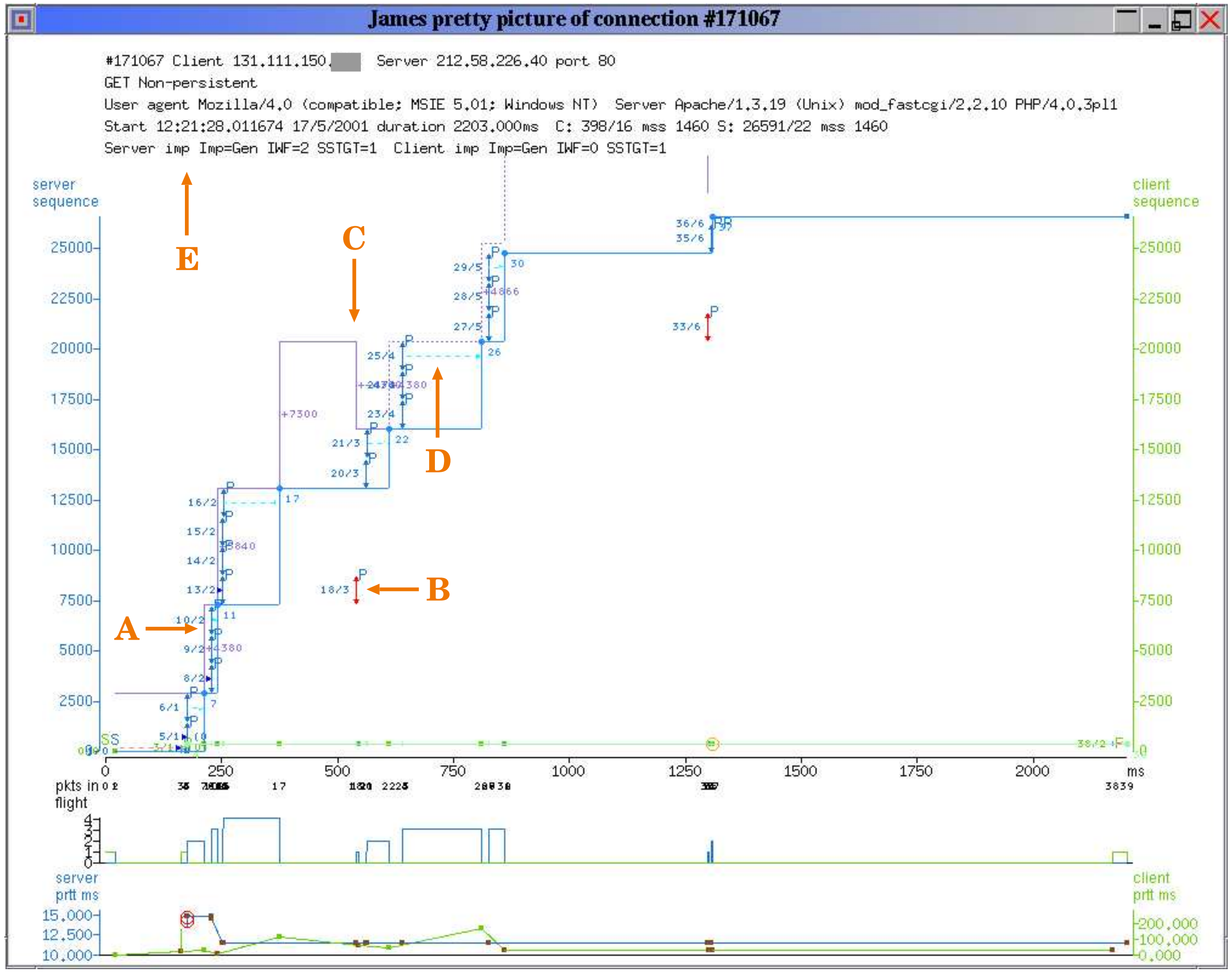
C The server's congestion window shrinks following the retransmission, resulting in a flight of only two segments immediately afterwards. The retransmission also causes the connection to enter congestion avoidance — shown by the broken congestion window line.

D Horizontal dashed lines indicate causal relationships between packets. Here packet #25 from the server triggers an acknowledgement — packet #26 — from the client

E The last line of the legend at the top of the main pane indicates that the modelling process has explained the behaviour the server's TCP implementations based upon a generalised base model of behaviour with an Initial Window of two segments; the client's behaviour is explained by a similar model, but the IW is unknown as less than one MSS of data has been sent. The term `‘SSTG=1’` denotes that the implementations enter the congestion avoidance phase when the congestion window *exceeds*[3] the slow start threshhold.

To ascertain the patterns of TCP activity involved in even the relatively short and uncomplicated connection visualised in Figure 4.3 would require the close examination of 38 packet headers, a time consuming task which might, even then, fail to identify all of the features present. To fully comprehend the activity of a substantial connection, or one with complex

[3] This is the default for the base TCP model — TCP implementations may optionally enter congestion avoidance when the congestion window *reaches* the threshold [Allman99a].



```
#171067 Client 131.111.150.[redacted]  Server 212.58.226.40 port 80
GET Non-persistent
User agent Mozilla/4.0 (compatible; MSIE 5.01; Windows NT)  Server Apache/1.3.19 (Unix) mod_fastcgi/2.2.10 PHP/4.0.3pl1
Start 12:21:28.011674 17/5/2001 duration 2203.000ms  C: 398/16 mss 1460 S: 26591/22 mss 1460
Server imp Imp=Gen IWF=2 SSTGT=1  Client imp Imp=Gen IWF=0 SSTGT=1
```

Figure 4.3: **The TCP visualisation tool's primary window**

features, rapidly becomes a daunting and error-prone task. Such difficulties are, however, minor in comparison with those presented by the need to relate the outcome of the connection modelling process to the packet level data contained in the trace — an essential step to ensure the accuracy of the model constructed. The figure illustrates that visualisation offers a succinct and comprehensive presentation of both the original data and the information synthesised from it, in which features are readily identified and relationships made explicit.

The tool opens a secondary window (not shown in Figure 4.3) which displays a textual representation of the trace file data associated with the connection and which may be toggled between packet and application level data. Displayed items can be selected and recursively expanded to show greater detail.

4.5.2.2 The Web Browser Activity Visualisation Tool

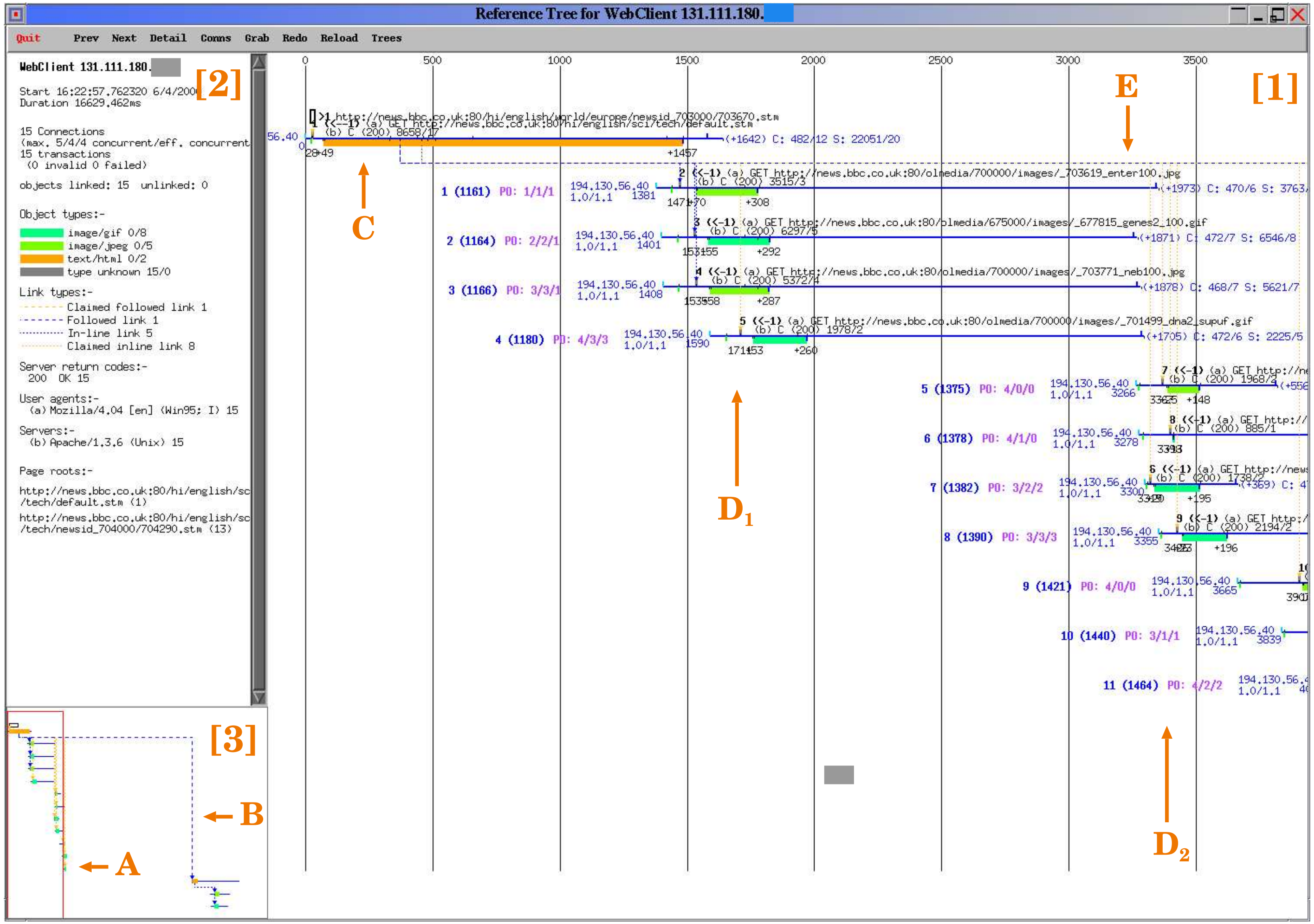
The Web browser activity visualisation tool presents the data extracted from the TCP, HTTP and HTML levels of the protocol stack for all HTTP activity originating from single hosts or client and server pairs. Figure 4.4 on the next page illustrates a small page download.

The tool's main pane [1] displays the TCP connections carrying HTTP transactions plotted against time as scaled horizontal bars with tics showing packet arrival times (at the probe) and annotated (in blue) with details of the connection. Client activity is shown above the bar, and server activity below it. HTTP activity is shown as requests and responses above and below the TCP connection line respectively. Request or response bodies are shown as blocks of colour representing the object type, and are annotated (in black) with the transaction's principal characteristics (e.g. the object's URL, the request type and the server response code).

A secondary pane [2] may be toggled between a display showing a key to the symbols used in the main pane and a summary of the activity shown, or details of individual selected TCP connections in the style of the TCP visualisation tool's secondary window. The TCP visualisation tool may be invoked by dragging over a connection bar in order to closely examine individual selected connections. A further secondary map pane [3] shows an overall view of the entire set of browser activity at reduced scale (the level of detail in the [scrollable] main pane will generate a graph larger than the tool's window for large pages or extended browsing sessions and the secondary pane serves to locate the main pane contents).

Chapter 7 explains how all activity associated with the downloading of entire Web pages is reconstructed from trace data; the tool presents the results of this reconstruction by showing the dependency relationships between objects as dashed lines. In-line links (e.g. those to contained images or frames, or representing redirection or automatic updates) are differentiated from 'followed' links (i.e. those followed by the user). The objects downloaded as constituents of discrete pages are thus grouped together and the user's progress from page to page identified. The way in which the browser uses TCP connections and the inferred relationships between connections and objects are illustrated in clear detail.

Figure 4.4 is annotated to demonstrate a sample of the key features of the example visualisation:


Reference Tree for WebClient 131.111.180.[redacted]

WebClient 131.111.180.[redacted]

Start 16:22:57.762320 6/4/200
Duration 16629.462ms

15 Connections
(max. 5/4/4 concurrent/eff. concurrent
15 transactions
(0 invalid 0 failed)

objects linked: 15 unlinked: 0

Object types:-

🟩	image/gif 0/8
🟩	image/jpeg 0/5
🟧	text/html 0/2
⬛	type unknown 15/0

Link types:-
- - - - - - - Claimed followed link 1
- - - - - - - Followed link 1
············ In-line link 5
············ Claimed inline link 8

Server return codes:-
200 OK 15

User agents:-
(a) Mozilla/4.04 [en] (Win95; I) 15

Servers:-
(b) Apache/1.3.6 (Unix) 15

Page roots:-

http://news.bbc.co.uk:80/hi/english/sc
/tech/default.stm (1)

http://news.bbc.co.uk:80/hi/english/sc
/tech/newsid_704000/704290.stm (13)

```
>1 http://news.bbc.co.uk:80/hi/english/world/europe/newsid_703000/703670.stm
1 (<-1) (a) GET http://news.bbc.co.uk:80/hi/english/sci/tech/default.stm
(b) C (200) 8658/17
56.40                                             (+1642) C: 482/12 S: 22051/20
0 28+49                          +1457
2 (<-1) (a) GET http://news.bbc.co.uk:80/olmedia/700000/images/_703619_enter100.jpg
(b) C (200) 3515/3
1 (1161) PO: 1/1/1   194.130.56.40 1.0/1.1 1381   1471+70 +308   (+1973) C: 470/6 S: 3763/
3 (<-1) (a) GET http://news.bbc.co.uk:80/olmedia/675000/images/_677815_genes2_100.gif
(b) C (200) 6297/5
2 (1164) PO: 2/2/1   194.130.56.40 1.0/1.1 1401   153155 +292   (+1871) C: 472/7 S: 6546/8
4 (<-1) (a) GET http://news.bbc.co.uk:80/olmedia/700000/images/_703771_neb100.jpg
(b) C (200) 5372/4
3 (1166) PO: 3/3/1   194.130.56.40 1.0/1.1 1408   153558 +287   (+1878) C: 468/7 S: 5621/7
5 (<-1) (a) GET http://news.bbc.co.uk:80/olmedia/700000/images/_701499_dna2_supuf.gif
(b) C (200) 1978/2
4 (1180) PO: 4/3/3   194.130.56.40 1.0/1.1 1590   171153 +260   (+1705) C: 472/6 S: 2225/5
7 (<-1) (a) GET http://ne
(b) C (200) 1968/2
5 (1375) PO: 4/0/0   194.130.56.40 1.0/1.1 3266   33625 +148   (+556
8 (<-1) (a) GET http://
(b) C (200) 885/1
6 (1378) PO: 4/1/0   194.130.56.40 1.0/1.1 3278   3393
6 (<-1) (a) GET http://news
(b) C (200) 1738/2
7 (1382) PO: 3/2/2   194.130.56.40 1.0/1.1 3300   33429 +195   (+369) C: 4
9 (<-1) (a) GET http:/
(b) C (200) 2194/2
8 (1390) PO: 3/3/3   194.130.56.40 1.0/1.1 3355   34023 +196
9 (1421) PO: 4/0/0   194.130.56.40 1.0/1.1 3665   3901
10 (1440) PO: 3/1/1   194.130.56.40 1.0/1.1 3839
11 (1464) PO: 4/2/2   194.130.56.4 1.0/1.1 40
```

Figure 4.4: **The Web browser activity visualisation tool**

A The red box in the map pane [3] identifies the section of the entire reference tree shown in the main pane [1] which can be scrolled by either dragging the box or the main pane itself.

B The map pane shows that the user goes on to visit another page following that currently occupying the main pane.

C The page's root HTML document identifies its referrer, not seen by the trace, which is represented by the small black box immediately above it.

D_1 and D_2 The browser is configured to download subsidiary objects using four concurrently open TCP connections.

D_1 Connections #1 – #4 are used to download the first four in-line images in the page. Each request occupied a single packet shown as a large tic above the connection bar (coloured grey for 'type unknown' as there is no object associated with the GET requests); dotted lines above the request tics connect them to the referring object (**C**) at the packet carrying the portion of the parent document containing the links. Although the links were seen in a packet at approximate time 450 ms the browser did not open connections upon which to request the objects until approximate time 1400 ms — hence introducing a delay of nearly a second into the page download.

E Although delivery of the first four image objects was completed by approximate time 1950 ms the browser does not *close* the relevant connections until approximate time 3300 ms, hence inhibiting the opening of the subsequent set of four connections, and introducing a further overall delay of about 1.3 seconds.

To manually identify and associate the activity involved in downloading the first page shown in Figure 4.4 would require the examination of 12 trace file records containing details of an equal number of transactions, and of 159 TCP packets — a complex and tedious task. To identify the links contained in the parent document would additionally involve the scanning of 8,658 bytes of HTML spread over 17 packets. If traditional `tcpdump` style traces had been collected the exercise would involve the manual examination of all 159 packets, their TCP and HTTP headers. The page illustrated is atypically small — pages with container documents measured in tens of kilobytes containing tens or hundreds of in-lined images are not unusual — it would be infeasible to manually examine the data describing activity in such cases, and to correctly interpret its internal relationships and meaning. The utility of the tool is amply demonstrated in the figure which presents all of the relevant data and the inferences drawn during analysis in an immediately accessible form. The overall pattern of activity is plainly discernible and features of interest clearly identifiable.

The tool's contribution to analysis design is discussed in Section 4.5.3, and its role in assessing the confidence invested in the veracity of analysis results in Section 4.7.5 on page 105.

4.5.3 Visualisation as an Analysis Design Tool

Although visualisation tools may be invoked to examine features of analysis results in detail, their main role is in the analysis development environment. The presentation of raw data in comprehensible and compact form assists in identifying relationships within the data and reasoning about those relationships when designing analysis algorithms.

Sections 4.5.2.1 and 4.5.2.2 illustrate the power of the visualisation tools and comment upon the difficulty of comprehending and interpreting large masses of associated data without a mechanism for its succinct presentation — an essential precursor to analysis design. Figures 4.3 and 4.4 demonstrate the way in which visualisation identifies and clarifies relationships, features and patterns of activity within the data — also essential to the design process. Both sections illustrate the volume and scope of trace data which may contribute to a single analysis result datum (e.g. the download time of a single Web page) and, by implication, the complexity of the analysis involved in its calculation.

The presentation of analysis output in conjunction with the data upon which it is based allows the relationships between raw data and analysis output to be examined and verified in detail, and the facility to repeat the analysis underlying selected results supports the close examination of the analysis process. Iterative design is supported by the facility to reload and re-execute analysis software on selected sets of data. Both visualisation tools may be instructed to *redraw* their displays: all analysis modules are *re-imported*, the underlying raw data is re-read from the trace file and re-analysed with full tracing enabled, and the display redrawn. Analysis code can therefore be modified *during the analysis process* and immediately re-run, and the modified analysis process examined in detail.

Although both of the tools described are specific to particular protocol sets they are constructed in such a way as to contribute to a generic framework. Functionality is divided between protocol-specific and display management classes (i.e. one set of classes provides and manages canvases and interactive features, another — given a set of raw data and results — knows how to draw them into the display provided). In some cases entirely new drawing classes may be required, but in general sub-typing will provide the appropriate functionality: the TCP tool's drawing class could be trivially sub-typed (with much removed functionality) to display the activity of UDP flows and the browser visualisation tool's drawing classes sub-typed to accommodate other higher level protocol activity.

The summary tool provides a convenient mechanism for recording and identifying items of interest within the data and any correlations which may require particular attention during analysis design, and to then closely examine and modify analysis algorithms. The facility to quickly select and examine data sets generated by analysis, and to then examine the derivation of multiple or individual data items supports similar design processes at a larger scale.

The tight integration between analysis code, summary tool, and visualisation tools, and the way in which their invocation can be cascaded, provides a rich and productive design environment. The support for examination of the analysis process during design also facilitates validation of the analysis methods employed, and hence underpins confidence in the results obtained. The part played by the tools in assessing confidence is further explored in section 4.7.5 on page 105.

4.6 Assembling the Components

The previous Sections of this Chapter have described the components provided by the analysis framework; an overview of how they may typically be combined to build a complex analysis process can now be presented — a Python script will:

1. Use the *file manipulation module* to return *TraceFile* objects representing the trace files to be analysed and the accompanying accumulated meta data.
2. Instantiate *data retrieval* class objects appropriate to the file record types to be read (e.g. TCP/HTTP connections).
3. Instantiate a *Filter* class object if further selection of records (e.g. by host, HTTP-1.0 persistent connections).
4. Instantiate an appropriately sub-classed *StatsCollector* object to invoke the required analysis methods of analysis classes and accumulate the results generated.
5. Call upon the file objects' *NextRec* record selection methods to step through the trace file(s) and:

   (a) Use the retrieval class objects' *read* methods to recover data from file.

   (b) Instantiate the required *analysis* class or subtype object and call the required analysis method(s).

6. At analysis completion:

   (a) The *StatsCollector* object will instantiate a *Summary* object, the user may:

      i. Examine results data by invoking the *Plotter* tool.

      ii. Examine the analysis log.

      iii. Invoke *visualisation* objects to re-analyse selected data under close observation.

      iv. Modify code, *re-import* and repeat Step 6(a)iii.

   (b) The data generated, or its subsets or derivatives can be saved.

The example above illustrates a non, or transversely, partitioned analysis operating on data contained within discrete DAUs. If further association of data, or a longitudinal partition of the analysis, is required step 5 might be replaced by a two-pass analysis using the `FileRec` class:

5a. First pass — call upon the file objects' *NextRec* record selection methods to step through the trace file(s) and:

   (a) Use the data retrieval object's read method to establish the record's collation key (e.g. host address).

   (b) Add the record's location to an existing *FileRec* object containing associated records, or at the first instance of the collation key instantiate a `FileRec` of the appropriate type.

5b. Further collate and partition the collected `FileRec` objects if required

5c. Second pass — for each partition:

   (a) Call the `FileRec(s)` *reconstruct* method to instantiate and populate the appropriate analysis class object.
   (b) Call the required analysis method(s).

Note that the above example does not represent a prescriptive formula for analysis processes, but rather an example of the way in which framework components may be easily and flexibly assembled to meet the requirements of analysis tasks. Standard components are used throughout, only the StatsCollector and analysis classes requiring modification through subtyping or the addition of further analytical methods. As the existing component collection grows through the addition of analytical methods and sub-types, it will be increasingly the case that analysis requirements will be met entirely from existing methods used in new combinations, or that only minimal modifications will be required in order to achieve the required behaviour.

As data extraction from additional protocols is added to `Nprobe's` repertoire, new retrieval classes will be automatically generated, the only manual effort required being to contribute appropriate trace file reading functions. Steps 6(a)i – 6(a)iv of the process described above will support fast development of new protocol analysis classes or the modification of those already existing.

4.7 Issues of Data Bulk, Complexity and Confidence

The Nprobe design reflects the expectation that it will be used to collect relatively long traces comprising many gigabytes, if not terabytes, of data, and that this data will be both comprehensive, and span activity at multiple levels of the protocol stack. Analysis of the collected data will generate commensurately rich and bulky results and explore and identify complex relationships within the data (e.g. interactions between protocols, complex behaviour within individual protocol levels). Consideration must therefore be given to the validity of the results and measures of *confidence* that can be attached to them.

4.7.1 Data Bulk — The Anatomy of a Small Trace and Its Analysis

Sections 4.5.2.1 and 4.5.2.2 on pages 94 and 96 comment upon the mass of associated data which may require integration during analysis to produce a single result datum. Table 4.1 on the next page, on the larger scale, indicates the magnitude of the data input to the analysis process by summarising the anatomy of a comparatively small trace[4] and its analysis. The average line rate observed was 82.66 Mbps over a period of approximately one and three-quarter hours but over nine million trace records were generated.

Table 4.1: **The anatomy of a small trace**

Summary of Trace		**Analysis Results**	
Duration	1 hr 42 min 5 s	HTTP Clients	40,518
Total Packets	124,368,030	Web pages	773,717
Total Octets	63,284,550,146	Analysis log entries	1,782,066
Average bitrate	82.66 Mbps	Data sets	63
TCP Host/host flows	1,722,917	Data points	8,630,943
TCP Connections	3,507,974		
TCP Packets	103,408,831		
TCP Octets	56,363,350,227		
HTTP Packets	50,254,988		
HTTP Octets	28,194,834,668		
HTTP Transactions	3,373,406		
Trace files (75 MB)	66		
Trace file records	9,107,483		

When `Nprobe` is used to monitor higher bandwidth technologies, or link utilisation is greater, and full length traces are taken, the data bulk will be one or two orders of magnitude greater. Analysis recreating the network activity involved in downloading Web pages and categorising delays identified approximately 770,000 distinct pages and generated approximately 1,800,000 analysis log entries and 63 data sets comprising over 8,600,000 individual values — these figures would also be commensurately greater for larger traces or analysis of a wider scope.

The sheer bulk of data input to analysis will impinge upon the accuracy or validity of the results obtained:

- The data will be less tightly homogeneous.
- Algorithms will have to be robust in the face of a less closely defined general case.
- The number and range of special cases will be greater.
- The probability of invalid or rogue inputs will be higher.
- Such cases will be both more diverse and more difficult to identify.
- The aggregate of input data contributing to each result datum may expand proportionately to the input data bulk.

The volume of results generated during analysis of large inputs will also contribute to the difficulty of verification:

[4] Gathered from the 1 Gbps link connecting the UCCS networks to the SuperJANET

- Verification by inspection becomes less feasible.
- Invalid results are less readily identified in large data sets, particularly those with dispersed or long tailed distributions.
- Mappings between input data and results are more difficult to identify and to navigate.

4.7.2 Data and Analysis Complexity

Because the data gathered by `Nprobe` may be collected from multiple layers of the protocol stack, and because the data collected from each layer may be very comprehensive, the relationships between data items will be both complex and sometimes subtle, reflecting the complex dynamics and interactions of the network and application activities observed. As the number of individual data contributing to each output datum increases the complexity of their potential relationships will grow exponentially; this growth will be limited by transitivity, but this, in itself, carries the risk that analysis errors will be propagated.

The complex nature of the phenomena studied dictates that elements of analysis will depend upon a degree of inference and may be based upon heuristic rules. Complex data encompassing equally complex relationships, inference, and a widely ranging set of possible input conditions all determine that there is considerable scope for error in the design and implementation of analysis processes, and the reasoning that underpins them. The audit trail between input data and the information extracted or synthesised from it will, additionally, become more complex and commensurately difficult to follow.

Sections 4.5 and 4.6 explain how complexity in analysis design is supported by the use of visualisation tools and the composition of mature analysis components provided by the toolkit. Sections 4.7.3 – 4.7.5 now go on to discuss the establishment of confidence in the information generated by analysis.

4.7.3 Determinants of Validity

The validity of analysis results will depend upon a range of factors the most significant being:

The veracity and accuracy of the raw data (i.e. rubbish in — rubbish out): As explained in Sections 3.3.3.3 to 3.3.3.7 on pages 58–66 the process of data extraction at the protocol level both implies a check on the semantic integrity of that data and may involve specific semantic tests. Section 3.3.5 on page 69 describes the situations which may arise where semantic constraints are broken by the contents of packets arriving at the probe, and the disposal of such situations: in effect a DAU is marked as terminating in an *error* condition if any of the associated data is semantically inconsistent *as it appears to the probe.* The section also introduces the distinction between *incorrect* and *misleading* data semantics — the former will generate an error condition, and data will be rejected during analysis, but the latter must be detected during the analysis process or by its contribution to anomalous results.

The design and robustness of the analysis algorithms employed: The truism that analysis algorithms must correctly interpret the data presented to them should not obscure consideration of the extent to which such algorithms must be robust in the face of unanticipated or unusual data. Section 3.3.5 points out that it is infeasible to provide data extraction software which will dispose correctly of every possible combination of network or application behaviour, or packet content — the number of possible permutations is simply too great, even in the absence of pathological conditions, incorrect behaviour, or incorrect protocol implementations. The same is, of course, true in the case of analysis software: there will, inevitably, be combinations of activity in the sometimes very complex operations observed and interrelationships between protocols which will not be anticipated during algorithm design.

Appropriate identification and interpretation of the relationships between data items: Analysis results will be incorrect if the algorithms employed do not correctly identify and interpret the relationships between the data items recorded in `Nprobe` trace files, even though the algorithms themselves may be technically correct. In this context confidence depends upon the validity of the knowledge and reasoning bought to bear upon the analysis design process. There is, unfortunately, no formalism, or system of proof, applicable to this critical factor.

In the absence of an appropriate formalism an assessment of validity, and hence of confidence, must depend upon informal, or heuristic, *indicators*.

4.7.4 Indicators of Validity and Confidence in the Absence of Formal Proof

Indicators of validity may be pertinent to either the raw data, intermediate, or final results and may serve to suggest overall measures of confidence, or to identify dubious results. Such indicators will include:

Protocol and Application Semantics: During analysis more sophisticated checks can be carried out on data to identify incorrect or unusual values arising from misleading protocol semantics than are possible during data collection.

Cross Protocol Semantics: The semantics of individual protocols will often bear upon those of the protocols with which they interact and may generate similar indicators. The HTTP response header lengths and the size of the objects delivered should sum, for instance, to the number of data octets carried from the server by the TCP connection transporting them.

Data self consistency: Both data and results can be checked for self consistency, often in conjunction with semantic checks.

Consistency with other known data or results: Unless there are known reasons why identifiable differences should exist, data and results should be consistent with other known values, although care must be taken that consistency is not the result of common errors. Ideally such consistency checks should be based upon data sets arrived at by independent and unrelated methods.

Independent verification: Verification may be sought through comparison with known accurate data (using consistency checks) or through data gathered specifically for the purpose, possibly using *active* methods. The round trip times calculated in Chapter 6 were, as an example, checked for feasibility using measurements obtained by the `ping` programme; the reconstruction of Web page downloads described in Chapter 7 can be verified by independently downloading a sample of pages and manually examining the HTML page source and `tcpdump` traces collected on the client machine.

Statistical Indicators: Statistical indicators may apply at both microcosmic and macrocosmic scales. Examination of results data may reveal distributions informally suggesting that analysis results are feasible, or may, conversely, suggest that the derivation of results should be examined more closely (e.g. if unexpected or inexplicable features are present). Checks that results match a particular statistical distribution will usually be too precise — indeed it may be part of the research goal to identify distribution characteristics. Small scale features of distributions (e.g. outlying points) may suggest errors in the analysis and that further examination is required.

Examination of samples from results : The derivation of individual data items contained in results can be examined for accuracy. The individual items may be a sample of the whole, a sample of a subset of the whole (e.g. those based upon TCP connections where loss has occurred), or be suggested by statistical indicators or analysis logs (e.g. outlying points or those derived in an unusual or particularly complex context).

The application of indicators runs across a spectrum from those which suggest specific tests applied automatically during analysis (e.g. those based upon semantics or data self-consistency) to those, more applicable to results, which require user intervention and reasoning (e.g. independent verification or the examination of statistical indicators). Which indicators are employed will also depend upon the stage of analysis development reached: the examination of individual values and their derivation will be more common early in the cycle and macrocosmic statistical indicators will assume a more significant role when using mature analysis processes.

4.7.5 Visualisation as an Informal Indicator of Confidence

Section 4.5.3 explains how the visualisation tools contribute to an analysis design environment supporting the development of robust code which produces valid results and hence engenders confidence. The tools also provide convenient access to a set of indicators of confidence.

The summary and plotter tools support the examination of statistical indicators at the macrocosmic scale. The facility to examine the derivation of individual data contained in the results through re-analysis and visualisation make scrutiny at the microcosmic scale convenient. Fast and comprehensive navigation of analysis logs facilitates the identification and examination of analysis in the case of dubious results or analysis failures, and allows for the examination of samples from analysis results.

4.8 An Assessment of Python as the Analysis Coding Language

This section assesses the contribution of the Python language's features to implementation of the analysis framework and code, and some of the difficulties arising from its use.

4.8.1 Python and Object Orientation

It is proposed that data analysis is an environment to which the object-oriented paradigm is eminently suited: sets of data items are grouped in hierarchies and aggregations of differing granularities, and at each hierarchical level a distinct set of analytical operations is required. Although Python does not enforce strict data hiding its class structure implies full encapsulation of data sets and the operations to be performed on them.

The very rich nature of the data gathered by `Nprobe` suggests that data analysis will be complex, and that it will be the subject of a potentially wide range of analytic tasks, each of which will draw from a different set of operations at each level of the data hierarchy. Section 4.2.2 shows how automatically generated retrieval classes contribute to a generic data retrieval interface and Section 4.3 explains how analysis and utility classes form a locus for analysis functionality which, by appropriate design and choice of analysis methods and the inheritance mechanism, provide a flexible and powerful analysis infrastructure with a high degree of code reuse.

The implementation of the summary and visualisation tools introduced in Section 4.5 as classes, which may be invoked from anywhere in the analysis code, in cascades, and recursively, allows a degree of integration contributing a flexible and productive development environment. The facility to re-import modules and to re-run code also makes a significant contribution to fast design.

4.8.2 Difficulties Associated with the Use of Python

Although the choice of Python as the language in which the data analysis code and environment have been written has proved itself in practice, there are, nevertheless, some disadvantages which must be noted:

Python lacks some low-level data types useful in the context of trace file analysis: Python provides two signed integer types: *plain* integers and *long* integers[5]. There is, therefore no direct Python representation of some integer types frequently occurring in `Nprobe` trace files:

32 bit unsigned *integers:* Which are heavily used in numeric data items to obtain maximum capacity in a 32 bit quantity and in protocol (e.g. TCP) header fields. The

[5] Python plain integers are based upon C *long* integers and hence provide at least 32 bit precision; Python long integers give unlimited precision.

manipulation of TCP *sequence* numbers also relies heavily upon the properties of unsigned integer arithmetic.

64 bit integers (i.e. C long long integers): Which are used by `Nprobe` for full time stamps.

The lack of these types does not present insuperable difficulties — all of these C types can be represented as Python long integers, but a conversion overhead is introduced, especially as conversion must be carried out at the Python, rather than the C level, in the data retrieval interface. SWIG-generated retrieval classes treat unsigned integers as signed, and accessor functions therefore return unsigned integers as (incorrectly valued) signed plain integers. A utility module — `np_longutils` — provides a set of functions employing bit-level manipulations to convert such items to correctly valued long integers. Conditional inclusion in a type-defining header file, part of the SWIG input, ensures that 64 bit integers are seen by SWIG as a class containing two unsigned 32 bit integers; similar functions can then be employed to convert these values to a Python long integer representation. A further utility module — `np_seq` — provides a set of functions which, applied to Python long integers, mimic the results of unsigned integer arithmetic for the manipulation of sequence numbers. All type conversion of this nature is normally carried out during the data population of protocol analysis classes as explained in Section 4.2.2.

The execution of Python code is slower than of C: Python, an interpreted language, runs more slowly than would the equivalent C program. This disadvantage is minor in the case of mature analysis code: although complex analysis of a large trace file may take several hours it is expected that traces will normally require once-only analysis, and the use of analysis classes equipped with a rich range of functionality as described in Section 4.8.1 makes the concurrent execution of multiple analysis tasks during a single run feasible. The drawback of relatively slow execution is more apparent during the iterative design of analysis algorithms and code, but must be balanced against the ease and speed of code generation in an interpreted high-level language, and the tools described in Section 4.5 are designed, in part, to alleviate this problem.

Python can be memory hungry: The memory overheads associated with object instantiation and Python's internal data representation result in a substantially higher memory usage per data item than would be the case if analysis code were written in C, and this can produce difficulties due to shortage of physical memory when analysing large trace files[6]. Because Python does not provide direct control over memory allocation it is, additionally, not possible to exploit locality of reference in the case of programs where virtual memory requirements exceed physical capacity. Careful *partitioning* of the analysis process may be required, together with other mechanisms such as the *FileReference* class described in Section 4.3.6.

Garbage collection contributes an unwelcome overhead: Python objects are reference counted, being destroyed and their memory deallocated when the count decrements to zero. A more sophisticated *garbage-collection* mechanism detects *reference cycles* creating reference counts which would never reach zero and would result in objects which are never destroyed. In such cases the reference cycles must be explicitly broken, or the Python

[6] Memory constraints will, of course, be felt whatever the language used and similar mechanisms employed to circumvent the consequent difficulties — the problem is simply exaggerated by the use of Python.

garbage collector must be relied upon to detect those cycles which are no longer *reachable* (i.e. encompass objects none of which are referenced from objects external to the cycle) and to destroy them. It is inevitable that complex analysis tasks will create many reference cycles, and that it will be difficult, or infeasible, to manually identify and break them — one disadvantage of the analysis infrastructure model is that it is not possible to tell in advance exactly how standard classes will be used in future analysis tasks, and it may therefore be inappropriate to *build in* the explicit breaking of cycles. As analysis will normally involve a high degree of iteration, any cycles created will recur very frequently and garbage collection will therefore become correspondingly expensive. The Python garbage collector is, fortunately, tunable, and the frequency with which it is invoked can be controlled — the correct balance must be found between too frequent invocation (in which case the overhead becomes unacceptable) and infrequent invocation, in which case objects persist unnecessarily long with consequent effects on total memory usage.

4.9 Summary

The gathering of data by a network monitoring probe is only the first stage of a process which must later progress to an analysis of the data gathered. `Nprobe` trace files are distinguished from those gathered by more conventional means by their complex format and the scope and variability of the data that they record. The complex data format and variable content call for a uniform interface to data retrieval from trace files; the scope of the data implies that analytical tasks will be more complex than normally encountered, that multiple similar tasks will be called for or that *trawling* for information in speculatively gathered traces will be desirable. These factors determine that the monitor design cannot be regarded as complete without the provision of an appropriate framework within which analysis can be designed and executed — `Nprobe` data collection and analysis are complementary components of a common system.

This chapter has described the implementation of a suitable analysis framework. Section 4.1 introduces the need for a framework in the context of `Nprobe`-gathered data, and in particular the requirement for an analysis development environment which readily supports the evolution and design of a range of analysis tasks. The development environment is based upon a toolkit which provides a consistent data retrieval interface, data analysis, analysis support and utility components, and tools for manipulating and navigating analysis results. Visualisation tools which present analysis input data and results in a succinct form are also provided.

The aim of the toolkit is to provide a set of building blocks which can be combined as required to support fast analysis development, and tools to support the design of new analysis components. Some components (e.g. the data retrieval interface, data conversion and support utilities, and results manipulation tools) provide an infrastructure common to all analysis, but others (e.g. data analysis and results-gathering components) will be selected and composed for the needs of specific analysis tasks. As new analysis components are designed and implemented they add to the existing stock.

The analysis framework is implemented in Python, whose rich high-level data types support the writing of complex analysis code, and whose modularity and object-oriented structure supports the composition and tight integration of the toolkit components. Section 4.2 introduces the data retrieval interface responsible for extracting the required data from the complex formatting of trace files and presenting it it in canonical form to analysis processes. Because the trace file format is dictated by the `Nprobe` data extraction modules, data retrieval classes are automatically generated from the `Nprobe` modules' data format specification, hence avoiding a complex and tedious manual chore, accommodating changes in file formats without requiring modification of analysis code, and reflecting additions to the range of protocol data collected.

The mechanism of data analysis is described in Section 4.3 which explains how analysis functionality resides in a series of protocol analysis classes in which data is associated, and which provide methods specific to analysis within that protocol. Where analysis spans protocols, or where multiple protocol instances are associated, associative analysis classes act as the data aggregation locus, provide appropriate analysis methods, or call upon the analysis methods of the associated protocol classes. By instantiating the appropriate analysis classes and using selected methods, complex analysis processes can be quickly constructed using existing components. New analysis components can be safely added by providing new methods to existing classes, and behaviour modified, if required, by using sub-typing.

The analysis of large trace files may require large amounts of memory, and the section concludes by introducing techniques for circumventing the difficulties which arise from memory constraints: analysis may be partitioned, or references to data locations in the trace file(s) stored rather than the data itself.

Analysis may also generate long and comprehensive logs of its execution, together with large and varied sets of results data. Section 4.4 introduces an analysis summary tool which supports the navigation of log files and the examination and manipulation of analysis results. The summary tool is integrated with the visualisation tools and allows the close examination of the input data and analysis process underlying selected results.

Section 4.5 introduces and briefly describes the visualisation tools, currently comprising a data plotter, TCP visualisation tool, and Web browser activity visualisation tool. The data plotter allows results and their derivatives to be examined from within the analysis process, and its integration with the other tools allows examination of the derivation of results in a manner similar to the analysis summary tool. The power of the visualisation tools is demonstrated by illustrations of their use and the way in which they present input and results data, and clarify the relationship between them. The role of the tools in analysis design is explained with emphasis on their support of iterative design, reasoning about relationships within the data, and close examination of the analysis process.

The use of the toolkit is illustrated in Section 4.6 which draws the preceding sections together with an explanation of how an analysis task might be constructed from individual components. Examples of a partitioned and non-partitioned analysis are given, and demonstrate the utility and flexibility of the system.

The potentially very large trace files analysed, the complexity of the analysis itself, and the volume and variety of results which may be generated, call for an assessment of the validity of the analysis and the confidence with which results can be viewed. Section 4.7 considers determinants of validity, how indicators of confidence may be identified, and the role of visualisation tools as indicators.

The chapter concludes with an appraisal of Python as the coding language for the analysis framework. The strengths of object orientation in the context of data analysis are discussed, together with some of the problems arising from the use of Python and how they are accommodated.

The toolkit has been used for the development of the analysis software used in the studies presented in the later chapters of this dissertation, and has confirmed both the rationale for its development and the utility of its implementation. In conclusion it is noted that other analysis of `Nprobe` traces has been carried out in support of Web traffic characterisations presented in a recently submitted paper [Moore02]. The principal researcher and author, who was previously unacquainted with the `Nprobe` system, designed and implemented the necessary analysis in a few hours and reports in the paper:

> "It is worth noting that the whole task of off-line processing of the data was constructed in 10's of lines of Python code."

Chapter 5

Modelling and Simulating TCP Connections

TCP activity does not take place in isolation: connections are opened and data transfers originated by processes higher in the protocol stack, the underlying IP and physical network layers determine crucial factors such as latency (e.g. Round Trip Times (RTTs) and serialisation delays), packet loss and bandwidths. Packet-trace based studies normally force inference of network properties from the activity observed at the transport level, and the limitations of most traditionally-collected traces (i.e. containing only IP/TCP headers) similarly confine observation of activity at higher, or application, levels to that of inference.

The traces collected by `Nprobe` do not contain any additional information about the network and physical layers but, because they may contain details of higher-level activity, allow TCP connections to be interpreted in context and, conversely, allow the higher levels to be studied in the light of the TCP connection activity which underlies them. One of the prime motivations for the development of `Nprobe` was to provide data for the detailed study of the interaction between the transport layer and higher-level protocols; in order to do this it is necessary to distinguish activity determined by the network, the transport mechanism and higher levels. This chapter describes a technique which allows such distinctions to be made by modelling the activity of individual TCP connections. Because the technique precisely defines the characteristics of the TCP connections studied and the behaviour of the applications using them, the output of the models constructed can be used as the input to accurate trace-driven simulations of the same connections in order to examine their performance with varying input parameters.

5.1 Analytical Models

Analytical models of TCP have been developed by many researchers. Mathis *et al.* [Mathis97] proposed a performance model predicting effective bandwidths under conditions of light to moderate loss, and which accommodates connections using SACKs. Padhye *et al.* [Padhye98]

[Padhye00] construct an analytic characterisation of TCP throughput which incorporates timeout-based and fast retransmissions, and the effects of small receiver-side windows.

Both these and other similar models are based upon an assumption of *steady state* (i.e. a bulk data transfer over an established and unending connection in which the sender maintains a full transmit buffer). The models are verified through a combination of simulation and measurement of real traffic.

5.2 The Limitations of Steady State Modelling

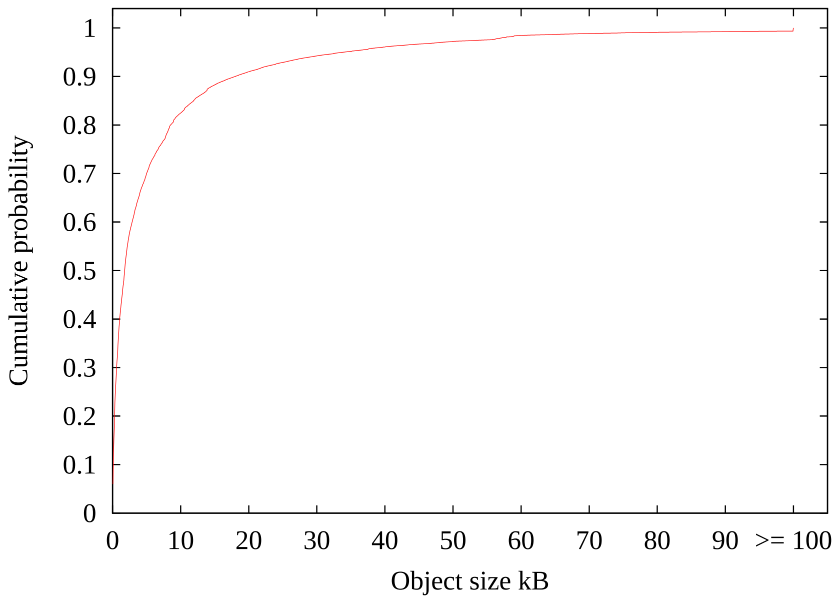
The great weakness of steady state models is that they do not reflect the reality of the majority of TCP connections: Brownlee and Claffy [Brownlee02] report, in a study of traffic observed on the campus OC12 link at UC San Diego, that 87% of Web streams were under 1 kB in length, 8% between 1 and 10 kB, and 4.8% between 10 and 100 kB. For non-Web traffic the proportions were 89%, 7%, and 1.5% respectively. The same authors, with others, report in [Brownlee01] that 75% of TCP flows were of less than ten packets and of length less than 2 kB. Although the small proportion of large-transfer connections may represent a majority of the bytes transferred, the preponderance of small transfers is of critical importance. The user will often be aware of large transfers and anticipate some delay; the characteristics of small connections, however, will frequently be cumulative (e.g. in the download of multiple Web-page components) and will effect perceived utility disproportionately to the number of bytes actually carried.

Figure 5.1, based upon an analysis of responses to HTTP GET requests in a one and three-quarter hour trace of the University of Cambridge's external link, shows approximately similar results. Figure 5.1(a) shows the distribution of delivered object sizes: approximately 39% of objects were less than 1 kB in size, 43% between 1 and 10 kB, and 17% between 10 and 100 kB. Figure 5.1(b) shows the distribution of the *number of TCP segments* required to deliver HTTP responses to the requests made over non-persistent connections: just over 60% of all responses are carried in a single segment, 90% in eight segments or less, and 92% in ten or less.

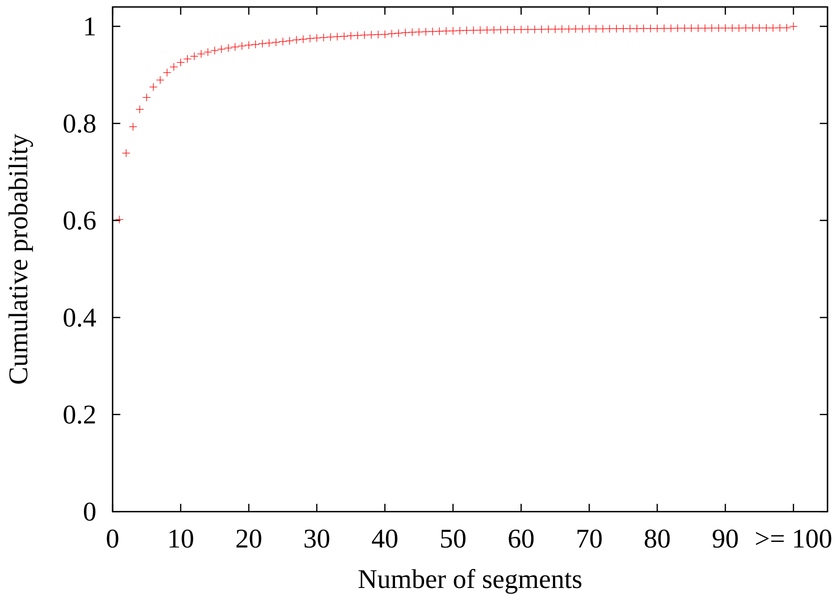
Much of the apparent discrepancy between Figures 5.1(a) and 5.1(b) (and between these and those of the studies cited) can be explained by reference to Figure 5.2 which shows the distribution of status codes accompanying server responses to these requests. Approximately 38% of the responses (304 — 'Not Modified' and 302 — 'Moved Temporarily') do not return an object; the HTTP response header itself — typically of a few hundred bytes — being transmitted in a single packet.

Steady state models characterise TCP connections primarily in terms of their RTTs, Maximum Segment Sizes (MSSs), and loss rates. The dominant feature of short[1] connections are those of *latency*: connection establishment, in the originator's response to establishment, and in the other party's response; and of slow start. Although steady state models normally incorporate

[1] In this context 'short' should be interpreted as meaning a connection carrying a small number of data segments, rather than 'short-lived'. Such connections are by definition 'mice', they are only probably 'dragonflies'.



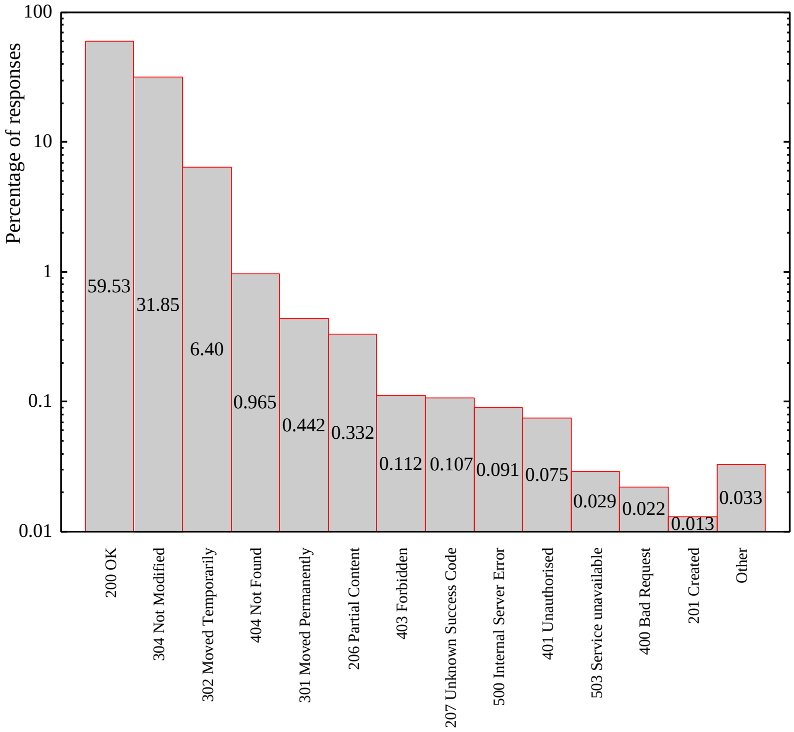
(a) Distribution of object sizes



(b) Distribution of number of segments required to deliver HTTP responses

Note: The data shown is for `GET` requests extracted from the trace summarised in Table 4.1 on page 102

Figure 5.1: **Distribution of HTTP object sizes and number of segments required to deliver HTTP responses**



Note: The y-axis is log scaled to allow comparison of the proportions of common and infrequent responses.

Figure 5.2: **Distribution of server return codes**

slow start characteristics as a response to loss, they do not, by their nature, recognise the significance of connections which operate entirely within this phase.

Some recent models of TCP have attempted to address the reality of finite, or short connections. Sikdar *et al.* [Sikdar01] develop a model extending that of [Padhye98] to incorporate the connection establishment phase and an approximation of slow start behaviour. Cardwell *et al.* [Cardwell00] also propose a model which extends [Padhye98] and accommodates the possibility that short connections will not suffer loss. Both models are verified by comparison with measured connections and by simulation.

5.3 Characterisation of TCP Implementations and Behaviour

TCP is primarily defined by a set of core Request for Comments (RFCs): RFC 793 *Transmission Control Protocol* [Postel81], RFC 813 *Window and Acknowledgement Strategy in TCP* [Clark82], RFC 896 *Congestion Control in IP/TCP Internetworks* [Nagle84], RFC 1122 *Requirements for Internet Hosts – Communication Layers* [Braden89], and RFC 2581 *TCP Congestion Control* [Allman99a]. The core RFCs are supplemented by numerous extensions and clarifications (e.g. RFC 2018 *TCP Selective Acknowledgment Options* [Mathis96], RFC 3390 *Increasing TCP's Initial Window* [Allman02], RFC 2582 *The NewReno Modification to*

TCP's Fast Recovery Algorithm [Floyd99], and RFC 2988 *Computing TCP's Retransmission Timer*).

The status of RFCs varies (e.g. 'STANDARD', 'PROPOSED STANDARD', 'INFORMATIONAL') as does the degree of prescription in their recommendations (e.g. 'MUST', 'SHOULD'); the recommendations are, moreover, for *minimal* standards of behaviour or functionality, rather than exact definitions or implementation directives. There are many TCP implementations, although often based upon a smaller number of core implementations and their variations; not all behave as intended and some (particularly in early manifestations) contain bugs or are not entirely RFC compliant. All TCP implementations, moreover, define a number of user-configurable parameters which may be expected to take a range of values.

As a consequence it is impossible to predict the behaviour of individual TCP connections with absolute confidence in the face of widely varying network conditions, higher-level protocol behaviours, peer implementations, and connection histories; even when the general characteristics of a particular known implementation are relatively well understood, nothing is absolutely guaranteed.

Several studies have characterised the behaviour of specific implementations, or of TCP connections in the round. The majority of these works have employed active techniques, normally constructing sequences of segments designed to elicit responses from the target implementation illustrative of its behaviour in a range of specific circumstances.

Comer and Lin [Comer94] used this technique to investigate retransmission timer, *keep alive* and *zero window* probing behaviours of a range of implementations without access to the source code. A similar study was performed by Dawson *et al.* [Dawson97], who used an instrumented kernel and *fault injection* techniques to investigate a range of commercially available implementations. Brakmo and Peterson [Brakmo95] used simulation, together with examination and modification of the source, to investigate performance problems in the BSD4.4 TCP implementation. A rather different approach was taken by Padhye and Floyd who describe a tool — TBIT [Pahdye01] — which probes Web servers[2] to investigate Initial Window values; congestion control algorithms; responses to SACKs, *time wait* durations, and response to Explicit Congestion Notification (ECN), of a wide range of servers. Rather than target a known set of implementations the NMAP tool [Fyodor97] is used to identify the target implementation.

All of these studies confirmed the differing behaviours to be found between and within implementations. In addition all identified flaws or bugs in the implementations and areas of RFC non-compliance.

A contrasting study by Paxson [Paxson99] used *passive* measurement of 20,000 TCP bulk transfers to observe and characterise a range of network pathologies and TCP behaviours. Measurements were taken using the **NPD** measurement framework [Paxson97b] at *both* endpoints in recognition of asymmetry between forward and return Internet paths.

[2] Web servers are chosen because of the predominance of HTTP traffic on the Internet — the technique can be generalised to any service reachable through a well-known address which can therefore be expected to respond.

5.4 Analysis of Individual TCP Connections

It is axiomatic that analytical models of TCP are generalised, and many are, additionally, essentially stochastic in nature. The shortcomings of models based upon steady state assumptions are discussed briefly in Section 5.2, but even those based upon the more realistic recognition of finite and short connections, such as [Sikdar01] and [Cardwell00], will not reliably describe the detailed behaviour of individual connections at the packet level: not all features, implementation variations, optional features, or network parameters can be generalised, and such models do not take into account behaviour of application-level processes (e.g. client or server latency, use of multiple serial or concurrent connections) or of human users (e.g. human browsing patterns). Although the steady state model is isolated from application-level behaviour (explicitly by assumptions, for instance, of constantly full transmit buffers), this is a weakness of finite-connection models as currently developed.

The characterisations described in Section 5.3, which are based upon active probing, are also limited in their prediction of the overall behaviour of individual connections: with the exception of [Pahdye01], they are limited to specific implementations, but more fundamentally, although probing is carried out on individual connections, they all describe specific behaviour assessed in the context of sets of carefully contrived conditions.

The work described in [Paxson99], being based upon passive measurements, does not subject the end implementations to predefined conditions and observes a wider range of characteristic TCP behaviour. Although the emphasis is upon the use of TCP connections to observe and infer *network* dynamics, the study is particularly relevant to the work in this chapter: analysis of the individual connections observed necessarily involved differentiating between TCP and network behaviour and relies heavily for this reason upon Paxson's `tcpanaly` tool [Paxson97a].

`Tcpanaly` was developed to *automate* the analysis of individual connections and, by isolating TCP behaviour, to identify idiosyncrasies, bugs, and RFC non-compliance in TCP implementations. The original hope that analysis could be carried out *on the fly* proved unrealistic, but off-line analysis demonstrated the effectiveness of the tool, which successfully identified a range of implementations and their shortcomings. Input to `tcpanaly` consists of TCP/IP headers collected by a packet filter based monitor. The underlying analytic mechanism is based upon modelling the state of the TCP implementation at each end point, the change in state arising from packet arrivals, and the packet transmission behaviour of each implementation as a result of the state modification. This mechanism is similar to that used by the modelling technique described in Section 5.5 of this chapter; although there are significant differences, the concepts of causality, data liberation and `ACK` generation are central to both.

A different approach to the analysis of individual connections was taken by Barford and Crovella [Barford00]. Their `tcpeval` tool also relies upon the identification of data liberations and `ACK` generation, but with the emphasis on Critical Path Analysis (CPA) of the TCP connections carrying HTTP transactions.

5.5 Modelling the Activity of Individual TCP Connections

Because Nprobe traces will normally contain details of activity at levels above the transport layer of the protocol stack, it is possible to construct models of individual TCP connection activity which incorporate this knowledge and can more accurately distinguish between network, transport, and higher levels than the studies in [Paxson97a] and [Barford00]. While tcpanaly and tcpeval make this distinction in order to isolate and describe activity particularly at the network and transport levels respectively, the modelling technique described in this chapter can also provide information pertinent to higher-level activity and, significantly, describe how activity at lower levels is seen by the application and consequently the user.

This section describes an *activity* model of individual TCP connections which reconstructs connection dynamics on a packet by packet basis by identifying the cause and effect relationships between segments in the context of models of TCP end-point state. A parallel model of application-level activity both informs the TCP model and is informed by it.

5.5.1 The Model as an Event Driven Progress

The timing of primary events observed when monitoring a TCP connection (i.e. the transmission of data segments and/or acknowledgements) will be determined by a variety of causes, which are themselves events occurring over a range of levels in the protocol stack. The series of segments, for instance, whose payload is an HTTP response comprising a Web object, is initiated by the receipt of the corresponding HTTP request. The exact transmission time of each individual segment or acknowledgement will, however, be determined by one or more of a number of preceding events and the current state associated with the connection — these in turn are determined by the events that precede them and the connection state at the time.

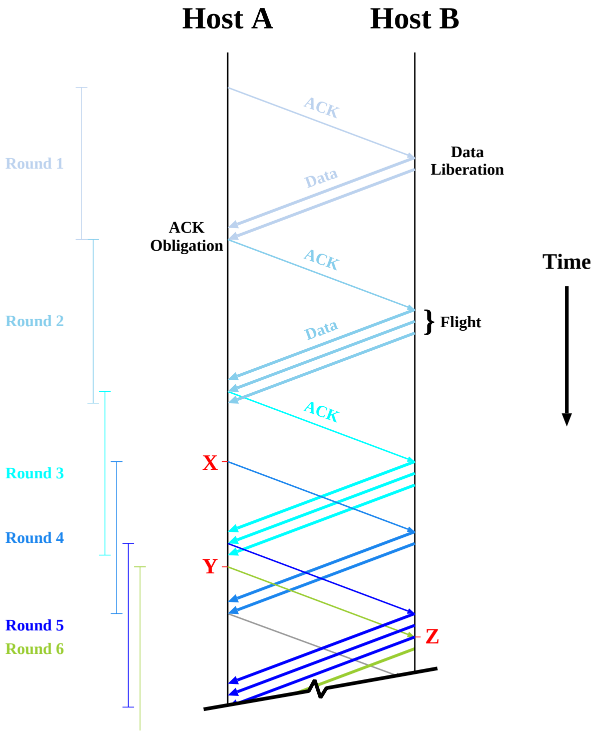
From the viewpoint of the monitor, the packets observed reliably represent *transmission* events and possibly the higher-level events represented by packet contents. The observed packets do not represent *receipt* events as packets may be lost between the monitoring point and receiving host. Receipt events can only be inferred from the observation of the transmission events which they trigger. A further category — *hidden* events — also identified only by inference include transmission events not seen because of packet loss, timer driven events (e.g. retransmission timeouts, delayed ACKs), or transmission buffer exhaustion.

5.5.2 Packet Transmission and Causality

The modelling technique described in this section is based upon the proposition that the observed activity can only be fully understood by the correct association of cause and effect — an HTTP response occurs because a request is received, but it is not possible to quantify the server's delay in responding simply by measuring the time between seeing request and response — why the corresponding data segments are transmitted at a certain time must be understood. The precipitating event may be the arrival of the request, a received acknowledgement advancing the sender's transmission window or enlarging its congestion window, the enlargement of the transmission window in response to an incoming *advertisement*, the transmission of the last data segment of the preceding response on a persistent HTTP connection, or simply the transmission of a preceding packet. Where cause and effect events are represented by observed packets the pair of packets form a *causative association*.

5.5.2.1 TCP-level Activity

Although TCP activity is initiated, and may be modified, by application level events it is largely determined by events and end-point state within its own level. The activity model is therefore TCP-centric, but is developed in the context of precipitating events in the associated model of higher-level activity, and itself contributes to the associated model.



Note: Each ACK received generates a data liberation which results in the transmission of a flight of data segments; arriving data segments create ACK obligations. The ACK and associated flight form a round. The ACKs transmitted by Host A at times X and Y refer to the third segment of flights 2 and 3 respectively but are *delayed*.

Figure 5.3: **Data liberations, ACK obligations, flights and rounds**

Because the underlying concept of segment based cause and effect is similar to that employed by [Paxson97a] and [Barford00], it is convenient to use the same terminology: data *liberations* occur as the result of ACK receipts which cause congestion window growth or advance the flow control window in the sender, and result in the transmission of a *flight*[3] of one or more data

[3] A flight, which will consist of one or more packets — its size — should not be confused with the number of segments *in flight* (i.e. those transmitted but not yet acknowledged from the viewpoint of the sender); the

segments; ACK *obligations* arise as a result of data segment arrivals at the receiver; the ACK and the flight segments carrying the data liberated by it form a *round*.

Figure 5.3 illustrates liberations, obligations, flights, and rounds in a time line diagram. The connection shown is in its slow start phase; the Host B TCP implementation grows its congestion window by one segment for each ACK received and the number of segments potentially in flight increases accordingly. Host A implements delayed ACKs — the second segments of flights 2 and 3 generate immediate acknowledgements, but the third segment is not acknowledged until A's delayed ACK timer fires at times X and Y.

Although a simple model based upon data liberations, ACK generation, and rounds underlies the activity model, it is in practice too simple to account for the activity observed in the case of many TCP connections. As indicated in Figure 5.3 the possibility of delayed ACKs must be taken into account, and it can not be assumed that data liberations always result in immediate transmission of the associated flight: in the figure an ACK arrives at time Z, but the associated flight must await the completion of the flight 5 segment transmissions currently in progress. The enhancements to the data-liberation model required by these and other more complex TCP-level behaviours are discussed in Section 5.5.9 on page 130. The incorporation of packet loss into the model is introduced in Section 5.5.5 on page 123, and the determination of TCP activity by higher-level activity is discussed in Section 5.5.2.2.

5.5.2.2 Activity at Higher Protocol Levels as a Determinant

It must be remembered that TCP connections and data transfers are initiated by application-level `connect` and `write` operations. Although these operations are infrequent and coarse grained in comparison with the manifestations of TCP-level activity observed or inferred from network activity, they determine the timing of TCP activity on the broad scale.

Because Nprobe traces contain detail of application-level activity, and because this detail identifies the packet from which it was extracted, events at the application level which cause TCP activity can be identified. Some application-level events (e.g. the active open of a connection, or the issue of an HTTP request on a persistent or non-persistent connection) precipitate the immediate transmission of a segment; some (e.g. the issue of a request) may precipitate other application-level events in the recipient which in turn cause the transmission of segment(s).

Alternatively, application-level events, for instance the issue of subsequent requests on a *pipelined* HTTP connection, may trigger immediate application-level events in the recipient, but any consequent TCP-level events are determined by activity at the TCP level (as the segments carrying the response must await the transmission of segments carrying previous responses). Whether application-level events precipitate immediate, or delayed, transmission events must be decided by the model in the context of the current TCP activity.

Other application-level detail, while not representing causative events, may also inform interpretation of TCP-level activity: HTTP header lengths and object sizes determine the boundaries between responses on pipelined connections and persistence negotiations may determine

latter is also referred to as the *flight size*.

which party initiates a connection close. TCP activity can, conversely, imply application-level events (e.g. a `FIN` segment on a non-persistent HTTP connection denotes an *completion of object* event).

5.5.2.3 Interaction Between TCP and Higher-Level Protocols

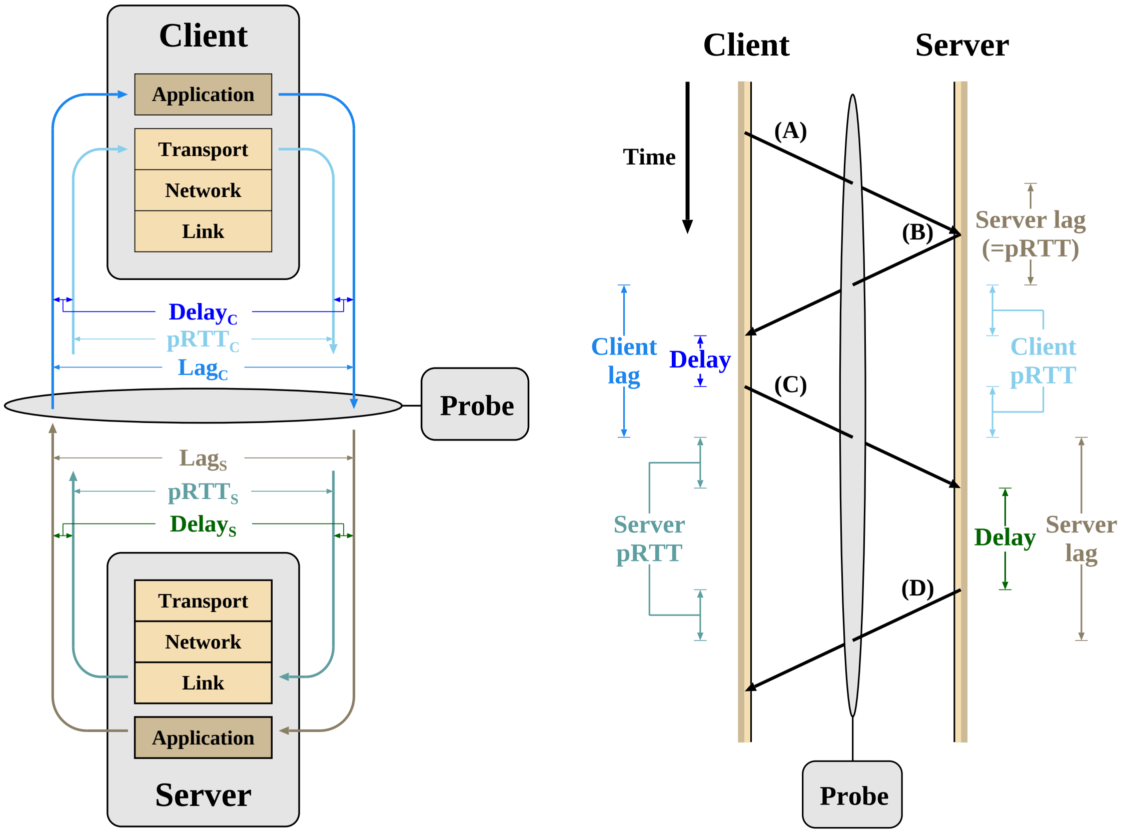
As noted in Section 5.2, analytic TCP models have largely been based upon steady state assumptions, a simplification which isolates TCP activity from that at higher levels. Studies based upon the analysis of individual connections have also simplified the models upon which they are based to minimise the impact of higher-level events: `tcpanaly` operates on traces of single bulk data transfers of 100 Kilobytes, hence limiting application-level activity to opening the connection and a single write operation; `tcpeval` isolates the connection set up and HTTP request/response phases from the main liberation-based model. These simplifications are not only convenient, but are also necessary in the absence of comprehensive knowledge of application activity.

Higher-level activity which overtly precipitates TCP activity has been discussed in Section 5.5.2.2, but more subtle interactions are also possible. The rate at which the receiver consumes data will affect the sender's transmission rate through the window advertisement mechanism. TCP transmission will cease if the sender does not maintain adequate data in the transmit buffer. In the former case, the effect is explicit through the observed window advertisements and is trivially incorporated into the liberation based model; transmit buffer exhaustion must be inferred from the sender's failure to transmit data at the expected time.

The amount of data to be transmitted can also modify TCP behaviour: Heidemann [Heidemann97a] notes how persistent HTTP performance can be compromised by delays in transmitting partial segments due to the operation of Nagle's algorithm [Nagle84]. Following the publication of Heidemann's findings, most Web servers operate with Nagle's algorithm disabled, but the activity model must be able to incorporate the behaviour of TCP connections where this is not the case: there is no guarantee that Nagle's algorithm will be disabled by all Web servers, and it will not be in many other applications. Because the model knows data transfer sizes Nagle effects can be identified and incorporated.

5.5.3 Monitor Position and Interpretation of Packet Timings

The monitoring point from which data is gathered may be anywhere between the communicating endpoints and it is therefore inappropriate to interpret packet arrivals in terms of conventional RTTs. RTTs, moreover, measure the *total* time taken by rounds and comprise network transit times, delays introduced by TCP itself and application delays — the motivation behind the development of the activity model is partly to distinguish between these components.



(a) The monitor sees the first packet of a causative pair in transit to the client or server and the second packet returning after some time lag. The lag comprises a partial round trip time plus any end-point delay. Note that the pRTT includes time spent in protocol stack processing.

(b) Packets (A – D) are associated in causative pairs (AB), (BC) and (CD). The pairs (BC) and (CD) are associated with lags comprising both pRTTs and application delays; the lag associated with (AB) does not include an application delay and therefore establishes a pRTT.

Figure 5.4: **Causative packet associations, lags, application-level delays and partial round trip times as seen at the monitoring point.**

5.5.3.1 The Monitoring Point, Packet Lags and Partial Round Trip Times

The model employs the concepts of *lags* between packets in causative associations, *partial* Round Trip Times (pRTTs), and end system *delays* as illustrated in Figure 5.4. The monitor sees packets en-route to a host and those returning from it. Those in the forward direction represent events which modify the TCP state of the host connection and which, in association with the state, may trigger events represented by those travelling in the reverse direction. These events may be interpreted, in the context of knowledge of causation at higher levels in the protocol stack, to maintain a current model of the connection's TCP state and to associate departing packets with causative arrivals. For each causative association the difference between timestamps represents the lag (i.e. the time taken for packets to traverse the network from the monitoring point to a communicating host, any delay at the host, and for returning packets to traverse the reverse path). A conventional RTT[4] is thus analogous to a *pair* of lags from the client and server sides of the monitor.

If any delay at the host is deducted from the relevant lag the residual time represents the *network transit time* or *partial* Round Trip Time (pRTT) of packets from monitor to host and back; a *pair* of pRTTs therefore represents the total network transit time between the two hosts. Figure 5.4(a) illustrates the relationship between lags, pRTTs and end-point delays.

5.5.3.2 Differentiation of Network and End System Times

The activity model discriminates the returning packets of causative pairs into those transmitted immediately on receipt of an incoming packet — in which case the lag time of the association is equal to, and establishes, a pRTT — and those transmitted after some delay. Figure 5.4(b) shows a time line diagram of causative associations with and without delay. End-point delays may be categorised as those due to:

- TCP implementation mechanisms (e.g. delayed ACKs , Nagle effects)
- Application delays (e.g. HTTP request processing and response generation)
- Serialisation delays (e.g. transmission awaiting that of previously queued packets)
- Combinations of two or more of the above

Because the activity model maintains models of the current TCP end-point state and application activity, it is able to both identify causative associations where lags include a delay and to categorise the delay. The majority of delays are identifiable as due to a single factor, but where more than one cause is possible the delay is taken to be due to the cause for which the model calculates the maximum notional lag magnitude.

For each identified delay the current pRTT is calculated by interpolation from nearby known pRTTs and deducted from the lag time to calculate the magnitude. It is axiomatic that a lag containing a delay does not yield an immediate pRTT and it has to be accepted that, in order to calculate delay magnitudes, some inaccuracy arising from interpolation of pRTTs is inevitable. The accuracy obtained by this technique will, however, normally be far better than that obtained by those where network transit times and end-point delays are not differentiated.

5.5.4 Unidirectional and Bidirectional Data Flows

The activity model is described for simplicity in terms of a unidirectional data flow. Such TCP flows are comparatively rare (the data transfer connections used by the File Transfer

[4] A similar technique is reported by Jiang and Dovrolis [Jiang02] who base RTT estimations on *rounds* — the activity model can achieve the same end, by combining pairs of pRTTs , but the differentiation of client and server pRTTs allows the calculation of delay magnitudes.

Protocol representing a significant exception) — even protocols such as HTTP , where the majority data transfer is unidirectional, normally include some bidirectional element (e.g. the transmission of the client request).

The model is, however, able to accommodate bidirectional flows without significant additional complexity. Where bidirectional flows do not take place concurrently, connection activity can be regarded in effect as two distinct unidirectional flows bounded by application-level activity; where the two flows occur concurrently causative associations are not invalidated, but care must be taken to differentiate `ACK`s *piggy-backed* on data segments from those whose timing is determined by normal `ACK` generation alone.

5.5.5 Identifying and Incorporating Packet Loss

Because the `Nprobe` monitor may be positioned at any point between communicating hosts packet loss presents particular difficulties. Packets may be lost:

Between the monitor and the receiver: The monitor sees the lost packet, but receiver state must not be modified to erroneously reflect its arrival.

Between the sender and the monitor: The monitor does not see the lost packet, but the loss must be detected by the model in order to adjust transmitter state appropriately.

In the first case, loss of data segments is trivially identified as the monitor will see a duplicate (retransmission) of the lost segment. An initial pass through the trace packet records marks the lost segment; when encountered the model adjusts the transmitter state but not that of the receiver.

In the second case the transmission of the sent, but unseen, segment must be inferred. In the majority of cases the loss will be suggested by a *sequence gap* in the segments seen by the monitor — also detected during an initial pass through the packets — during which a *dummy* packet can be inserted into the packet records to ensure that transmitter state is adjusted at the correct point. If the missing segment is part of a flight, the time that it would have been seen by the monitor can be estimated with reasonable accuracy from the timings of the accompanying segments.

In both cases loss will also usually be indicated by the generation of duplicate `ACK`s generated by the receiver. The possibility of individual segment loss can also be *eliminated* by the assumption that all acknowledged segments have been received[5].

There is more difficulty in identifying data segments lost between the sender and monitor where, at the time of loss, no subsequent segments are transmitted and hence no sequence gap is identified. In this case the model must rely upon either a subsequent data liberation manifesting the sequence gap or its own *expectation* that an unseen segment should have been transmitted. In the former instance the preliminary pass will identify the lost packet in the

[5] This assumption is regarded as safe — a TCP receiving an `ACK` for an unsent sequence would reset the connection and the model would be rejected as invalid.

normal way, in the second there is the possibility of ambiguity: the expected packet may have been lost, its transmission may have been subject to an application delay[6] or both delay and loss may be present. A heuristic solution is employed based upon the model's current estimation of the sender's retransmission timeout, application-level activity and the data size of the eventually transmitted segment.

When data segment loss is detected, the model must reflect the consequent effects upon TCP state and subsequent events, and must differentiate between timeout triggered retransmissions and *fast retransmits* [Allman99a][7]. The possibility of a fast retransmit will have been flagged by the observation of three or more duplicate `ACK`s , and the timing of the retransmission will normally indicate which has occurred. The model must incorporate the connection (re)entering a slow-start or fast recovery phase and adjust the value of its congestion window and slow-start threshold accordingly; the notional retransmission timer value must also be adjusted.

The loss of `ACK` segments presents rather more difficulty than that of data segments as the clue provided by retransmission is absent; it is primarily for this reason that the detection of lost data segments does *not* place reliance on the absence of the relevant observed `ACK`. Conversely, because `ACK` obligations result only from activity at the TCP level no possibility of confusion between lost `ACK`s and application-level delays arises.

It is useful, at this point, to introduce more of Paxson's terminology [Paxson97a]: `ACK` obligations may be *optional* — TCP may acknowledge a data arrival (e.g. when new in-sequence data arrives) or *mandatory* — an `ACK` must be generated (e.g. when out of sequence data arrives, for at least every second full sized segment, and at the upper bound of `ACK` delays [500 ms]). `ACK`s arising from in-sequence data may be *normal* (i.e. those for two full sized segments), *delayed* (i.e. for single segments) or *stretch* (i.e. for more than two full-sized segments). The activity model adds the term *sequence* acknowledgement for those generated by the arrival of out of sequence data.

`ACK` loss occurring between sender and monitoring point may be indicated by the failure to observe expected `ACK`s (either normal, or delayed after an appropriate period); unfortunately stretch `ACK`s are not uncommon[8] which renders the expectation of mandatory `ACK`s for every second segment unreliable as an indicator of loss on connections where they are found. The loss of stretch `ACK`s themselves can be detected because they inevitably acknowledge sequences *within the same flight.*

The cumulative nature of `ACK`s means that any failure to update the sender's state in the case of losses before the monitoring point is healed by subsequent `ACK`s. Similarly, `ACK`s lost between the monitor and the receiver are indicated by the release of an unexpectedly large flight following the receipt of a subsequent `ACK` — the flight size also distinguishes this case from that of data segment loss before the monitor. When flight sizes are determined by the

[6] TCP mechanism delays are disqualified — the model would anticipate such delays and a segment transmission would not be expected.

[7] The 'NewReno' modification to the fast retransmit algorithm [Floyd99] is not yet incorporated into the model — SACKs are not yet collected by `Nprobe` or modelled.

[8] With the exception of a maximum `ACK` delay of 500 ms, RFC 1122 [Braden89] couches its recommendations for `ACK` generation in terms of 'SHOULD' rather than 'MUST'.

congestion, rather than the flow, window, the corresponding indicator is a failure of expected window growth.

Fortunately the case critical to the accuracy of the model is that where ACK loss (wherever it occurs) results in retransmission, for which identification mechanisms are comparatively robust, and the retransmitting host's state can thus be corrected accordingly. The removal of possible ambiguities in detecting loss is also made easier because *expectations* can usually be expressed both in terms of sequence, and of observation time.

It may appear that a modelling process which depends upon both inferring loss and delay through observed activity is analogous to lifting one's self by the boot straps. The set-up phase of the connection, however, provides a reliable foundation for any following time-based heuristics. Application-level delays are absent from this phase, default retransmission timeouts (initially three seconds) are sufficiently large to be unambiguously identifiable, and an approximate magnitude for the connection's pRTTs is established.

5.5.6 Packet Re-Ordering and Duplication

Although, with the exception of retransmissions, it is assumed that data segments are transmitted strictly in order, the activity model must recognise that packets may be re-ordered by the network. As with packet loss, re-ordering may occur both upstream and downstream of the monitoring point. In general re-ordering may be distinguished from the case of packets lost before reaching the monitor and their retransmission, following intervening packets, because re-ordering inevitably occurs within the same flight[9], and because insufficient time will have elapsed for a retransmission to have taken place.

Upstream data re-ordering is trivially detected during the initial pass through packet records, and the relevant packets so marked to avoid confusion with sequence gaps denoting lost packets; downstream occurrences can only be inferred through subsequent connection activity. Because re-ordering does not effect the sender, and because, once the re-ordered sequence has been delivered, the receiver state is identical to that had not re-ordering taken place, the model is faced with little difficulty subject to the proviso that:

- Re-ordering is not confused with retransmission
- Any sequence ACKs generated are not taken as indicators of packet loss (the distinction is drawn by a closely subsequent normal or delay ACK)
- Fast retransmits due to multiple sequence ACKs are recognised[10]

ACK segment re-ordering has a lower incidence than that of data segments: Paxson reports

[9] This observation is supported by Bellardo and Savage who conducted a survey of packet re-ordering [Bellardo02] using active techniques which exploited characteristic TCP behaviour. They report finding the incidence of re-ordering of minimum-sized TCP packets to be less than 2 per cent when separated by more than 50 μs , tending to zero at 250 μs.

[10] This will occur only in the case of a re-ordering distance greater than three segments — no such distances have yet been observed.

a ratio of approximately 1:3 [Paxson99] for bulk transfers where a high proportion of ACKs might be expected to *cluster* due to large flights of data segments. For the majority of short-lived connections the findings reported in [Bellardo02] (see Footnote 5.9) suggest that ACK re-ordering will be extremely rare. Where ACKs are reordered, their impact on both receiver and model are minimal (due to their cumulative nature), although the model should ensure that the ACK following the delayed ACK is not confused with a stretch ACK .

Packets may also be duplicated by the network. Where data duplications are seen by the monitor, they can normally be distinguished from duplication due to retransmission by their arrival time. Duplications are detected during the initial pass through the packet records, marked, and subsequently rejected by the model, as they would be by the receiver. Duplicated ACKs can be ignored by the model; they will introduce inaccuracy only in the unlikely event that three duplications trigger a fast retransmission.

5.5.7 Slow Start and Congestion Avoidance

Congestion window growth must be tracked by the model during slow-start and congestion-avoidance phases of the connection. Accurate identification of flight sizes (Section 5.5.8 and Code Fragment 5.1 on the facing page) is necessary to enable the model's predictive element (Section 5.5.8.2) to verify that window-growth behaviour is accurately understood.

TCP implementations may enter congestion avoidance either when CWND is *equal* to the Slow-Start THRESHold (SSTHRESH), or when it becomes *larger*. The model notes the point at which CWND = SSTHRESH and determines the implementation's behaviour on the basis of CWND growth thereafter.

5.5.8 Construction of the Activity Model

The core of the activity model is a representation of the TCP state at the communicating end points; packet events (as represented by the header records collected by Nprobe) are presented in order to the model and state modified — the exact interpretation of events and their impact upon state are dependent upon the state at the time of the event. The representation of state identifies cause and effect relationships between packet events, and these and the state itself. A model of higher-level activity is incorporated and provides the context for the TCP-level activity observed; this model is typically relatively simple, activity consisting of request/response events and data transfer sizes. Other relevant information (e.g. the course of HTTP persistence negotiations, or whether pipelining is employed) is also recorded.

The model makes a preliminary pass through the packet records in order to group data segments into flights, and to mark any retransmitted, re-ordered, or duplicated packets identifiable at this stage. The simple, but reliable, algorithm used to identify flights is reproduced in Code Fragment 5.1.

```
        TFACT = 2

        # Calculate data transfer duration and threshold
        dur = self.sldata-self.sfdata
        thresh = (dur/self.dsegs)/TFACT

        flt = 0
        lt = self.pktlist[0].tm
        # step through the packets
        for p in self.pktlist:
            if p.len or p.flags & (TH_SYN | TH_FIN):
                if p.tm-lt > thresh:
                    # belongs to next flight
                    flt += 1
                # assign flight to packet
                p.flt = flt
                lt = p.tm
            else:
                # not data segment - no flight membership
                p.flt=None
```

Fragment 5.1: **TCP data segments are assigned to the same flight if the interval between their arrivals is less than a threshold value based upon the average inter-segment arrival period for the connection.**

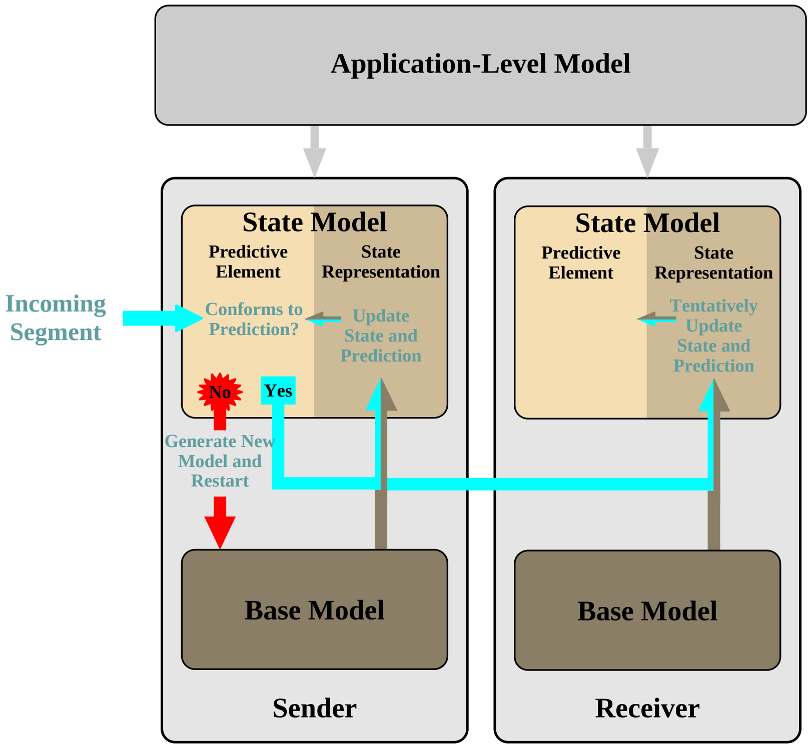
5.5.8.1 Base and Dynamic State Representation

The TCP state at each end point is represented by two sub models: a *base* model representing the rules governing the TCP mechanism and behaviour, and a *dynamic* model representing the endpoint state at any given point in time. A base model is established for each host endpoint which establishes the modification in state associated with each packet event and any resulting activity; the events themselves maintain and modify the dynamic model.

Differing base models are required to represent the range of TCP implementations encountered; for each implementation sub-models may be required to reflect connection-specific parameters (e.g. maximum segment size).

5.5.8.2 Self Validation and Iteration

For any moment in time the dynamic state model for each connection endpoint *predicts* the outcome of a packet arrival and any packet departure events which may be triggered. By observing packet departures, therefore, the correctness of the dynamic model may be confirmed, and, by inference, the base model validated for that connection. If a dynamic model displays violation of causality, the degree and nature of the discrepancy are used, together with the current base and dynamic models, to generate a fresh base model for that endpoint which would not give rise to the inaccuracy.



Note: If incoming segments violate the model's predictions a new base model is generated and the model re-started, otherwise state is adjusted and the next segment processed.

Figure 5.5: **Base, state and application-level models**

Each new TCP connection is initialised with a pair of *generic* base models of TCP behaviour: packets are presented as arrivals to the appropriate model, and as departures to the other, which are thereby validated or fail by violating the predictions made. If necessary new base models are iteratively generated and tested[11] until one is found which correctly predicts and matches the behaviour of the connection. Successful models are saved for future use, together with the heuristic rules used in their generation.

Base models, and their sub models, are represented by an alphanumeric code. When an iteration failure calls for the generation of a new base model, its code is checked against any models previously employed for that connection so as to avoid the possibility of repetitive loops. If a new model is generated which has previously been tested, or if a new model can not be generated to accommodate the preceding failure, then the model as a whole is rejected as a failure.

In practice few iterations of the model are generally required: the model seeks to understand and interpret only the connection activity seen, which for the great majority of short con-

[11] It would, perhaps, be more efficient to *rewind* the model to the error point than to recommence entirely with the new base model. If analysis code were written in C this might be feasible — state could be pushed on to a stack at each packet. Unfortunately Python does not provide an efficient memory copy mechanism analogous to the The C Programming Language (C) `memcpy` routine.

nections requires only a simple generic base model, and once a host has been seen its base model can be cached for reuse during the remainder of the analysis[12]. Successful pairs of models can be found for the majority of connections to new hosts with very few iterations — approximately 95 per cent of connections finding an accurate model with three iterations or less.

5.5.8.3 Confidence and the Validity of the Model

Although the overall model will fail if a suitable base model can not be derived, precautions must be taken against illusory models (i.e. those which produce no overt failures but which nevertheless do not accurately account for the observed connection activity). An additional test of successful models is therefore carried out based upon *incremental confidence.*

Some features of TCP activity and their representation by the model are trivially verified (e.g. an in-order segment is transmitted), others require more complex interpretation which may involve heuristic tests, or may give rise to possible ambiguity (e.g. the inference that a downstream segment has been lost). The interpretation of each packet event, and the accuracy with which it meets the model's predictions can therefore be associated with a *confidence factor* weighted to represent the complexity of the event prediction; a *confidence score* reflects the model's confidence in its disposal. Each apparently successfully modelled connection will consequently be accompanied by a confidence *rating* R ($0 \leq R \leq 1.0$) calculated as:

$$R = \frac{\sum\limits_{n=1}^{n=N} (C_n \times C'_n)}{\sum\limits_{n=1}^{n=N} (C'_n)^2}$$

where:
N is the number of packet events
C'_n is the confidence factor associated with event n ($0 < C' \leq 100$)
and
C_n is the confidence score associated with event n ($0 \leq C \leq 100$)

If the model's confidence rating falls below a threshold value R' then the model is rejected as invalid. The exact values ascribed to C and C' for any event, and to R', are arbitrary, and require 'tuning' in the light of experience as the activity model is developed.

[12] Persistent caching of base models is possible, with the caveat that host systems may change over time, but is not currently implemented as continuing development of the activity model may invalidate entries.

5.5.9 Enhancement of the Basic Data-Liberation Model

The basic data-liberation/ACK-obligation model of TCP behaviour will fail to characterise TCP activity in all but the most trivial steady-state established connections — although these are the main determinants of activity, connections' behaviour is considerably more complex. The way in which the model incorporates packet loss, re-ordering, or duplication is described in Sections 5.5.5 and 5.5.6; other desirable enhancements include:

The receiver's ACK *strategy:* Differing ACK generation behaviours will result in varying data liberation patterns as illustrated in Figure 5.6.

The model is able to distinguish delayed ACKs because they advance the window by less than two segments. A record of the times at which delayed ACKs are seen enables the model to approximate the period and phase of any heartbeat timer[13]. Stretch ACKs are recognised because they advance the window by more than two segments — differentiation between stretch and lost ACKs is discussed in Section 5.5.5.

TCP timers: In some situations the model depends upon retransmission timeout values to resolve ambiguities or to generate arrival event expectations (see Section 5.5.5 on page 123). Each end point's RTT estimation and retransmission timer is therefore modelled; the sum of server-side and client-side lags approximating the current RTT. This estimation is *out of phase* by the period taken by an ACK to travel between monitor and receiver, but the inaccuracy introduced is minor compared to the coarse precision required to distinguish retransmission events.

The model does not represent the TCP persist timer, as its representation is not necessary for the identification of zero-window probes; the keep-alive timer is similarly omitted as connections involving long periods of quiescence have not been studied to date, and keep-alive probes are also readily identified.

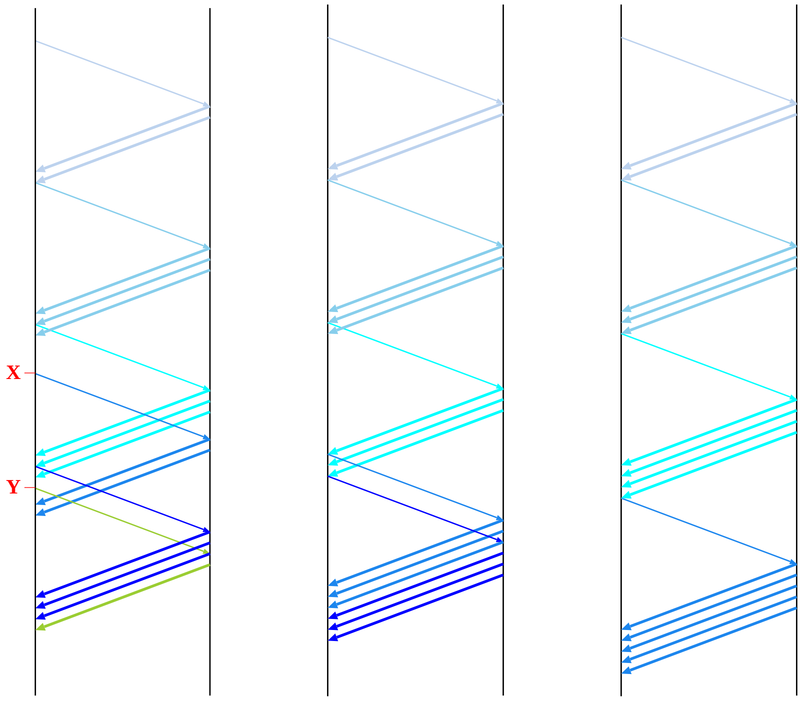
Maximum segment size: Nprobe records details of TCP MSS options, if seen, allowing each base model to be initialised with the correct, or default, value. The model must, nevertheless, check the MSS used by each end point as some implementations use a value *14 octets less*[14] than that advertised.

Window advertisements: The receiver's current window advertisement must be recorded, both to identify whether it, or the congestion window, is determining segment transmission, and to identify non-transmission due to window closure. Zero-window probes and transmission due to window growth are identified with reference to the current window size.

Initial window size: Base models are initialised with an Initial Window (IW) of two segments [Allman99a], but the size of the initial flight is checked and the value adjusted to guard against the possibility of the larger window allowed by RFCs 2414 [Allman98] and 3390[Allman02].

[13] Paxson notes that Solaris TCP uses a 50 ms interval timer, rather than a heartbeat timer; this possibility has not yet been incorporated into the model.

[14] Coincidentally the length of an *ethernet* header.



(a) Delayed `ACK`s generated at times X and Y

(b) No delayed `ACK`s have been generated

(c) All acks generated are stretch

Note: The receiver's acknowledgement strategy, and the period and phase of the delayed-`ACK` heartbeat timer, affect the pattern of data liberations and the interleaving of rounds. All of the connections shown deliver 14 segments in slow-start.

Figure 5.6: **The effect of receiver acknowledgement strategies**

Sender window: TCP implementations will place an upper bound on the number of segments in-flight based upon the size of the buffer committed to holding unacknowledged data. This bound is likely to be encountered only in the case of large data transfers on connections with particularly high bandwidth-delay products but should be recognisable by the model.

Application-level behaviour: Application-level activity in terms of initiating data transfers, etc. is implicitly recognised by the model, but it must also be capable of recognising when the application fails to deliver data to the sending TCP, which could otherwise have been sent at that time.

It is assumed that flights of segments are transmitted as back-to-back packets and an approximation of upstream bottleneck bandwidth B_U Mbps can therefore be estimated as shown in Figure 5.7(a) using the formula:

$$B_U = \frac{(s + ((n-1) \times O_P)) \times 8}{t}$$

where:

n is the size of the flight
O_P is the per-segment packet overhead in octets
S_i is the initial sequence number of segment i of the flight
$s = S_n - S_0$
T_i is the arrival time of segment i of the flight
and
$t = T_n - T_0$ in microseconds

Downstream bottleneck bandwidths are less accessible, but an estimation can be based upon the rate of returning ACKs using the technique of Instantaneous ACK Bandwidths (IABs) used by Mogul [Mogul92] and shown in Figure 5.7(b), and explained here, in simplified form. The IAB of two ACKs — B_I Mbps — is calculated as:

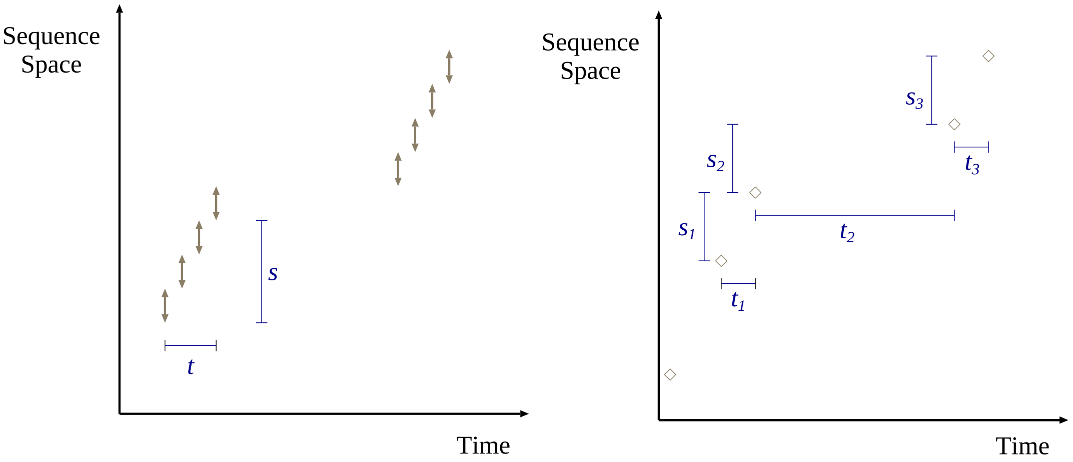
$$B_I = \frac{s}{t_A}$$

where:

$s = (s_A + (n_A \times O_P)) \times 8$
s_A is the number of octets acknowledged
n_A is the number of segments acknowledged
O_P is the per-segment packet overhead in octets
and
t_A is the time interval between the acknowledgements in microseconds

Figure 5.7(b) on the facing page shows the ACKs which might be generated by the segments shown in Figure 5.7(a) on the next page. IABs will indicate the downstream bottleneck bandwidth if the packets upon which they are based maintain queueing at the bottleneck: s_1/t_1 and s_3/t_3 will yield meaningful results if it is assumed that packets in the first and second flights queue; the value given by s_2/t_2 will probably *not*, as the buffer at the bottleneck may have drained between the two flights. Mogul demonstrates that a frequency analysis of the IABs generated by a connection produces a median value representing the connection's bottleneck bandwidth; values below the median represent segments which have not queued, and those above it represent ACK *compression* on the return path[15]. If the upstream bottleneck passes a lower bandwidth than that downstream then no information about the downstream bandwidth is available.

[15] Mogul's study is an investigation of ACK compression and its effect on TCP's self-clocking mechanism. The IAB technique itself is originally owed to Shepard [Shepard91].



(a) Upstream bandwidth estimate based upon flight size and duration

(b) Downstream bandwidth estimate based upon analysis of instantaneous `ACK` bandwidths

Figure 5.7: **Calculation of up and down-stream bottleneck bandwidths**

The studies carried out with `Nprobe` to date have concentrated on HTTP traffic with its characteristic predominance of short connections. The accuracy of IAB-based bottleneck estimation relies upon an ample sample of `ACK`s, and consequently this feature remains to be fully implemented.

5.5.10 The Model Output

Because the activity model accurately analyses TCP and higher-level activity and behaviour, and infers the contribution made by the network, its output is potentially a characterisation at both the individual and macrocosmic scales. The principal motivation for the development of the model has been the distinction of network/TCP and application level delays: the primary model output therefore comprises application-level delays and pRTTs.

A secondary output, consisting of a detailed characterisation of each connection, is available as an input to the simulation process described in Section 5.6, but could, in aggregate, also form the basis for wider studies. The model's output is defined and aggregated by a sub-type of the `StatsCollector` class described in Section 4.3.5 on page 89.

5.6 Simulation of Individual TCP Connections

Studies, such as that of the contribution of single connection delays to whole Web page download times described in Chapter 8, call for an accurate assessment of the impact of connection features (e.g. packet loss and recovery) at the granularity of the single connection. Although the accuracy of analytic models has been improved (e.g. by [Sikdar01][Padhye98] for short TCP connections) they do not encompass enough of the factors determining a connection's activity and duration to reliably predict individual outcomes when parameters at the level of detail provided by `Nprobe` traces are varied — to do so calls for accurate *simulation* of the connection based upon such fine-grained detail.

5.6.1 Assessment of the Impact of Packet Loss

The approach to assessing the impact of packet loss taken by Barford and Crovella [Barford00] is to use network analysis techniques to identify the *critical path* through the rounds of a connection. The contribution of connection set-up latency, application delay, and loss to the path are identified and quantified. This technique isolates the set of rounds determining the Payload Delivery Time (PDT) of the connection, and the network delay introduced into those rounds due to loss, but does *not* determine the overall effect of loss on the PDT because it is based upon the critical path as it is determined *in the presence of the loss*. In the absence of loss the critical path would be shorter, or could follow a different interleaving of rounds.

The major determinant of TCP PDT is the network RTT and the number of *rounds* required in connection set-up and to deliver data. When loss occurs, the effect on overall PDT is determined by an increased number of rounds rather than the delay between initial and re-transmission of the lost segment in all but the shortest connections.

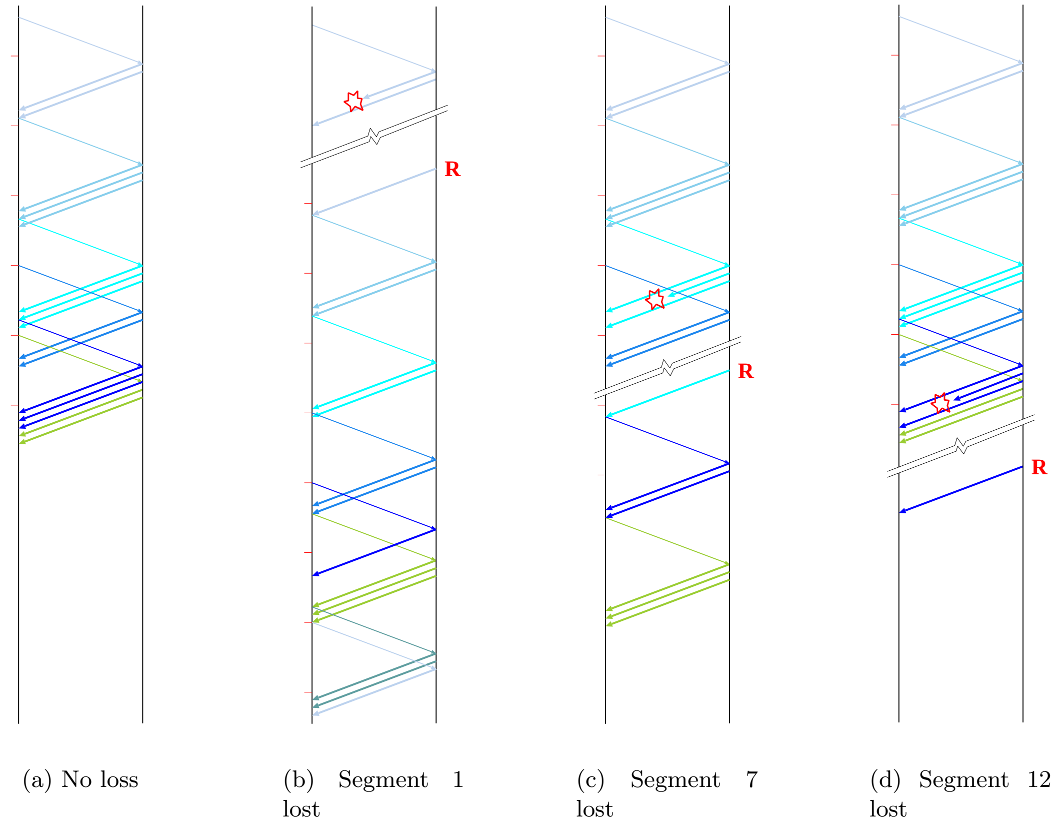
Packet loss may increase the number of rounds as determined by the sender's retransmission policy (i.e. the use of fast retransmits and possibly fast recovery); the receiver's acknowledgement policy may determine fast retransmits. The position of the loss in the segment stream, particularly if resulting in the connection re-entering slow-start (and the modification of SSTHRESH — hence adjusting the point at which CWND growth becomes linear rather than exponential) will also affect the number of subsequent rounds, and their interleaving as shown in Figure 5.8.

Estimation of the connection delay due to loss must therefore rely upon establishing the PDT of the connection *without loss* through accurate simulation. Similarly any other *what if* analysis, whether based upon Critical Path Analysis or not, must rely upon simulation.

5.6.2 Construction of the Simulation

The method employed to simulate individual connections is analogous to the construction of the activity model but with the following transpositions:

- The predictive element of the model becomes a posting of future packet events.
- Interpretative elements (e.g. pRTTs or application-level delays) become input parameters.
- Packet arrival events are concrete, rather than tentative.



(a) No loss

(b) Segment 1 lost

(c) Segment 7 lost

(d) Segment 12 lost

Note: The connections shown transfer 15 data segments. 'R' indicates packet retransmission, red tics indicate the receiver's delayed ACK heartbeat, and non-data–liberating ACKs are omitted for the sake of clarity. Connection (b) spends its entire lifetime in congestion avoidance. Although the congestion window re-initialises in (c) recovery is faster as the new value of SSTHRESH is higher. Re-entering slow-start has little impact on (d). If the sender implemented fast retransmit and recovery the impact of loss on (c) and (d) would be less, but (b) would not be affected as insufficient ACKs would be generated following the loss.

Figure 5.8: **Growth in rounds as a result of packet loss**

- The base model of connection behaviour is fixed, and is not modified during the connection's lifetime.

As in the model, simulated connection activity is based upon data liberations and ACK obligations; the connection itself is modelled as the state at the two end points. Packet arrivals modify state and may cause further packets to be transmitted — represented in the simulation as posted packet arrival events. Other posted events include factors such as the receiver's delayed ACK heartbeat timer firing (which will cause a delayed ACK event if an acknowledgement is outstanding) and zero-window expansion.

5.6.2.1 The Simulation Viewpoint

Because the simulation is based upon data collected at `Nprobe's` arbitrary monitoring point between hosts, it, in common with the activity model, must recreate connection activity in terms of time delays between packet events as seen at the monitoring point. pRTTs, application-level, and other delays are recombined to create lags between causative packet associations.

The unmodified simulation will be *short* by the total time taken for the first `SYN` segment to travel from the originating host to the monitor, and the final segment to travel from monitor to host. One-half of the relevant pRTT is added in compensation, but will introduce possible inaccuracy due to path asymmetries.

5.6.2.2 Input to the Simulation

Input to the simulation comprises its basic parameters and the detailed characterisation of the end-point TCP behaviours and application-level activity determined by the activity model:

The base model: determining the connections behaviour and parameters, such as initial congestion window size and delayed `ACK` period and phase. The default base model is one of generic TCP behaviour based upon RFCs 793, 813, 1122, and 2581, without fast retransmission and recovery. If the activity model has identified behaviour modifying the generic base model then the modified base model is passed to the simulation.

A list of data transfers: incorporating details of request/response delays at client and server and whether transfers are pipelined.

A list of application-induced features (e.g. window-advertisement adjustments and any zero-window periods, and transmit buffer starvation).

A list of (numbered) segments to be dropped: dropped segments modify the sender's state, but are not scheduled as arrival events. The simulation models the connection's retransmission timers in accordance with RFC 2988 and uses the appropriate values to post retransmission events if fast retransmits are not being used, or are not triggered.

The construction of a simulation with unmodified input parameters should produce a notional connection essentially identical to the observed connection upon which it is based. Any of the input parameters may be adjusted as required to investigate the desired what if scenarios.

5.6.2.3 Underlying Assumptions

The assumptions upon which any simulation is based are reduced as the level of input detail rises. The fine-grained characterisation of behaviour and activity produced by the activity model minimises the number of assumptions that must be made when generating the simulations described, although with the caveat that simulation may give rise to states with an outcome not assessed by the informing model. Such cases are minimised because many connections are often seen from a specific host, and characterisations of its TCP implementation behaviour can therefore be aggregate-based; where they do arise accuracy must depend upon appropriate generalisation of default behaviour.

A further, and inescapable, class of assumption is that other factors remain invariant when one or more input parameters are modified (e.g. changes in data transmission patterns do not affect the end points' ability to source or sink data, RTTs, or packet loss). Simulation results should be interpreted in the context of such assumptions.

5.6.3 Simulation Output

The primary simulation output is a list of the packets generated and Payload Delivery Times. Unmodified input parameters are already known and do not require duplication.

When a detailed analysis of simulation output is required, the output can be input to the activity model and the desired data extracted and aggregated as for observed connections. Care must be taken that any shortcomings in the original model are not perpetuated through the simulation and remodelling processes.

5.7 Visualisation

The results of activity-model analysis are incorporated into the TCP connection visualisation introduced in Section 4.5.2.1 on page 94. Causal relationships are presented, together with the model's congestion and flow-control window predictions, pRTT, and application delay estimations.

Support for analysis model and simulation development are provided by the visualisation tool. The Python TCP base model class interacts with the visualisation tool to present a menu allowing the results of activity modelling of each connection with a variety of bases to be assessed, and features such as the congestion window, and `ACK` high-water, indicators can be interactively *slid* to investigate their fit to observed data. The tool also allows simulations to be generated and the results modelled and displayed in order to present the effects of parameter modification.

5.8 Validation of Activity Models and Simulations

The activity model conducts the internal assessment of validity and confidence described in Section 5.5.8.3. The confidence which can be associated with analysis results in general, discussed in Section 4.7, is also pertinent to results obtained from the model and simulations. In the latter case, however, an additional difficulty arises because the results obtained contain a notional element which can not be traced back to known data.

5.9 Summary and Discussion

This chapter has introduced the analysis of individual TCP connections using an *activity model* which uses TCP/IP header fields, and the details of higher-level protocol activity collected by Nprobe, to reconstruct and interpret connection activity at the packet level. The model does not require data collection adjacent to a connection end point, and distinguishes application-level, TCP-level, and network effects.

Table 5.1: **Principal distinctions between tcpanaly and the activity model**

Tcpanaly	Activity Model
Designed to analyse generated test traffic of large data transfers	Must analyse whatever traffic is captured by the monitor (e.g. short connections)
Emphasis on identifying implementation bugs and RFC non-conformance	Emphasis on discrimination between TCP and application-level behaviour
Identifies limited set of test implementations through their static *built-in* characteristics	Implementation characteristics inferred through observed behaviour and modification of a generic behavioural model
Single continuous data transfer	Correlates multiple transfers and client/server interaction
Analysis of packet-filter–collected TCP/IP packet headers	Analysis of Nprobe-gathered TCP/IP packet header records integrated with application-level data
Must allow for packet filter losses, reordering, and duplication	Not introduced by Nprobe
Traces gathered at, or adjacent to, connection end point	Analysis must accommodate arbitrary monitor position
Network loss and reordering upstream of packet filter	May be up or down-stream of monitor

A TCP connection simulation implementation is also introduced, which generates TCP-level activity, also on a packet-by-packet basis, and which minimises underlying assumptions of TCP and higher-level activity and behaviour by taking its input from the fine-grained detail provided by the activity model. By varying the simulation's input parameters accurate what if scenarios can be investigated in the precise context of the individual connections being studied.

The activity model compares with Paxson's tcpanaly tool [Paxson97a] and shares a common basis in the underlying data-liberation model of TCP activity. There are, however, significant differences between the two, as summarized in Table 5.1: the demands made upon the activity model are greater, and its output and function are more complex. Tcpanaly does not accommodate known details of higher-level activity, and places less emphasis on identifying and quantifying application-level effects; it was designed to analyse connections carrying large data transfers between known TCP implementations, whereas the activity model must deal with connections of arbitrary length, and between whichever implementations are encountered. Both recognise that analysis of connection activity can not be based upon a fully generic model of TCP behaviour: the `tcpanaly` solution is to equip the tool with the known characteristics of the test implementations used; the activity model uses a generic *base* model which is modified to reflect the implementation-specific behaviour observed.

The activity model is not intended to uniquely identify the end-point host TCP implementations, the majority case of short connections without packet loss provides insufficient data, but to accurately interpret the observed activity sufficiently to discriminate the contributions of network, TCP, and higher-level protocols. Implementations are therefore categorised by *behaviour* rather than marque, and the reservation arises that there may, therefore, be no cross check of the model's interpretation against TCP implementation. It is, however, possible to confirm that the model consistently identifies the same model of behaviour on all connections from the same host *with the same level of activity complexity* — a correlation which can be investigated with base-model caching disabled. A further indication is provided, when analysing TCP/HTTP connections, by examining the HTTP `User-Agent` and `Server` header fields. Although these fields only yield a low level of implementation detail, a good correlation between operating system/version and the model's interpretation across all hosts is established.

Development of the activity model is continuing to ensure robust interpretation of increasingly complex connection activity, but in its present state effectively all connections without loss are correctly interpreted, and better than 90 per cent of those with loss. Chapter 6 describes a series of tests designed to assess the model's ability to discriminate and quantify Web server latency, concluding with a study of latency at a popular server. Chapter 8 describes the use of the activity model and simulation to investigate delay in Web page downloads. The technique provides a new and valuable facility to distinguish between the factors contributing to connection and application performance.

Chapter 6

Non-Intrusive Estimation of Web Server Delays Using Nprobe

The study described in this chapter was undertaken in order to assess the development of the *activity model* described in Chapter 5. It is not a demonstration of the full scope of data collection, or study complexity that `Nprobe` was designed to meet.

6.1 Motivation and Experimental Method

The performance of Web servers is a matter of considerable importance to the Internet Community, one metric of interest being response times to the requests received. Whilst these can be measured using both existing active and passive techniques, such measurements are likely to be inaccurate. At the worst TCP connection latency may be included (confirmed by the WAWM project [Barford99a] to make a major contribution to the time taken by HTTP transactions); at the best, even when the interval solely between request and response is measured, the contribution of server latency and network RTT to the observed delay are not differentiated.

Web content is increasingly generated dynamically, and often tailored on-the-fly to the user accessing the site. This places a considerable burden on the server through the execution of server-side programs accessed through mechanisms such as the Common Gateway Interface (CGI), and the use of scripting languages such as DHTML, ASP or PERL. *Back-end* processing involving database accesses is also often involved. Thus, servers may be expected to become more vulnerable to high or over-load conditions, and the potential requirement to monitor their performance and response latencies will become more acute.

A series of `Nprobe` traces of Web object downloads were analysed using the activity model to discriminate and quantify server latencies and *partial* Round Trip Times (pRTTs). Although the study emphasises *initial* server delays (i.e. from complete receipt of a request until the first segment of the response is dispatched), the analysis could equally well be used to identify all components of delay whether contributed by the server, browser, network, or TCP behaviour.

Three sets of experimental tests, based upon artificially generated traffic and described in Section 6.3, were conducted to assess the techniques used. In the study described in Section 6.4 on page 154 the techniques were then applied to real-world traffic. The target servers in the initial tests were set up specifically for the purpose, and were free of other, unknown, loads.

6.2 Use of the Activity Model

Sections 5.5.2 and 5.5.3 on pages 117 and 120 of Chapter 5 describe causal relationships between packets observed by the monitor, and how network, TCP, and application-level time components can be differentiated by the activity model. Section 5.5.3.2, in particular, describes how application-level delays are calculated.

In the experiments described in this chapter the calculation of server latency is based upon the measured delay between observing the final request packet from the client, and the first packet of the matching response from the server. This delay forms the *lag* from which a *pRTT* , interpolated from those established by *non-delayed* packets (i.e. those triggering an immediate return transmission by the receiver), can be deducted to calculate the component contributed by the application level. The activity model must thus correctly identify the appropriate causative associations in activity at both TCP and application levels.

In the case of the tests conducted using pipelined persistent connections described in Section 6.3.3, the model was required to establish valid causation in a more complex context where transaction boundaries are less evident, and where the timing of responses might be determined by activity at either the TCP or application levels, queueing behind preceding responses, or packet serialisation delays.

All connections carrying the transactions of the observed server load were presented to the activity model, which was used to identify instances of server latency and to differentiate the associated pRTTs. The model output, in this instance, comprised a list of latencies and pRTTs indexed by time. The latencies calculated for pipelined transactions were further distinguished by type as explained in Section 6.3.3.

6.3 Assessment Using an Artificially Loaded Server

The first set of tests, described in Section 6.3.1, observed traffic between a server and loading clients which were all connected to the same Cisco LX3500 100 Mbps Ethernet switch. The network RTTs were therefore considerably smaller than the expected server delays. In the second set of tests (Section 6.3.2) a more remote server, situated in the Computer Science Department of the University of Glasgow, was used and loaded by the same set of machines in the Cambridge Laboratory. This yielded an observation of transactions with RTTs and server delays of approximately the same order of magnitude.

Both servers ran the Apache 1.3.9 Web Server over Linux: on an Intel Pentium III 500MHz based PC in Cambridge and, in Glasgow, an Intel Pentium 200MHz based PC. The objects requested consisted of static objects — files of random bytes of varying sizes.

Two patterns of artificially generated load were produced:

- One or more *background* loads generated by `Httperf` [Mosberger98] consisting of repeated single requests at specified rates.

- An *observed* load generated by `Httperf` comprising repetitions of a single `GET` request for a 1024 byte document followed, on completion, by a series of ten concurrent requests for a 512 byte object. The estimated server delays are based upon observation of this load as the background load was varied with time.

The set of objects forming the background and observed loads was chosen to ensure that all requests could be satisfied from the server's cache, hence avoiding random delays due to disk reads. The cache was primed by a set of requests made before each test commenced.

A low priority *idle loop* process was run on each server for the duration of the tests, which simply recorded the number of times it was able to increment a counter during each 100 ms period — hence providing an indication of spare CPU capacity at any time during the experiment. The process was launched and terminated via CGI requests, enabling its operation and results to be synchronised with those derived by monitoring the network.

In each test the idle loop was first launched, followed by the observed load at time 10 s. Background loads were progressively added, and later removed, at further 10 s intervals. The client and server machines, load characteristics, load generating program, etc. for each test were defined by a simple configuration file providing the input to a script running on a *master* machine which controlled the various components of the experiment. The master was responsible for starting *slave* scripts on each of the loading clients, instructing them of the load to be generated and issuing commands to start and stop load generation at the times defined in the configuration file.

In the three experiments described in this section it was expected that server latency *would* rise with load, that the pRTT between monitor and server *might* rise as network throughput increased, and (trivially) that the number of free CPU cycles would fall. The results are shown in Figures 6.1 – 6.4: in each, Sub-figure (a) shows the total number of objects delivered per second and serves to confirm that the specified loads were actually presented to the server; Sub-figures (b) and (c) present the server latencies and pRTTs discriminated and calculated by the activity model; and (d) demonstrates the correlation between server delay and CPU usage.

In each Sub-figure (d) server delays averaged over successive correlation intervals are plotted against an average CPU load factor for the same interval. The tests were not intended to saturate the server, and even at the highest background loading spare cycles are available.

The CPU load factor ϕ ($0 \leq \phi \leq 1.0$) expressed as the ratio of CPU cycles absorbed by servicing the current load to those available at zero load is calculated as:

$$\phi_t = \frac{C_0 - C_t}{C_0}$$

where:
C_t is the idle loop count for period t
and
C_0 is the idle loop count at zero load

The *spread* of points plotted for each background load indicates the consistency of the load factor (x-axis) and server latency (y-axis). It is difficult to predict the correlation between varying load and server latency using a queueing model, due to the deterministic nature of service times (which must be assumed constant), and the general distribution of request inter-arrival times[1] (which, due to the nature of the loads generated does not conform to any standard distribution).

The average latency of observed load responses at *zero* background load can, however, be predicted with some confidence. It is known that the observed load results in less than full server utilisation, and that the burst of requests is not issued until the initial response has been received — the two can therefore be assumed not to impinge upon each other's servicing. It can be further assumed that the burst requests arrive at very nearly the same moment in time. The time in system (i.e. response latency) for each burst request will therefore consist of its own servicing time *plus* waiting time while its predecessors are serviced, i.e. for a burst of N requests and service time T_S the mean time in system T_N for each request is given by:

$$T_N = T_S + \left(\frac{N-1}{2}\right) T_S = T_S \left(1 + \frac{(N-1)}{2}\right) \tag{6.1}$$

The initial request of each observed load will not queue and will therefore simply have an in-system time of T_S; the average latency over the whole observed load T_O will therefore be given by:

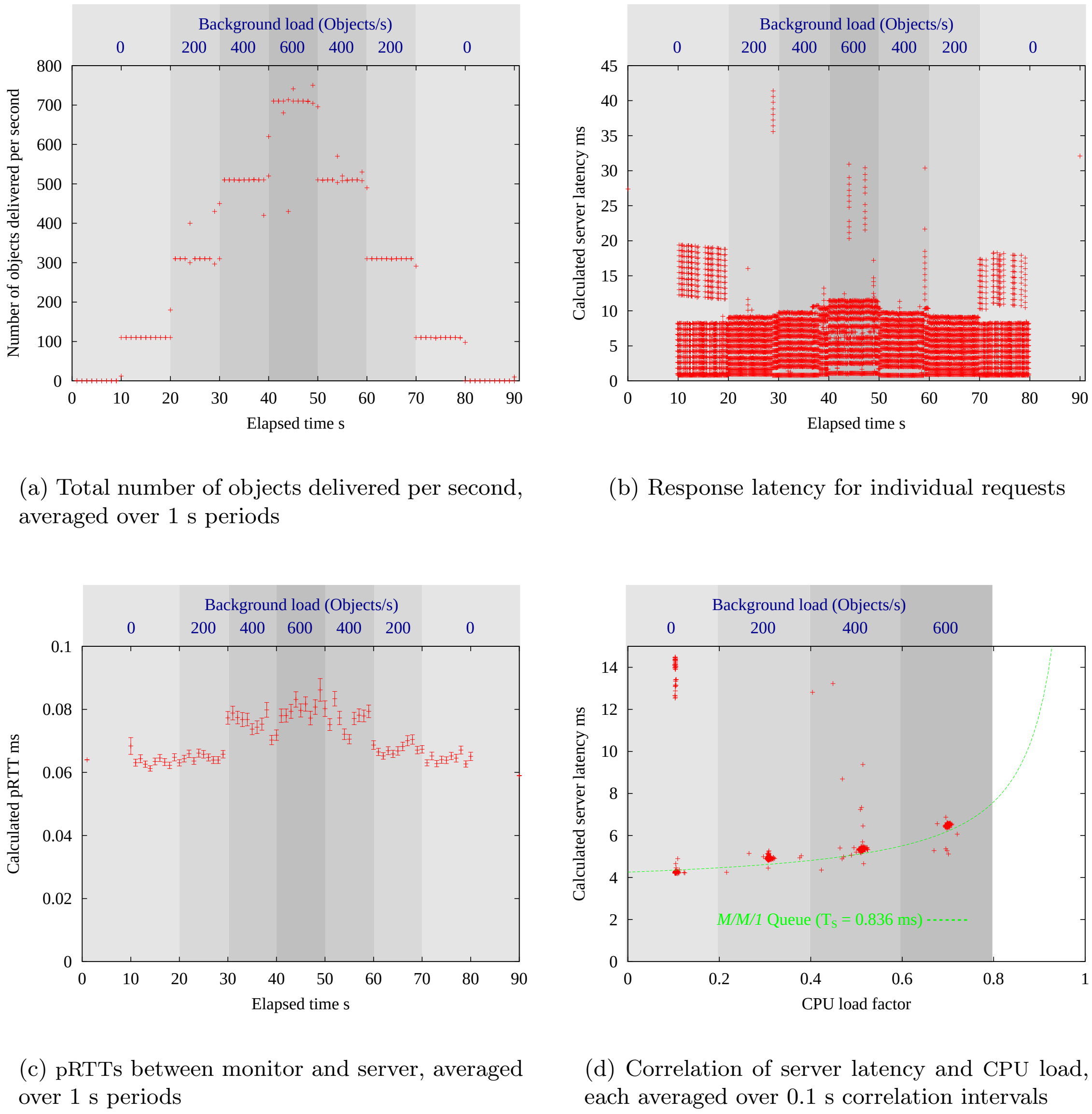
$$T_O = (T_S + (N \times T_N))/(N+1) \tag{6.2}$$

As background load is applied, observed load requests may be forced to queue as a result of requests already in the system, or requests arriving during processing of the burst. It is suggested that the waiting time T_W contributed by such queueing (irrespective of the queueing model employed) would be additional to the average zero-load latency T_O. In each sub-figure (d) the result of such additional waiting time with rising background load, obtained

[1] It should be remembered that the experiments were designed to test the activity model's capacity to distinguish perturbations in server latency rather than to investigate queueing behaviour — in which case it would have been possible to arrange, at least, an exponential distribution of requests.

by modelling the system as a simple $M/M/1$ queue[2] with $\rho = \phi$, is shown superimposed upon the observed values. It is stressed that the system is *not* being modelled as a simple queue — the queueing function is shown for comparative purposes only.

6.3.1 Client and Local Server with Small Round Trip Times



(a) Total number of objects delivered per second, averaged over 1 s periods

(b) Response latency for individual requests

(c) pRTTs between monitor and server, averaged over 1 s periods

(d) Correlation of server latency and CPU load, each averaged over 0.1 s correlation intervals

Figure 6.1: **Local server: load, calculated server latency and pRTT, and delay function**

Figure 6.1 show results typical of a test run with small RTTs between clients and server. The

[2] Hence with waiting time $T_W = \dfrac{\rho T_S}{(1-\rho)}$ and time in system (average latency) $T_Q = T_O + T_W$

observed load request bursts were spaced at 0.1 s intervals, and background load requests for a 1024 byte object were transmitted at a rate of 200 per second. Figure 6.1(a) shows the number of objects served per second over time.

The calculated server delays for the observed load during the period of this test are shown in Figure 6.1(b), which clearly demonstrates increasing server response times as the machine is loaded and unloaded. Delays are quite widely scattered during the periods when only the observed load is present (t = 10 – 20 s and t = 70 – 80 s). This is due to CPU scheduling artifacts as the single HTTP daemon competes against other processes running on the machine; under higher load Apache spawns more server processes which masks the effect. The delays of approximately 27 ms and 32 ms at times t = 0 s and t = 90 s are those of the CGI request sent to the server to activate and terminate the test, and reflect the longer delays associated with such requests.

The calculated pRTTs between the monitoring point and the server are shown in Figure 6.1(c). For clarity the values are averaged over 1 second periods, the error-bars representing the standard error of the mean for each period. At high load, some evidence of packets queueing in the network switch and/or the server interrupt handler can be seen, consistent with the range that would be expected, and values become more dispersed. The switch was carrying no other traffic, so, although not stressed, any contention for resources (e.g. during the periodic burst of concurrent requests) is evident. Comparison with Figure 6.1(b) shows that, for this experimental arrangement, the server delays and pRTTs differ by approximately two orders of magnitude, and that they are successfully differentiated by the activity modelling technique with little or no evidence of cross-talk.

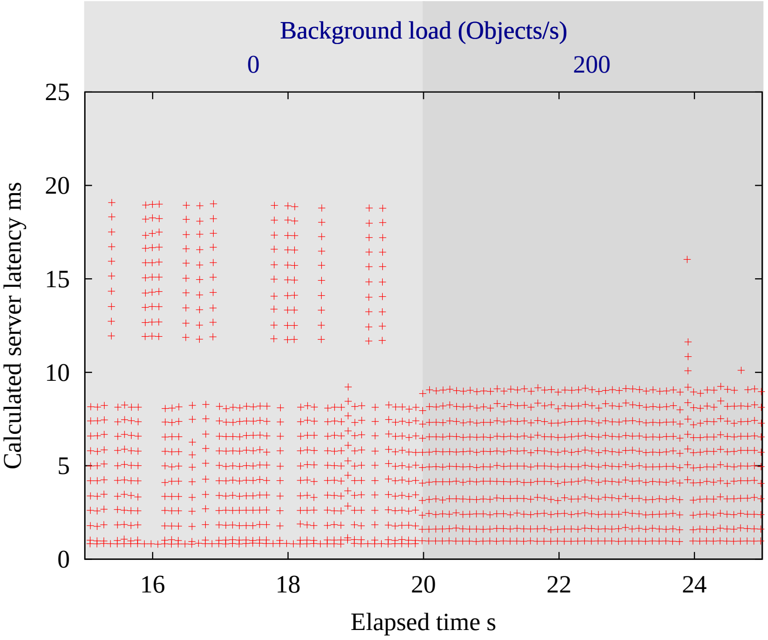


Figure 6.2: **Local server: detail of individual server delays**

Figure 6.1(d) demonstrates that server latencies and the CPU load factor remain largely consistent within each background load, with the exception of the few higher latencies seen during the periods of lowest loading. A simple $M/M/1$ queue model with is shown superimposed upon the observed values, with a service time $T_S = 0.836$ ms (3 s.f.), obtained by substitution of the mean server latency at zero background load in Equation 6.2. With the exception of a minority of scattered values (and notably the groups of exceptional delays at zero background load — which are excluded from the mean latency in calculating the mean service time) the observed values conform surprisingly well to the predictions of the $M/M/1$ model.

Figure 6.2 shows greater detail of the response delays for each request for t = 15 – 25 s (i.e. during the period when the first background load is added to the observed load), and demonstrates the precision with which individual delays are isolated. The regular spacing of request bursts at 0.1 s intervals is apparent, and the distribution of delays clearly reflects the way in which the observed load is generated — the burst of 10 concurrent requests following the initial request are transmitted back to back, each of the sequence queueing in the server after its predecessors, and consequently being subject to an increasing delay. It can be seen that approximately 30 per cent of the responses to bursts of concurrent requests before the server load is increased at t = 20 s are delayed by approximately an additional 12 ms, although the increasing delay within the burst remains consistent with the other bursts, and the corresponding initial request is not subject to the additional delay.

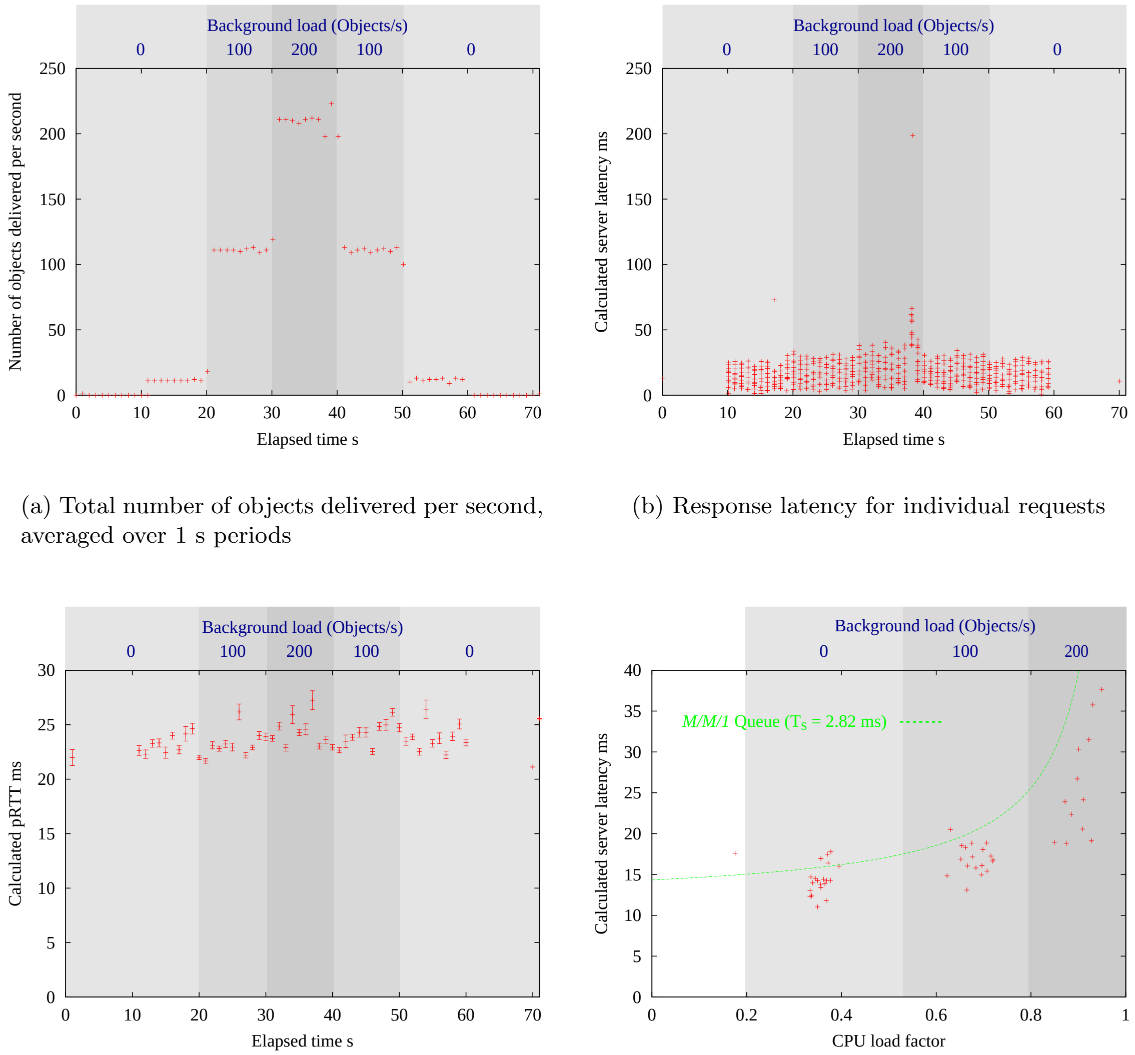
6.3.2 Client and Remote Server with Larger Round Trip Times

Figure 6.3 shows results obtained by repeating the previous tests but observing a more distant server. This is a less powerful machine than that used for the local-server tests, and the observed load was therefore reduced to a request burst interval of 1 s and the added background loads to requests for a 512 byte object at a rate of 100 per second. Only two background loads were applied.

Figure 6.3(b) shows the calculated server delays, which are more distinguishable than those in Figure 6.1(b) due to the greater spacing of the observed load request bursts, which can now be seen at 1 s intervals. The effect of increasing and decreasing load over time can also be seen, but is rather less apparent than in Figure 6.1(b) as this figure is scaled to show the very long delay at t = 38 s. The structure of the request bursts can once again be seen, although the increasing delays due to queueing in the server are now less regular than those seen during the previous experiment. It is concluded that the greater variation in round trip times leads to a less regular arrival rate in the server's request queue, with the consequent decrease in consistency of the queueing times themselves. The server latency exhibited by this, less powerful machine, is approximately twice that seen in the previous experiment, with occasional gross delays.

This experiment did not reveal the occurrence of the much greater delays for some request bursts seen in Figures 6.1(b) and 6.2, with the single exception at t = 38 s. It is not known whether this difference is due to the lower loads presented, to scheduling differences between Linux 2.2.5 and Linux 2.2.16 (running on the Glasgow and Cambridge machines respectively), or to other, unknown causes.

pRTTs between the monitoring point and the server are shown in Figure 6.3(c), again averaged



(a) Total number of objects delivered per second, averaged over 1 s periods

(b) Response latency for individual requests

(c) pRTTs between monitor and server, averaged over 1 s periods

(d) Correlation of server latency and CPU load, each averaged over 1 s correlation intervals

Figure 6.3: **Distant server: load, calculated server latency and pRTT, and delay function**

over 1 second periods. The pRTTs to the more distant server are now of the same order of magnitude as the identified server latency, their variation over time and dispersion remaining approximately in the same proportion to their absolute magnitude as seen in the case of the much smaller pRTTs shown in Figure 6.1(c). It is noticeable that the highest pRTT values are in most cases associated with greater dispersion over the 1 second periods shown, but that the correspondence between increasing background load and pRTTs is not clear — the load imposed by the tests was only a small proportion of the total traffic traversing the network components involved.

In contrast with the previous experiment where clients and server were connected by a single

100 Mbps switch link, the packets now observed have had to traverse many switches/routers and some lower-bandwidth links. However, the fine structure in Figure 6.3(b) suggests that it is still possible to extract pRTTs and server delays with accuracy. Although the potential for cross-talk between round trip times and calculated delays is far greater in this experiment, there is still little to suggest that it is present in any significant degree.

The correlation between CPU load and server latency shown in Figure 6.3(d) for each background load remains consistent[3], although less tightly so than in the previous test — it is surmised that, because the server on this machine consumes a higher proportion of the CPU than that in the previous test (a load factor of approximately 0.33 – 0.95 compared with 0.11 – 0.72), performance is more vulnerable to other demands upon the system. A simple $M/M/1$ queue model with service time $T_S = 2.82$ ms (3 s.f.) is shown superimposed upon the observed values.

6.3.3 HTTP/1.1 Persistent Connections

The experiment described in Section 6.3.2 was repeated, but using HTTP/1.1 persistent connections (i.e. the objects were all requested and served on a single TCP connection). The results of a typical test are summarised in Figure 6.4.

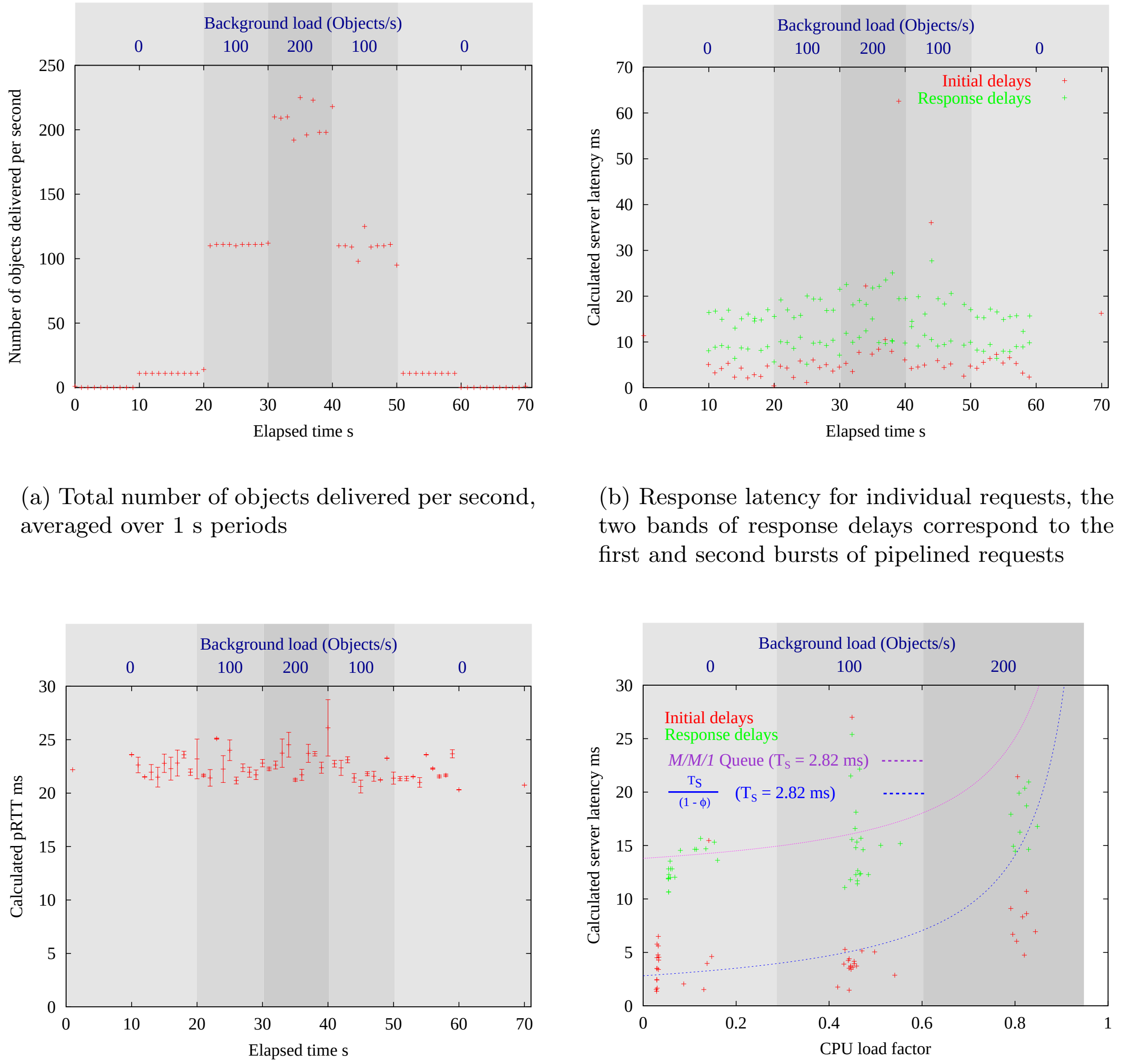
The requests sent on the persistent connections were *pipelined* (i.e. some requests were sent *without* awaiting the receipt of preceding replies). Requests were transmitted in three bursts: for object #1, for objects #2–#4, and finally for objects #5–#11, with a pause between each burst while the outstanding replies were received. Figure 6.5 on page 151 illustrates the pattern of activity on a typical connection; the request bursts are marked **A**, **B** and **C**.

The use of persistent connections and pipelining in this way gives rise to some interesting observations. Server delays can now be categorised as *initial* delays — the interval between the first request and response (corresponding to server delay on non-persistent connections), *response* delays — delays between subsequent requests and their response, and *null* delays – where the response is available but is queued for transmission behind its predecessor(s), and where TCP mechanisms may also determine timing. As null delays are the result of TCP and network characteristics they contribute nothing to the assessment of server performance.

Figure 6.4(b) distinguishes between initial and response delays. It is interesting to note that two bands of response delays can be identified at approximately 10 ms and 15 ms. The lower band represents the delay in response to request #1 (the first of a burst of three requests transmitted in *separate* segments), and the upper band the delay in response to request #4 (the first of a burst of seven requests transmitted in the *same* segment. The two bands are less distinct as load rises; it is not clear whether the difference in response times is due to scheduling effects, or because the server processing required for the transmission of response #1 can commence immediately upon receipt of the single request. Figure 6.6 on page 152 shows the request-burst activity on the connection in greater detail.

The correlation between server latency and CPU load shown in Figure 6.4(d) also distinguishes

[3] The single extremely high delay seen at t = 38 s has been omitted.



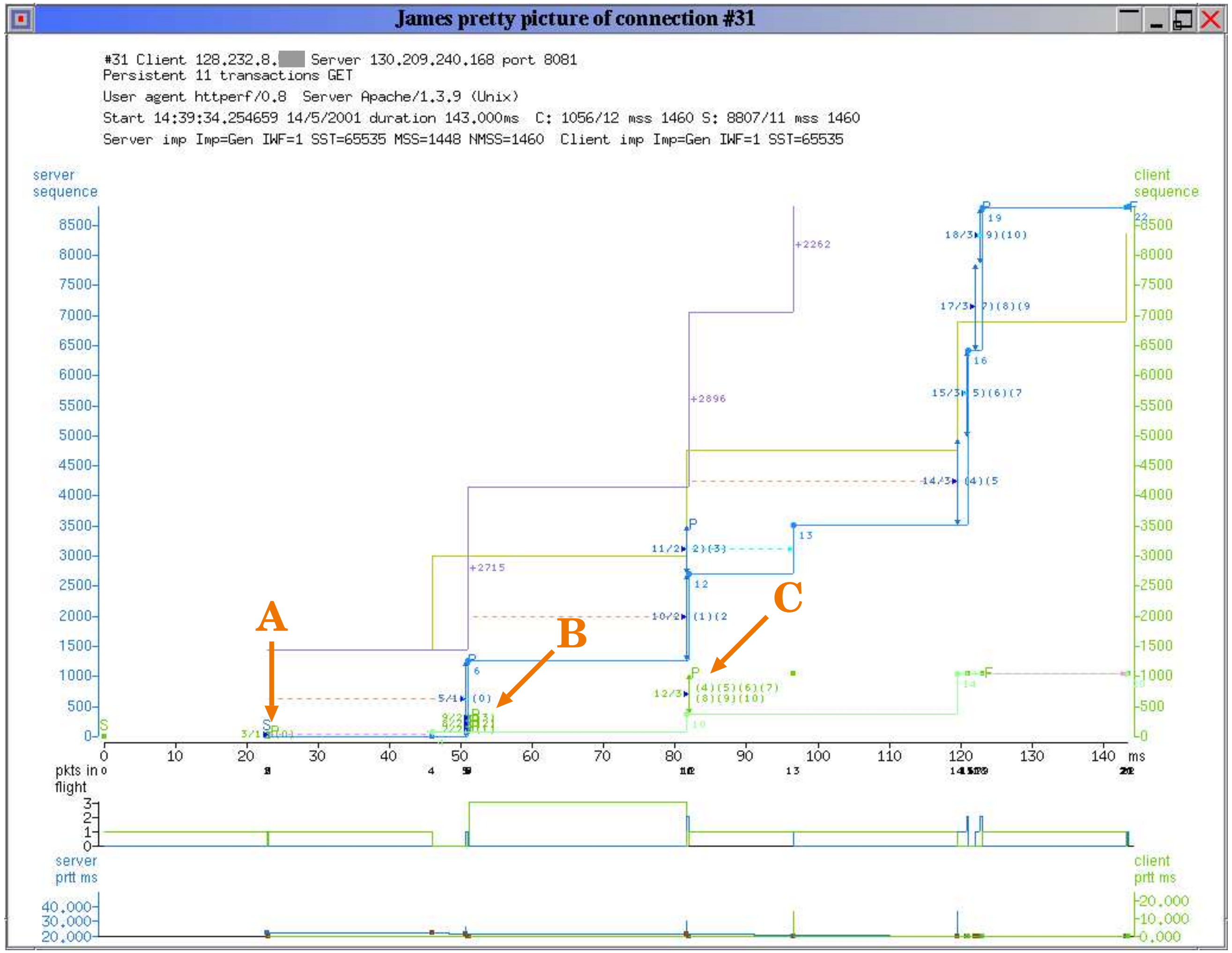
(a) Total number of objects delivered per second, averaged over 1 s periods

(b) Response latency for individual requests, the two bands of response delays correspond to the first and second bursts of pipelined requests

(c) pRTTs between monitor and server, averaged over 1 s periods

(d) Correlation of server latency and CPU load, each averaged over 1 s correlation intervals

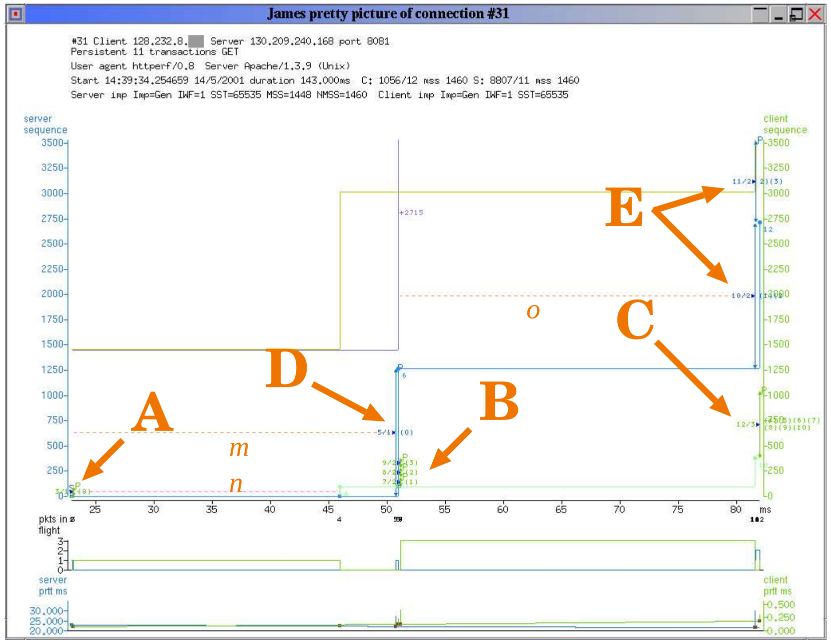
Figure 6.4: **Distant server with pipelined requests on a persistent connection: load, calculated server latency and pRTT, and delay function**



```
#31 Client 128.232.8.[redacted] Server 130.209.240.168 port 8081
Persistent 11 transactions GET
User agent httperf/0.8  Server Apache/1.3.9 (Unix)
Start 14:39:34.254659 14/5/2001 duration 143.000ms  C: 1056/12 mss 1460 S: 8807/11 mss 1460
Server imp Imp=Gen IWF=1 SST=65535 MSS=1448 NMSS=1460  Client imp Imp=Gen IWF=1 SST=65535
```

Note: The bracketed figures to the right of each data segment arrow indicate the request/response carried by the segment. **A**, **B**, and **C** mark the request bursts for objects #0 (packet #3), #1 – #3 (packets #7 – #9), and #4 – #10 (packet #12) respectively. The objects are returned in packet #5, #10 – #11, and #14 – #18. Objects #2, #5, #7, and #9 are split between segments.

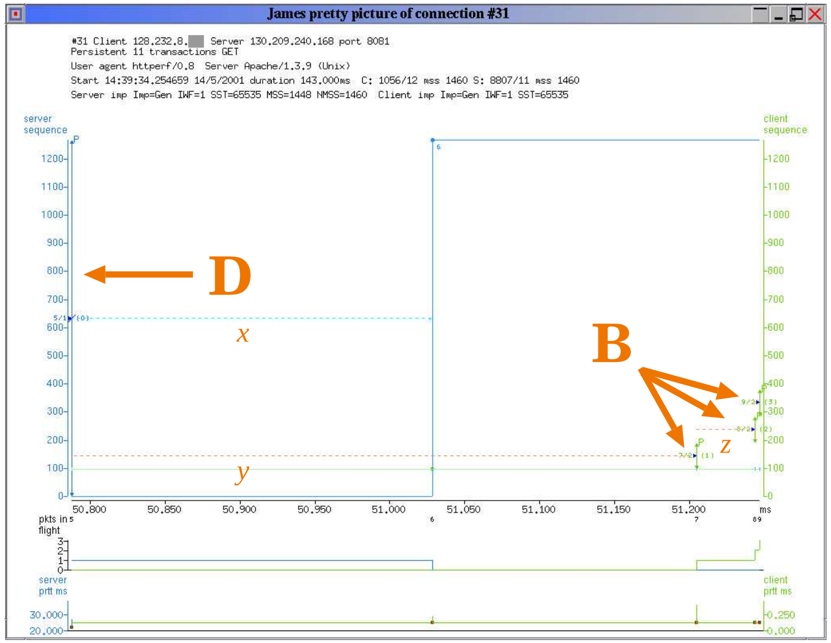
Figure 6.5: **Connection activity for pipelined HTTP requests to the distant server**



James pretty picture of connection #31

```
#31 Client 128.232.8.[redacted] Server 130.209.240.168 port 8081
Persistent 11 transactions GET
User agent httperf/0.8  Server Apache/1.3.9 (Unix)
Start 14:39:34.254659 14/5/2001 duration 143.000ms  C: 1056/12 mss 1460 S: 8807/11 mss 1460
Server imp Imp=Gen IWF=1 SST=65535 MSS=1448 NMSS=1460  Client imp Imp=Gen IWF=1 SST=65535
```

(a) The distribution of requests between bursts A, B, and C: D indicates the response to request A, and E that to request B. The horizontal dashed line *m* indicates that packet #5 carries the response to the request of packet #3 and establishes an *initial* server delay; *n* associates packet #3 with its delayed `ACK` (packet #4); and *o* associates request/response #1 to establish a *response* delay.



James pretty picture of connection #31

```
#31 Client 128.232.8.[redacted] Server 130.209.240.168 port 8081
Persistent 11 transactions GET
User agent httperf/0.8  Server Apache/1.3.9 (Unix)
Start 14:39:34.254659 14/5/2001 duration 143.000ms  C: 1056/12 mss 1460 S: 8807/11 mss 1460
Server imp Imp=Gen IWF=1 SST=65535 MSS=1448 NMSS=1460  Client imp Imp=Gen IWF=1 SST=65535
```

(b) Request burst B: requests #1 – #3 are transmitted in three segments (packets #7 – #9). The burst is triggered by the receipt of response #0 (D) as indicated by the dashed line *y*. Dashed line *z* indicates that request #2 is triggered by the transmission of request #1, requests #2 and #3 are transmitted back to back. *x* indicates that packet #6 carries a delayed `ACK` for response D.

Figure 6.6: **Detail of request bursts A, B and C shown in Figure 6.5**

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between initial and response delays. Comparison with Figure 6.3(d) shows that pipelining reduces the CPU load factor by between approximately 20 per cent and 15 per cent at the lowest and highest loadings, and this may explain the slightly more consistent load factor at each background load seen during this test[4]. Server latencies, however, exhibit a relatively wide variation, which may be due to inconsistencies in the number of objects served in relation to the scheduling of server threads, as a result of pipelining.

The single *initial* request latency of each observed loading can now be compared with the standard $M/M/1$ queue model, where time in system (latency) $T_Q = T_S/(1-\rho)$, shown in Sub-figure 6.4(d) with $T_S = 2.82$ ms (3 s.f.).

The pipelining of requests #1 – #3 and #4 – #10 requires a reworking of Equation 6.1 calculating the average latency of a request burst at zero background load: within each burst the number of requests, and hence the accumulated queueing time, is less - but additional latency is introduced where the transmission of a response is delayed awaiting *subsequent* responses *transmitted in the same segment*. This is more readily illustrated by Table 6.1, which summarises the typical response pattern shown in Figure 6.5, than formulaically. A mean latency for all responses over the two pipelined request bursts T_B becomes (with reference to Table 6.1):

$$T_B = T_S + 3.9T_S = 4.9T_S$$

Table 6.1: **Calculation of additional latency in units of the mean service time T_S for average latency of pipelined request bursts.**

	Req.	**Pre**	**Post**		**Req.**	**Pre**	**Post**
Burst 1	1	0	1	**Burst 2**	4	0	1
	2	1	0		5	2	2
	3	2	0		6	3	1
					7	4	2
					8	5	1
					9	6	1
					10	7	0
TOTAL		3	1			27	8
BURST TOTAL			4				35
							4
OVERALL TOTAL							39
Mean value per response over ten responses							**$3.9T_S$**

Note: Queueing while preceding burst members are serviced contributes **Pre** latency, and delay while waiting for service of subsequent responses to be transmitted in the same segment contributes additional **Post** latency.

The $M/M/1$ queue model for the pipelined requests is also superimposed upon the observed

[4] Also compare Figure 6.4(d) with Figure 6.1(d) where a lower CPU load factor is associated with more consistent values

values.

Comparison of Figures 6.3(b) on page 148 and 6.4(b) on page 150 indicates that initial delays on pipelined connections are of approximately the same magnitude as the delays seen on non-persistent connections. The response delays[5] seen in Figure 6.4(b) are higher than those of non-persistent connections, but must be set against the greater saving of a connection-establishment latency for each transaction. Figure 6.4(b) does not show null delays, and the number of measurements is therefore considerably less than when using non-persistent connections, although the number of objects requested are the same in both cases. Each null delay represents a saving of at least a single RTT per transaction compared to non-pipelined requests on a persistent connection. Interestingly, despite the obvious efficiency of pipelining, there is little evidence for it being widely exploited by current browsers.

6.3.4 Discussion of the Experimental Results

The results presented in Sections 6.3.1 – 6.3.3 suggest that the technique of activity modelling is able to successfully discriminate between network and application-level time components, with precise evaluation of both, and with little evidence of cross-talk. The anticipated positive correlation between CPU load and server latency is seen, but a comparison with the system's behaviour and the predictions of modelling it as a simple queue are, as expected, mixed. The observed behaviour of the local server bears a closer resemblance to $M/M/1$ queue behaviour then that of the less loaded distant server, where latencies do not rise as rapidly with load as in the model.

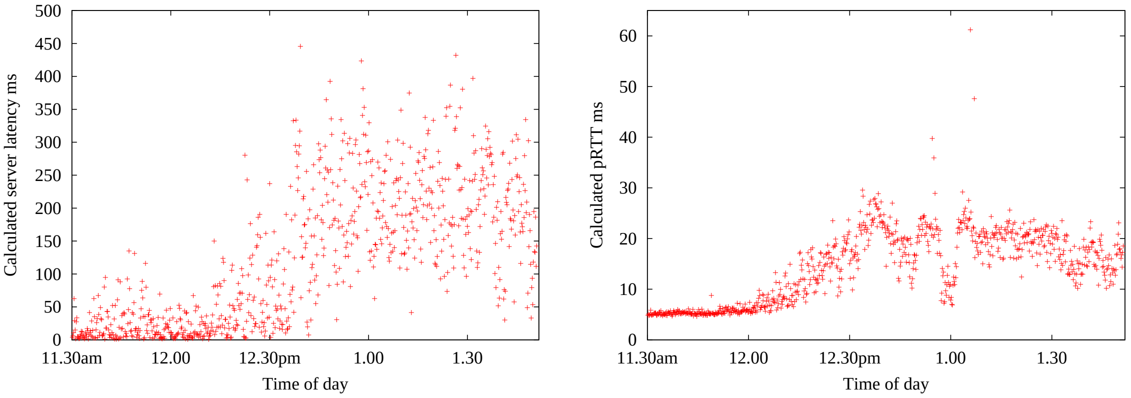
The accuracy of the technique can also be assessed by examination of the inter-arrival times for requests and responses as observed at the monitor. Appendix C discusses the results in this context, and shows that the zero background load latencies obtained by the Equation 6.2 model are in close agreement with those obtained by examination of the distribution of response inter-arrival times.

6.4 Observation of Real Web Traffic to a Single Site

The assessment tests described in Section 6.3 were followed by a study of real traffic: all HTTP requests from the University site to a well-known news server during periods of the day when the rate of requests made might be expected to vary. Figures 6.7 and 6.8 show the results obtained between 11.30am and 1.50pm, during which time approximately 90,000 TCP connections to the server, carrying 114,000 HTTP transactions in 2,522,500 packets were seen.

Figure 6.7(a) shows server delays; the delays increase sharply from around 12.15pm, presumably as people nationwide browse during their lunch break. The dispersion of delays increases

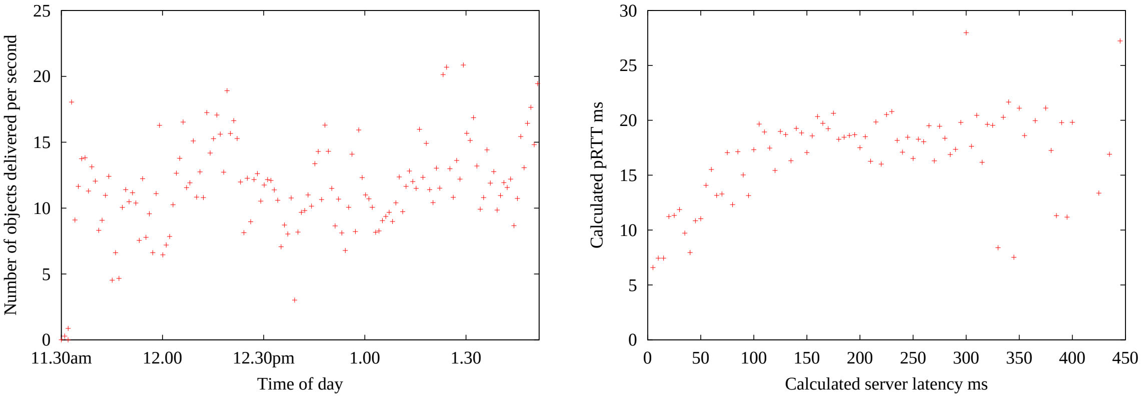
[5] The lower band of delays can be considered analogous to a subsequent request on a non-pipelined persistent connection as they refer to response delays for a single request made after the receipt of the response to its predecessor.



(a) Calculated server response latency

(b) Calculated pRTTs between monitor and server

Figure 6.7: **News server: calculated latency and pRTT . The values shown are averaged over 10 s intervals.**



(a) Number of local requests monitored

(b) Correlation of server delays and server-side pRTTs

Figure 6.8: **News server: measurement context. The values shown are averaged over 60 s intervals**

correspondingly. It should be remembered that these delays pertain to the retrieval of individual objects, and that the total time taken to download entire pages will be subject to a correspondingly greater increase with load — the reconstruction of *whole* page downloads is discussed in Chapter 7 and a study based upon the trace introduced here is presented in Section 8.4 on page 181.

Figure 6.7(b) shows how server-side pRTTs increase and become more dispersed over the same time period. The server and network loads observed in Figures 6.7(a) and 6.7(b) are determined by browsing patterns nationwide. In comparison Figure 6.8(a) shows the number of requests per second originating from the University site (i.e. the traffic which was monitored in order to calculate the delays and pRTTs shown). It can be seen that although an increase in delays and pRTTs is detected, reflecting national usage trends, this is independent of the rate of traffic monitored, which remains approximately constant throughout the experiment, and indicates that the results obtained are not effected by local load conditions.

The relationship between the calculated server delays and pRTTs for the observed period is shown in Figure 6.8(b). It can be seen that, while there is a strong correlation between pRTTs and increasing delays up to a value of approximately 150 ms, the network transit time remains approximately constant for higher delays. The implication is that (for the links involved) network performance is more robust than server performance in the face of increasing load.

6.5 Summary

The activity model described in Chapter 5 has been developed to differentiate and quantify the activity and time components contributing to a TCP connection's life time and behaviour by the network, TCP, and application-levels. This chapter has described the use of the model to analyse the TCP connections carrying Web traffic, with emphasis on isolating and assessing server latency.

Section 6.3 describes experiments in which `Nprobe` observed artificial HTTP traffic to and from a dedicated server to assess the accuracy of the activity model and its ability to correctly discriminate between TCP and application-level phenomena. A series of tests presented varying loads to the server to promote small differences in response latency, and were repeated with both geographically close and distant servers to vary the ratio of RTT to server latency. In all tests the model successfully isolated and measured latency and RTT, producing precise and accurate results.

A final, and more demanding, series of tests were based upon the observation of persistent HTTP connections with pipelined requests and are described in Section 6.3.3. The model was able to accurately associate transactions and the TCP segments carrying them using information collected from HTTP headers, and to distinguish characteristics of server latency arising from connections of this type which have been hitherto inaccessible without end-system instrumentation.

The accurate assessment of application-level delays is desirable, but previous techniques based upon passive monitoring risk introducing inaccuracy because the contribution of network RTTs can not be precisely evaluated and removed. Conversely RTT estimations will be inaccurate when application-level effects are included in the apparent network transit times measured. Section 6.4 describes a study of Web traffic between the University site and a popular news server. The growth in server latency experienced as the site becomes busy during the lunch break is clearly defined, and the trends in RTT, although an order of magnitude less than latency, successfully discriminated. The behaviour of a busy server as it reaches demand saturation is identified.

The utility and accuracy of the activity model has been demonstrated, and results not previously accessible using passive techniques have been obtained. An accurate measure of application performance has been demonstrated — although the HTTP traffic monitored conforms to a relatively simple model of client/server interaction, the techniques underlying the results obtained are applicable to a wide range of protocols and applications.

Chapter 7

Observation and Reconstruction of World Wide Web Page Downloads

World Wide Web (WWW) traffic forms by far the largest single category carried by the current Internet. As such, its study motivates a considerable and wide body of research. At the largest scale, characterisation informs network planning and traffic engineering, and at the smaller scale its underlying mechanisms, their interactions, and performance continue to attract attention as their dynamics are studied and performance improvements sought. This chapter describes how the data contained in `Nprobe` traces is used to reconstruct the activity involved in the download of whole Web *pages*, in contrast to more usual research based upon examination of the TCP *connections* used to download *individual* objects.

7.1 The Desirability of Reconstructing Page Downloads

Although the underlying Hypertext Transfer Protocol (HTTP) has wide applicability and is frequently used for single document, or object, transfers, its primary employment is to request and download Web *pages* comprising multiple objects. Detailed study of the dynamics of page downloads must encompass not only network, TCP, and HTTP activity, but also the behaviour of browser and server; accuracy also demands that the set of objects involved — the page's components — must be correctly identified.

A great deal has been learned from the examination of individual TCP/HTTP connections, but as explained later in Section 8.2 on page 176 such examination may fail to answer even such fundamental questions as how delay in downloading a page's constituent objects affects the download time of the whole page. Although the interaction of the protocols involved can be studied at the granularity of a single TCP connection, this runs the risk common in any concentration upon a system component in isolation — that the system as a whole, and the interplay of its parts, are not fully understood. By using trace data pertinent to the full range of protocols involved in Web activity, not only can the set of individual objects concerned be properly identified, but the interrelationships and interactions of the activities by which they are retrieved, and the behaviour of the entities concerned, can be analysed in the context of the whole.

7.2 The Anatomy of a Page Download

The typical Web page consists of a *container* document, normally written in Hypertext Markup Language (HTML), which may stand alone for simple documents, but normally contains *in-line* links to other *subsidiary* page components (e.g. images) which are automatically downloaded. More complex documents may contain further, subsidiary, container documents — *frames* — also downloaded via in-line links. Pages may also contain a *scripted* element: executable scripts run at page download or close time, or under user control. Scripts may be embedded in the container document or independently downloaded, and may themselves download further components, or fresh pages, either automatically or upon user demand. The layout and style of the page may be internally defined, or may be specified by one or more automatically downloaded Cascading Style Sheet components. The page itself, or one or more components (e.g. *tickers*), may, additionally, be automatically refreshed either once or periodically. Pages usually contain external, or *reference*, links (to other discrete pages), which are normally followed by the user and do not contribute to the current page download. Components of whatever type are habitually referred to as *objects*.

Container and subsidiary components usually reside upon the same (origin) server, but in some cases (e.g. central repositories of advertising material, Content Distribution Networks (CDNs)) sub-sets of components may be fetched from secondary servers. Because browsers can maintain caches of previously downloaded objects, not every link encountered results in a new request for the target object; requests may be *conditional* upon the freshness of the cached object and do not necessarily receive the object as a response.

Objects are normally retrieved via HTTP `GET` requests, but may also sometimes be returned as the response to other request types (e.g. `POST`). The request for a page will result in the return of the container document followed by a burst of requests for in-line objects which may be *cascaded* if those objects include frames or script elements. The identification of all objects is by Uniform Resource Indicator (URI) [Berners-Lee98], but the close coupling of identity and location inherent in object retrieval is reflected in the inevitable use of the URL subset [Berners-Lee94][Fielding95].

HTTP uses TCP as its transport mechanism. Early browsers opened a separate connection for each transaction, each download thus being subject to connection establishment latency, and commencing in the slow start phase. Additional load was placed upon the network, and servers had to maintain and service an unnecessarily large number of connections. Improvements to this strategy were suggested by Mogul and Padmanabhan [Padmanabhan95]. Of particular relevance were *persistent* HTTP connections — multiple requests carried over a single connection, and *pipelining* — requests transmitted without waiting for the response to their predecessor. Experimental data supported their recommendations and showed a significant reduction in overall download latency. A following paper by Mogul [Mogul95] demonstrated the reduction in latency that could be achieved, and presented the results of extensive simulations which also showed the reduction in server resources under TCP `TIME-WAIT` states of various durations. HTTP/1.1 [Fielding97], published in January 1997, incorporated persistent HTTP connections and pipelining, together with a protocol allowing connection persistence to be negotiated between HTTP/1.0 and HTTP/1.1 clients and servers.

Nielson *et al.* [Nielsen97] evaluated the performance of persistent HTTP connections and pipelining, concluding that significant improvements required the use of both techniques but were less noticeable when data was carried over low-bandwidth links. This observation was reinforced by Heidemann *et al.* [Heidemann97b] who conclude, as a result of the analysis of traffic models, that lowest link bandwidths in excess of 200 Kbps are required in order to realise a subjective improvement in performance seen by the user. The models used were validated in another paper [Heidemann97a] by comparison with real traffic. This paper also identifies areas of TCP/HTTP interaction where persistence introduces delay due to the effects of Nagle's algorithm [Nagle84].

The most common pattern of TCP activity seen during a page download is the opening of a single connection used to download the container document, followed, as the browser encounters in-line links, by the opening of one or more connections for the retrieval of subsidiary components. The number of following connections concurrently open is typically limited to two in order to limit undue bursts of demand on both network and server. If persistent connections are being used, all subsidiary components are normally downloaded on two connections, otherwise one connection is opened for each. Observation of very many downloads by `Nprobe` to date suggests that, despite potential performance improvements, persistent connections are used only in a minority of downloads (approximately 10%) and pipelining in hardly any[1].

7.3 Reconstruction of Page Download Activity

Page downloads must be examined in terms of the objects downloaded (HTTP transactions), the TCP connections used and their dynamics, and client and server activity. In order to quantify the contribution of these elements, each must be identified, but the interactions between them can only be fully understood in the additional context of:

(a) The arrival time of each in-line link at the browser[2].

(b) The full set of objects and their dependency structure (i.e. how do the objects relate to each other, which objects contain links causing others to be downloaded).

[1] This may be explained by many popular browsers being configured to use non-persistent connections by default. User-configurable browser properties vary greatly between browser marques, and between versions of the same browser. The option to employ pipelining is offered by very few, and is pointless in many cases as few servers support it

[2] Analysed in terms of lags and delays, as explained in Section 5.5.3 on page 120, because of the monitor's position independence. The term *arrival time* is used hereonwards for convenience and is valid in the context of observed causative associations where the *delay* between components is of interest (e.g. browser-contributed latency in opening a connection may be inferred from the difference between the time when the packet carrying an HTML link is seen by the monitor and that of the the corresponding `SYN` segment — a correction for the appropriate pRTT must be made).

The dependency structure within a page can be represented by a sparse Directed Acyclic Graph (DAG) with objects as nodes and links as edges — it is convenient to refer to this structure as a *reference tree*. Because pages may be arbitrarily linked to one another, the reference structure of multiple pages does not necessarily form an acyclic graph, but again may be represented as such if the progress through a cycle is regarded as a return to an node visited earlier (to do so reflects the reality of re-using cached documents and page components). Because components (e.g. page decorations) are often shared between sets of pages the overall reference structure forms a set of DAGs with a number of shared nodes.

7.3.1 Limitations of Packet-Header Traces

Traditional traces, based upon TCP/IP headers do not provide the context described: the data required to satisfy (a) are absent, and (b) must rely upon inference which may be misleading. A burst of connections carrying HTTP traffic between two hosts may imply that a page is being downloaded, but will fail to recognise concurrent page downloads, or associate components from multiple servers. Analysis of the individual connection activity may recognise the boundaries between transactions on persistent connections (e.g. a data packet from the client [request] followed by one or more from the server [response]), but will fail in the presence of pipelining. The nature of the server's responses is unknown, hence retrieval of small objects may be indistinguishable from non-delivery responses (e.g. `not modified` to conditional requests). Nothing can be inferred concerning the structure of the page (e.g. the presence of frames), and phenomena such as redirection, or automatic reloads, will not be recognised.

Studies of web performance using traditional traces have often concentrated upon *single* TCP connections but, as explained in Section 8.2.1 on page 176, there is often no direct relationship between single-connection performance and overall page download times. Where multiple connections have been considered, the inferential element may introduce considerable inaccuracy. The full set of data required to accurately reconstruct page downloads can, uniquely, be captured in `Nprobe` traces because of the monitor's capacity to extract data from the full range of relevant protocols. Data extraction from the IP, TCP, HTTP and HTML levels of the protocol stack is described in Sections 3.3.3.3 to 3.3.3.4 on pages 58–63 and 3.3.3.6 to 3.3.3.7 on pages 64–68.

7.3.2 Reconstruction Using Data from Multiple Protocol Levels

Page downloads are reconstructed and analysed using objects of the `WebHost` associative analysis class described in Section 4.3.3 on page 88. TCP connections are assigned to each object by client IP address; the structure of `Nprobe` trace files immediately associates each HTTP transaction with the TCP connection carrying it.

The relationship between objects is established by construction of the page reference tree(s), as described in Section 7.4, using HTML link and HTTP header data. The reference tree determines the relationships between transactions, the connections carrying them, the connections themselves, and hence any interactions of interest between protocols — the DAG representing the reference tree also represents an analogous graph in which the nodes are TCP connections, and which establishes the relationship between connections.

Figure 7.1 on the next page shows the relationships between the container document and in-line image objects for the early part of a typical page download. Analysis and deconstruction of the connection, using the activity model, identify time components derived from connection activity using TCP/IP header and HTML-level data. Thus L_{Req} and L_{Resp} indicate the lags from which browser request (`SYN-ACK` → request) and server response (request → first packet of response) latencies are calculated for the download of transaction #3.

The notation 'PO: N/N/N' (**A**) denotes the number of connections *presently open* as each new connection is opened, calculated by the three criteria (initial `SYN` → final `FIN-ACK`), (server's `SYN-ACK` → final `FIN-ACK`), and (server's `SYN-ACK` → first `FIN`) respectively — observation of many downloads suggests that all of these tests are applied by various browsers in deciding when a subsequent connection may be opened. For the connection shown the browser is maintaining four concurrently-open connections using the first criterion, hence connection #4 opens as a result of the full close of connection #0, and #5 follows #2.

The delay between the browser 'seeing' an in-line link and initiating a transaction to fetch the relevant object contributes browser *connection* latency, quantified using HTML link and TCP connection data, and shown as L_{Conn} in the enlarged detail of Figure 7.2. Where connection open time is dependent upon the close of an earlier connection L_{Conn} is determined by connection timings as shown in Figure 7.1.

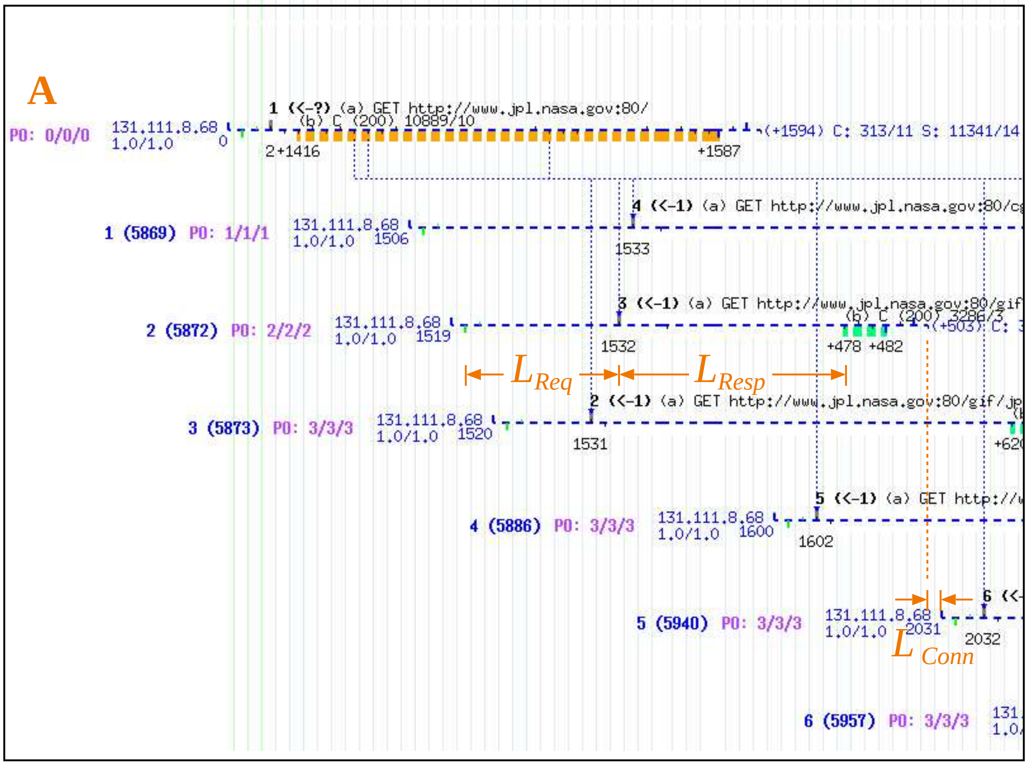
Connection ordering is normally determined by the ordering of the transactions carried, but it is interesting to note that this is not the case for the first three secondary connections (#1 – #3) shown. It is surmised that the browser has opened these connections speculatively as their request latencies are larger than those of following connections, which are ordered as expected. Figures 7.1 and 7.2 show detail of a page download with the visualisation tool in *detail* mode: the ordering of events is maintained but time periods in which no events take place are 'sliced out' in order to allow detail to be shown — the horizontal time scale is therefore non-linear. In contrast, Figure 7.3 on page 166 shows the entire page download in *time* mode; horizontal scaling is now linear, and the relationship in time between events is clear.

7.4 Constructing the Reference Tree

Construction of the reference tree depends upon data from two sources: HTTP request headers, which contribute '`Host`' and '`Referer`' fields; and the HTML content of container documents, which contribute the list of contained links extracted by `Nprobe` .

7.4.1 Referrers, Links and Redirection

For each container document identified during data collection, an associated list of link records (described in Section 3.3.3.7 on page 66) is attached to its Data Association Unit (DAU) trace



Note: The container document and early in-line images are shown. The visualisation tool is in *detail* mode; the fine vertical lines denote the missing *slices* of time between events. Blue dotted lines represent the links associating objects, and show that HTML link data also identifies the data segment carrying the link and hence its *arrival* time at the browser (see Footnote 7.2). The reference tree also establishes the relationship between the TCP connections opened by the browser.

Figure 7.1: **Detail from the Web activity visualisation of a typical page download**

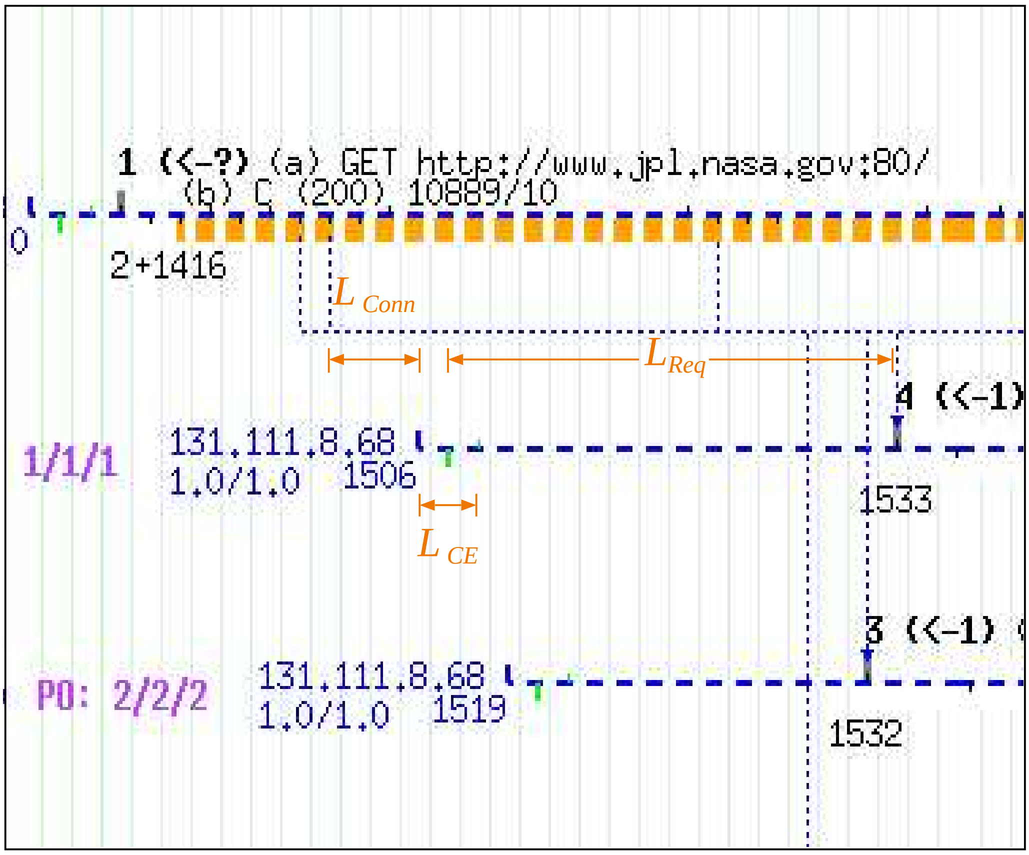
record. Not all links present in a document are guaranteed to be contained in this list: parsing functions for scripted elements have not yet been incorporated into the `Wan` software, and the HTML parsing function (whilst made as robust as possible) necessarily emphasises on-line parsing speed rather than absolute reliability.

Each downloaded object is associated with its container object (or referring page) by identifying, in order:

(i) *The referrer named in the request* `Referer` *field:* It is assumed that this field, if present, correctly identifies the URL of the referring document.

(ii) *A link to the object in the current container object:* if (i) has been successful the current container is thus identified and this step serves to verify the `Referer` field. If the request header does not contain a `Referer`, field step (i) is omitted; if a referrer identified in (i) does not yield the appropriate link, it is assumed to reflect an omission by the on-line parse.

To accommodate cascaded dependencies, subsidiary containers (e.g. frames) are pushed onto a stack as they are encountered; if the required link is not associated with the



Note: The request latency L_{Req} is measured from the receipt of the server's `SYN-ACK` and is consequently separated from L_{Conn} by less than the full TCP connection set-up latency L_{CE}.

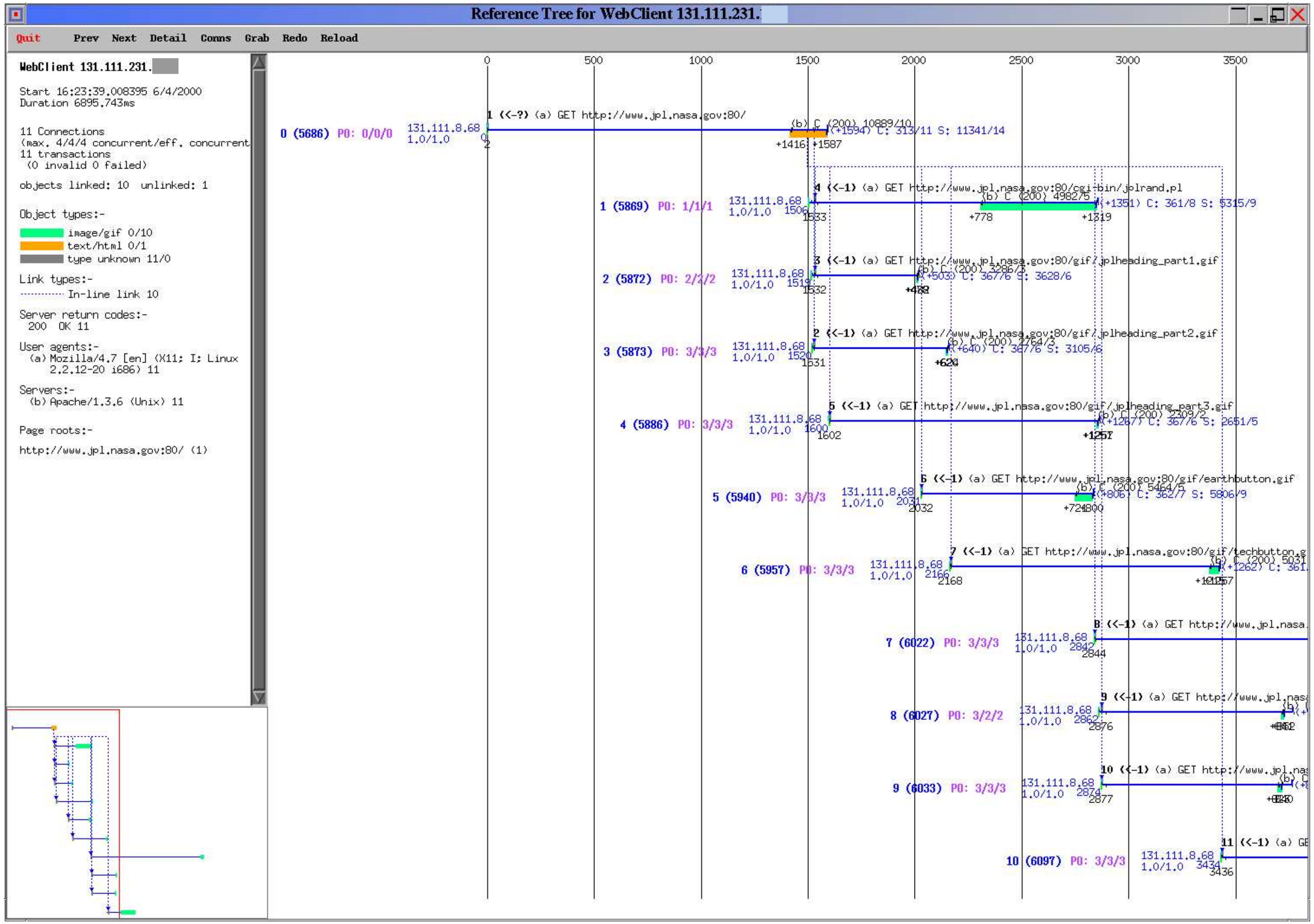
Figure 7.2: **Close detail of Figure 7.1 showing the browser connection latency**

current container, the stack is popped until the container is found (if step (i) has identified a container not at the top of the stack all higher documents can be immediately popped).

and if (i) and (ii) fail:

(iii) *A link contained in container objects previously seen:*

When a link is identified in either step (ii) or (iii) its record identifies its arrival time and *type* (e.g. in-line or external, container, frame, or script). In most cases the link type can be checked for consistency with the HTTP response `Type` header field for the linked object. Where a link has not been identified (e.g. due to a monitor parse fail or its inclusion in a scripted element) a *dummy* is created for inclusion in the reference tree: its arrival time is assumed to be that of the link to the immediately preceding downloaded object, and its type is decided in the context of its target object type and subsequent download activity.

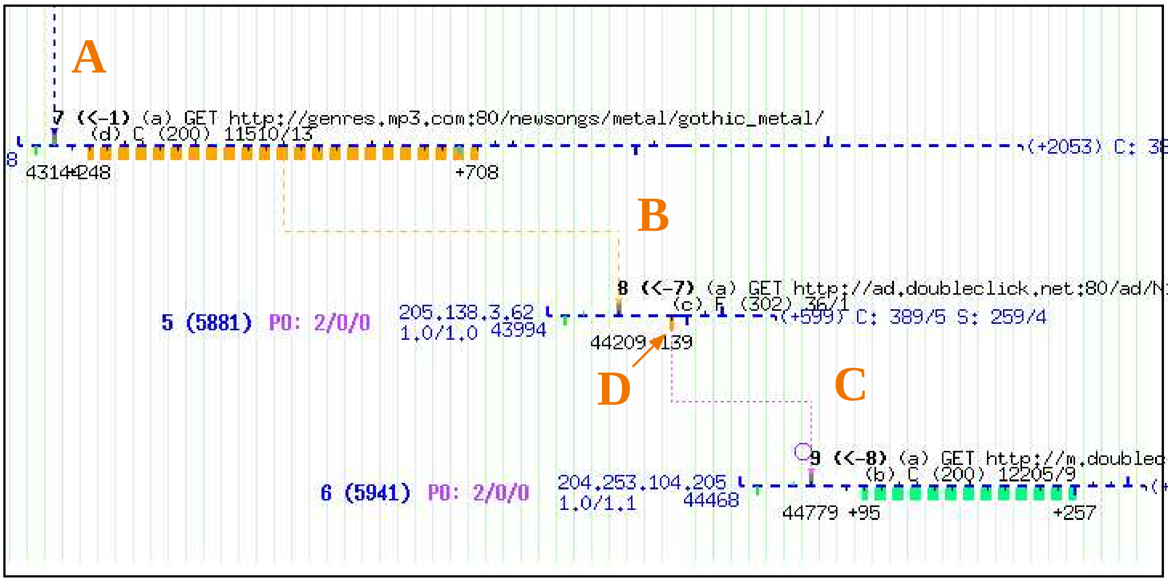


```
WebClient 131.111.231.[redacted]

Start 16:23:39.008395 6/4/2000
Duration 6895.743ms

11 Connections
(max. 4/4/4 concurrent/eff. concurrent
11 transactions
 (0 invalid 0 failed)

objects linked: 10  unlinked: 1

Object types:-
🟩 image/gif 0/10
🟧 text/html 0/1
⬛ type unknown 11/0

Link types:-
··········· In-line link 10

Server return codes:-
 200  OK 11

User agents:-
 (a) Mozilla/4.7 [en] (X11; I; Linux
     2.2.12-20 i686) 11

Servers:-
 (b) Apache/1.3.6 (Unix) 11

Page roots:-

http://www.jpl.nasa.gov:80/ (1)
```

```
0 (5686) P0: 0/0/0   131.111.8.68 1.0/1.0   0 2
  1 (<-?) (a) GET http://www.jpl.nasa.gov:80/
  (b) C (200) 10889/10  (+1594) C: 313/11 S: 11341/14   +1416 +1587

1 (5869) P0: 1/1/1   131.111.8.68 1.0/1.0   1506 1533
  4 (<-1) (a) GET http://www.jpl.nasa.gov:80/cgi-bin/jplrand.pl
  (b) C (200) 4982/5  (+1351) C: 361/8 S: 5315/9   +778 +1319

2 (5872) P0: 2/2/2   131.111.8.68 1.0/1.0   1519 1532
  3 (<-1) (a) GET http://www.jpl.nasa.gov:80/gif/jplheading_part1.gif
  (b) C (200) 3286/3  (+503) C: 367/6 S: 3628/6   +488

3 (5873) P0: 3/3/3   131.111.8.68 1.0/1.0   1520 1531
  2 (<-1) (a) GET http://www.jpl.nasa.gov:80/gif/jplheading_part2.gif
  (b) C (200) 2764/3  (+640) C: 367/6 S: 3105/6   +624

4 (5886) P0: 3/3/3   131.111.8.68 1.0/1.0   1600 1602
  5 (<-1) (a) GET http://www.jpl.nasa.gov:80/gif/jplheading_part3.gif
  (b) C (200) 2309/2  (+1267) C: 367/6 S: 2651/5   +1257

5 (5940) P0: 3/3/3   131.111.8.68 1.0/1.0   2031 2032
  6 (<-1) (a) GET http://www.jpl.nasa.gov:80/gif/earthbutton.gif
  (b) C (200) 5464/5  (+806) C: 362/7 S: 5806/9   +724 800

6 (5957) P0: 3/3/3   131.111.8.68 1.0/1.0   2166 2168
  7 (<-1) (a) GET http://www.jpl.nasa.gov:80/gif/techbutton.g
  (b) C (200) 5031  (+1262) C: 361.   +1257

7 (6022) P0: 3/3/3   131.111.8.68 1.0/1.0   2842 2844
  8 (<-1) (a) GET http://www.jpl.nasa.

8 (6027) P0: 3/2/2   131.111.8.68 1.0/1.0   2862 2876
  9 (<-1) (a) GET http://www.jpl.nas
  (b) (+

9 (6033) P0: 3/3/3   131.111.8.68 1.0/1.0   2874 2877
  10 (<-1) (a) GET http://www.jpl.nas
  (b) C (+

10 (6097) P0: 3/3/3   131.111.8.68 1.0/1.0   3434 3436
  11 (<-1) (a) GE
```

Figure 7.3: **The whole of the page download shown in partial detail in Figures 7.1 and 7.2; the visualisation tool is in time mode.**

Web pages and their components are frequently moved to fresh locations[3]. In such cases it is desirable to establish the transitive dependency from referrer to relocated object in order to identify delays due to redirection. Redirections are identified by the server's return code, the relocated object being located by one or both of: an HTTP `Location` header field (used by the browser to automatically issue a new request for the relocated object), and a textual object for presentation to the user, normally containing an external link to the object.



Note: The long-dashed blue line **A** denotes an external link followed by the user to a new page (object #7). The page's referrer is an earlier page (object #1, as denoted by the notation **(⟨−1)**). The page contains an in-line image, requested as transaction #8, but which has been relocated. The long-dashed orange line **B** indicates that the object dependency is established by referrer only, and the dotted purple line **C** denotes an in-line automatic redirection.

Figure 7.4: **Detail of download redirection**

When trace collection encounters redirection, the presence of a `Location` header field, or body containing an external link, prompts the addition of an appropriately typed in-line, or external, link to the HTTP transaction's link records. The redirection is therefore automatically assimilated into the reference tree during construction. Figure 7.4 shows the detail of a redirection: the fine dotted line and symbol '○' (**C**) indicate that the response to request #8 (server return code 302 `Moved Temporarily`) has been redirected and is now requested from its new location as transaction #9. The single response packet contains an HTML object (**D**) giving the URL of the new location, but automatic redirection has taken place.

[3] Figure 5.2 on page 114 shows a typical figure of approximately seven per cent of all `GET` requests receiving a '`Moved` . . . ' response from the server for the trace summarised.

7.4.2 Multiple Links, Repeated Downloads and Browser Caching

The same link is frequently included multiple times in a container document (e.g. to small page decorations), and in multiple pages. Browser caching will normally result in a single request for the target object; in which case the object download is assumed to be triggered by the first occurrence of the link in the current container document (it is assumed that any download of the object in response to links in earlier containers will already have been made). Objects are sometimes requested multiple times (the browser may not be caching the object, may be faulty, or the object may have a nil lifetime) in which case the multiple requests are associated with link occurrences in order.

A difficulty may arise when the user returns to a previously visited page (either through use of the 'back button' or by following a cyclic link. If the container object has been cached, but other components are requested, then the delimiter of the fresh container request is absent, and the component requests may appear to be much-delayed multiple requests originating from the original page. This situation can normally be identified due to intervening page downloads, but can cause confusion if components are shared. The converse case (the container is re-fetched but components are satisfied from the browser cache) is not problematic as the reference tree simply omits the cached objects, as it would in the case of fresh page downloads where components are cached. When components requests are observed which do not form part of the current page download (identified as such because they have a different referrer, the relevant links are absent from the container, and an arbitrary threshold period has been exceeded), a revisit is assumed and a dummy link inserted into the reference tree.

7.4.3 Aborted Downloads

Users may abort page downloads — usually as a result of delay — either by using the browser's 'stop' button, or by recommencing the download using the 'refresh' button. These cases can not be identified by a failure to download all components, which may result from caching.

Recommenced downloads may be indicated by the abort of one or more currently active connections, followed by a continuation of normal download activity (and possibly one or more repeated requests for objects already seen). Aborted connections are themselves indicated by premature termination (a lone `SYN` or a connection reset). Care must be taken over apparently reset connections, as browsers from the Internet Explorer stable tend to respond to the server's `FIN` segment on non-persistent connections with a `RST` segment, rather than complete the normal full four-way connection close. Such `RST`s can normally be identified, as the transaction is complete, and there is no indication of inconsistent TCP state. A similar cessation of activity will be seen in the case of total aborts, but without the recommencement of the download.

Aborted downloads are a matter of considerable interest, particularly their correlation with the user's subjective experience of delay. Future `Nprobe` development will include further empirical assessment of activity in this situation and will aim to make its identification as robust as possible.

7.4.4 Relative References, Reference Scopes and Name Caching

Because a textual match is required to associate link, referrer, and request URLs , and because these are frequently given in abbreviated or relative form, all occurrences are converted into canonical form before contributing to construction of the reference tree. Although deprecated, URLs may sometimes include dotted decimal IP addresses rather than machine names.

Relative URLs are resolved in the context of the current relative base, normally that of the container document, but HTML provides mechanisms for defining alternative, defined, bases and their scope. The on-line HTML parse identifies such base elements and scope delimiters, and includes appropriate records in the list of extracted links. During reference tree reconstruction relative URLs are therefore resolved in the correct context.

HTTP requires that all requests contain a (textual) `Host` header field identifying the origin server for the requested object. The given host name is used to resolve abbreviated URLs (e.g. of the form “/”), and also to check the host part of URLs for consistency. A problem can arise when dotted decimal addresses are used in request URLs and the `Host` field is omitted. In such cases the canonical URL is established by reference to the analysis process’s own cache of name bindings described in Section 7.5 on page 172.

7.4.5 Self-Refreshing Objects

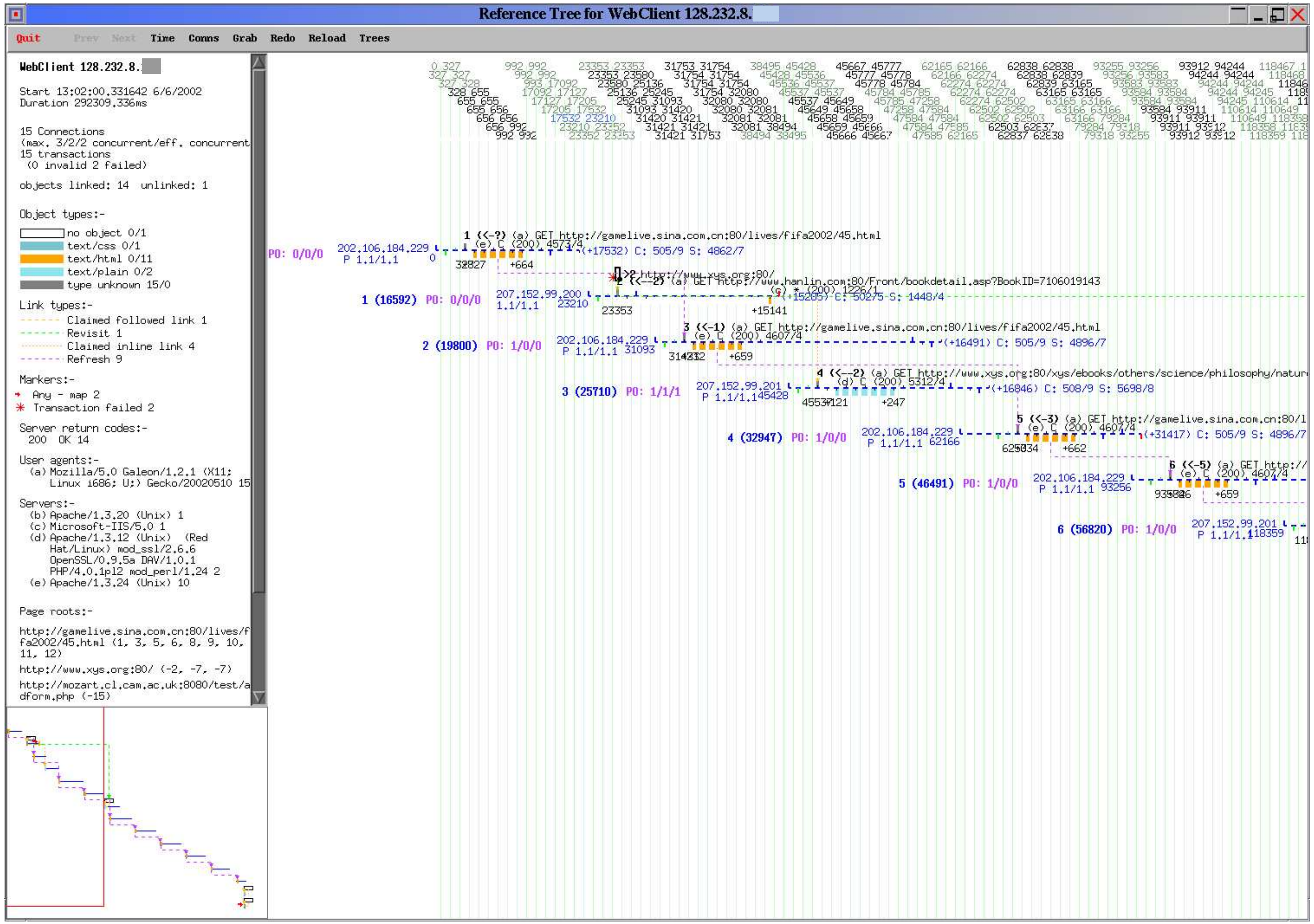
HTML documents may contain ‘`HTTP-EQUIV = REFRESH`’ META tags which cause the browser to reload the same, or another, object after a defined period, and which may result in repeated downloads if the refreshed object also contains the same directive. The mechanism may be used to redirect requests (in which case it is identified by the `Wan` code and accommodated in a manner similar to normal redirection as described in Section 7.4.1) or, more usually, to implement features such as *tickers*.

The mechanism is, for tree reconstruction, equivalent to the inclusion of an in-line link (as it results in an automatic download). Refreshes must be identified and excluded from the assessment of page-download times.

Figure 7.5 illustrates a self-refreshing object repeatedly downloaded to drive a ticker: the periodic refresh can be seen in the map window. The activity shown is extracted from a long trace, in which the object is refreshed at 31 s periods for over 40 minutes. The user continues to browse — transaction #2 is part of another page download (the root is not seen in this 9.4 s excerpt and is therefore represented by a dummy object). The transaction is aborted by a browser `RST` (indicated by a red packet tic) before completion, but not before an in-line text object is downloaded (transaction #4) - this connection is terminated by a server `RST`.

7.4.6 Unresolved Connections and Transactions

It may not be possible to immediately associate some transactions with a referring object: the `Referer` field may be absent, and no matching link found. In the case of container



WebClient 128.232.8.

Start 13:02:00.331642 6/6/2002
Duration 292309.336ms

15 Connections
(max. 3/2/2 concurrent/eff. concurrent
15 transactions
(0 invalid 2 failed)

objects linked: 14 unlinked: 1

Object types:-
□ no object 0/1
▬ text/css 0/1
▬ text/html 0/11
▬ text/plain 0/2
▬ type unknown 15/0

Link types:-
------- Claimed followed link 1
------- Revisit 1
-------- Claimed inline link 4
------- Refresh 9

Markers:-
→ Any - map 2
✳ Transaction failed 2

Server return codes:-
200 OK 14

User agents:-
(a) Mozilla/5.0 Galeon/1.2.1 (X11; Linux i686; U;) Gecko/20020510 15

Servers:-
(b) Apache/1.3.20 (Unix) 1
(c) Microsoft-IIS/5.0 1
(d) Apache/1.3.12 (Unix) (Red Hat/Linux) mod_ssl/2.6.6 OpenSSL/0.9.5a DAV/1.0.1 PHP/4.0.1pl2 mod_perl/1.24 2
(e) Apache/1.3.24 (Unix) 10

Page roots:-

http://gamelive.sina.com.cn:80/lives/fifa2002/45.html (1, 3, 5, 6, 8, 9, 10, 11, 12)

http://www.xys.org:80/ (-2, -7, -7)

http://mozart.cl.cam.ac.uk:8080/test/adform.php (-15)

```
0 327      992 992      23353 23353  31753 31754  38495 45428  45667 45777  62165 62166  62838 62838  93255 93256  93912 94244   118467 1
327 327    992 992      23353 23580  31754 31754  45428 45536  45777 45778  62166 62274  62838 62839  93256 93583  94244 94244   118468
327 328    993 17092    23580 25136  31754 31754  45536 45537  45778 45784  62274 62274  62839 63165  93583 93583  94244 94244   11846
328 655    17092 17127  25136 25245  31754 32080  45537 45537  45784 45785  62274 62274  63165 63165  93584 93584  94244 94245   118
655 655    17127 17205  25245 31093  32080 32080  45537 45649  45785 47258  62274 62502  63165 63166  93584 93584  94245 110614  11
655 656    17205 17532  31093 31420  32080 32081  45649 45658  47258 47584  62502 62502  63166 63166  93584 93911  110614 110649
656 656    17532 23210  31420 31421  32081 32081  45658 45659  47584 47584  62502 62503  63166 79284  93911 93911  110649 118358
656 992    23210 23352  31421 31421  32081 38494  45659 45666  47584 47585  62503 62837  79284 79318  93911 93912  118358 1183
992 992    23352 23353  31421 31753  38494 38495  45666 45667  47585 62165  62837 62838  79318 93255  93912 93912  118359 118
```

Figure 7.5: **A self-refreshing object repeatedly downloaded to drive a ticker. The figures at the head of the main window indicate the boundaries of the missing time slices in the detail view.**

documents it is assumed that the referrer has not been seen because its download fell outside the monitoring period, or because the request originates from a bookmark or user-provided URL . Such transactions become the roots of discrete reference trees.

In the case of subsidiary page components a simple heuristic is employed — if the transaction falls within a group of others known to originate from the current container, then that container is taken as the referrer. A dummy link is created similar to that in the case of resolved transactions with no identified link.

Aborted connections upon which a request has been issued can be integrated into the reference tree in the normal way, but where connection attempts have been unsuccessful, or connections are aborted before a request is made, no transaction request exists with which to integrate the connection into the reference tree — it is desirable to do so because such connections may indicate aborted or recommenced downloads (Section 7.4.3 on page 168). It is normally possible to resolve such connections using a similar heuristic to that employed in the case of unresolved transactions.

7.4.7 Multiple Browser Instances and Web Cache Requests

Multiple concurrent page downloads can occur when a single user instantiates more than one browser, or in the case of multi-user hosts. This may cause confusion in the construction of reference trees, if identical pages, or those with common components, are concurrently downloaded. Although transactions are associated with a browser using the client IP address of the connections carrying them, such potential confusion can be minimised by using the finer-grained association provided by the browser employed — this information is provided by the HTTP `User-Agent` header field. It is suggested that multiple concurrent downloads of the same page, to the same host, using the same browser marque and version are relatively rare, and where they do arise inaccuracies are likely to be, to some extent, self-cancelling.

Where the requesting entity is a Web cache, it is expected that a smaller set of page components will be requested, the majority of objects being satisfied from the cache, and the possibility of multiple concurrent requests for identical objects being filtered out by the caching operation. The reference trees constructed will be sparse, and massively interleaved, but are of less significance than those in respect of studies based upon browsers — the focus of interest is likely to be on cache performance.

Any future study of cache performance using `Nprobe` (it would, for instance, be informative to position monitors both up and down stream of caches) will add impetus towards the extraction of data pertaining to object *freshness* and *lifetime*, and caching directives, from HTTP header fields. An analytic methodology to associate and compare such traces remains to be developed.

7.4.8 Timing Data

The transaction data recorded by Nprobe includes the timing of significant events (e.g. start and end of requests, responses and objects, link arrivals). TCP data includes significant connection timings (e.g. open, close, SYN, FIN and packet arrivals). All major components of page downloads can therefore be analysed correctly in the time domain.

The timings provided by Nprobe are attached to events *after any packet delivery reordering necessitated by loss* in order to reflect, as accurately as possible, when content would have been delivered to the application. This mechanism can account only for losses and delayed delivery where the monitor is aware of retransmission (i.e. where loss has occurred *upstream* of the monitor). Where traces are known to have been collected immediately adjacent to a client this may be adequate, but where there is the possibility that significant down-stream loss may have occurred, connections must be filtered through the activity model to attach the *effective* application delivery time to each packet and associated events.

7.5 Integration with Name Service Requests

Domain Name Service (DNS) requests made prior to connection opening have been shown by Habib [Habib00] to contribute to download latency. When an Nprobe monitor is positioned so as to observe DNS requests from the client they are incorporated into the page-download reconstruction.

Where the construction of canonical URLs demands a name binding between a dotted-decimal IP address in a requested URL, and the requester's HTTP Host header field is missing, the binding is supplied from a cache maintained by the analysis process. The cache is populated from three sources:

- Bindings contributed where the Host field is present
- DNS requests observed by the monitor
- A persistent cache maintained by all analysis processes

Bindings are *not* obtained by correlating server addresses and Host fields as they would be incorrect in the case of requests made to caches.

Persistent caches are maintained on both a global basis, and specific to individual traces (as name bindings may change over time, and between traces). Where a mapping cannot be obtained from the trace-specific cache, it is located, if possible, from the global cache. The name binding module provided as part of the analysis tool kit provides a stand-alone method for extracting the server addresses from traces and building caches by issuing the appropriate DNS requests.

7.6 Visualisation

The Web activity visualisation tool graphically reproduces the relationships between objects and connections as represented by the reference tree. Relationships in time between components are also illustrated. The alternative *detail* and *time* modes allow for inspection of detail, or scaled relationships in time, and the selectable secondary pane contents provide detailed inspection of the underlying trace data. A draggable cursor accurately indicates time intervals, even in the non-linearly–scaled detail mode, and hence supports evaluation of time based relationships.

The tool presents the structure and context of page downloads in readily comprehensible form, and aids the identification of relationships between transactions, connections, and between the two. It is particularly valuable in the development of analysis of page downloads, and in recognising both typical, and dysfunctional, patterns of behaviour.

7.7 Web Traffic Characterisation

Because `Nprobe` is unique in collecting a range of transaction data from the HTTP header content of the observed traffic, the potential exists for characterisation based upon data not previously available, or available only in limited, or partial form, from server logs, content, or using active techniques. Such characterisations could include, for instance, the proportions of requests eliciting particular server responses, conditional requests, characterisation of object lifetimes, and so on; the possible range is wide.

The ability, also unique, to accurately recreate page structures also makes possible more accurate characterisations of metrics such as the number of component objects, overall data transfer sizes, or the proportions of different component types. There remains a further, and most significant, area of characterisation which has hitherto been impossible — that of whole page download times; without the facility to accurately associate all components of a page, no measure of overall time has been possible. The matter of page download times, and the impact of individual connection delays, is discussed more fully in Chapter 8.

7.8 Summary

Commonly available passive monitoring tools, because normally limiting data collection to TCP/IP headers, restrict the study of Web downloads to that of single connection activity. Inference, based upon host addresses and patterns of activity over multiple connections, may suggest the grouping of individual objects into pages, but inferential methods are likely to be inaccurate because of factors such as concurrent downloads, frames, redirection and multiply-hosted pages.

It is suggested in this chapter that Web page downloads must be examined as a whole if the contribution of the various components of the download *system* and their interactions are to be identified. A full understanding can be achieved only by investigating the full set of page objects, the connections used to download them, and activity at all of the protocol levels involved. In Chapter 8 it will be seen, for instance, that the contribution of individual object delays to whole page download times can only be assessed in the context of the whole download set.

The protocol-spanning data collected by `Nprobe`, and its level of detail, allow page downloads to be accurately reconstructed during post-collection analysis, and hence examined as a whole. This chapter has introduced the technique used, and has shown how integration of the available data makes explicit the relationships between system components, and detail accessible at both coarse and fine granularities.

The ability to accurately reconstruct whole page downloads will present new opportunities to present Web traffic characterisations based upon this unit. The explanation of the analysis and reconstruction techniques that have been developed show that the comprehension and correct interpretation of the complex and diverse data are, once again, assisted and made feasible by the tools provided in the post-analysis toolkit.

Chapter 8

Page Download Times and Delay

No one who has used a browser to access pages from the World Wide Web has escaped the experience of over-long download times. While times in the order of seconds are acceptable, those exceeding even a few tens of seconds become increasingly annoying.

Identification of the various elements contributing to the download time of Web objects has been the subject of much research. It is, however, the download time of a set of objects comprising an entire *page* which is of critical importance to the user — particularly in the presence of delay leading to subjectively long waits. In this chapter the contribution of delays in downloading individual objects is related to the effect on the download time of whole pages, and techniques are introduced for assessing both the degree and the distribution of delay. The potentially disastrous effects of packet loss early in the lifetime of the TCP connections used is considered, and is assessed in a case study of downloads from a popular site. The effect of such *early* loss is examined in the context of a trace-driven simulation of the same set of pages downloaded using exclusively persistent connections.

8.1 Factors Contributing to Overall Download Times

Overall page download times are determined by a number of factors:

The number and size of the constituent objects: How many objects must be downloaded, how many are cached by the browser and how many may be satisfied by conditional requests

The composition of the page: Is delay introduced by redirection, and can sub sets of objects only be requested after the receipt of subsidiary container documents (e.g. frames)

Server latency (i.e. the period between receipt of the complete request and the start of response transmission)

Browser latency (i.e. the period between the browser receiving a segment of the response containing an in-line link to a subsidiary object and the transmission of a request for that object)

TCP connection latency (i.e. the time taken to establish a TCP connection)

Network RTTs

Available bandwidth

Packet loss: What proportion of packets are lost, when in the connection's lifetime, and the TCP implementations' recovery strategy

The browser's use of TCP connections: Are persistent connections used, and if so are requests pipelined, how many concurrently open connections are maintained, and does the browser open and close connections in a timely manner

While it is axiomatic that packet loss causes delay, disproportionate or avoidably high contributions by any of these factors may also be considered delays. Whereas some factors (e.g. the number of constituent objects or the use of persistent connections) have a direct effect on page download time, others' immediate effect is on the download time of individual objects, and only indirectly influences the whole page.

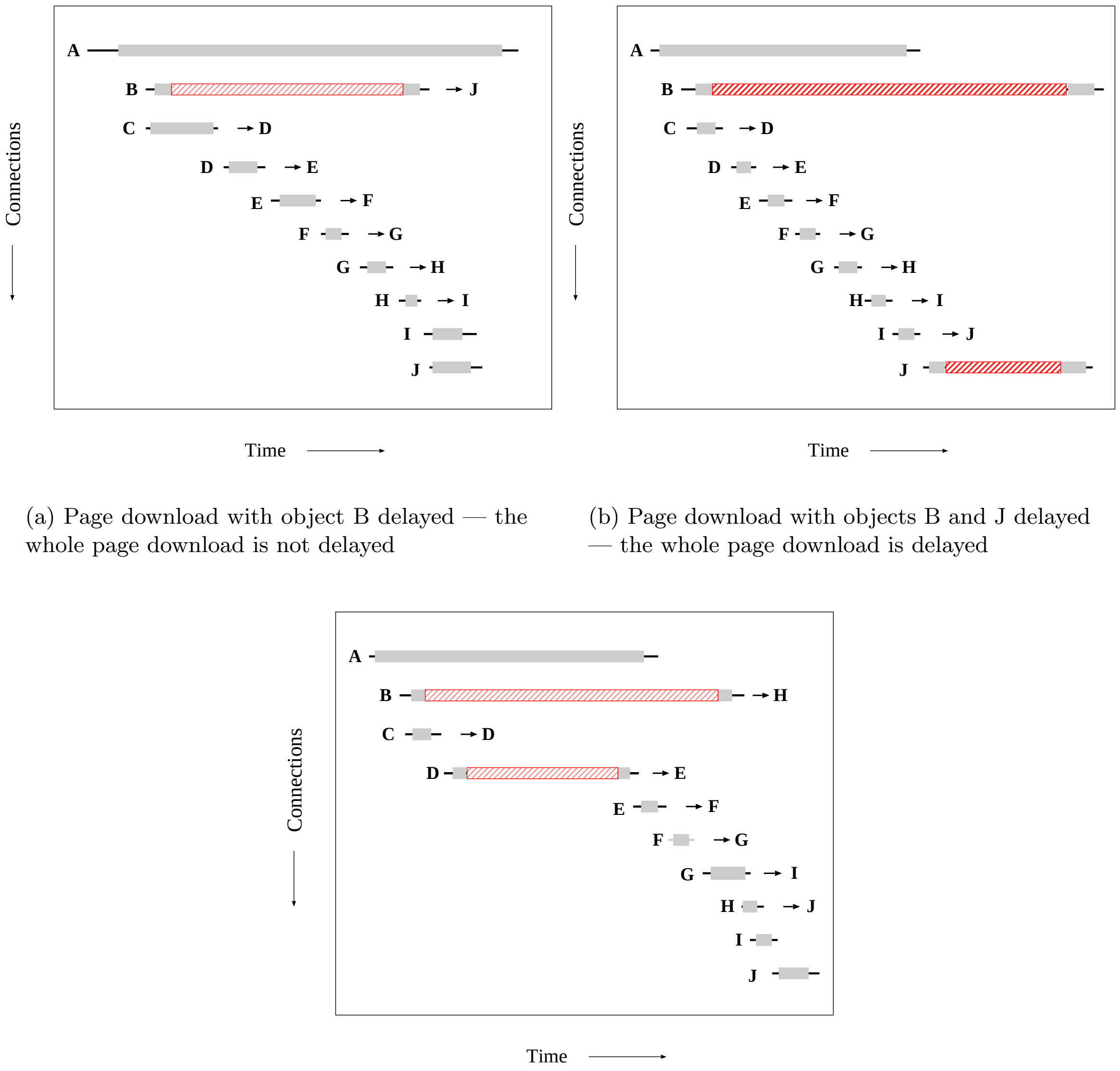
8.2 The Contribution of Object Delay to Whole Page Download Times

Because browsers typically use parallel TCP connections to download the set of objects, and because they may not use these connections in a timely manner, overall page download times are not simply the sum of the individual object download times, and delays at the page scale are similarly not the sum of delays suffered by individual objects. To fully analyse the time components of page downloads it is therefore necessary to consider the full set of constituent object deliveries, the connections used, and their interrelationships over the total download period. The download of a Web *page* must be distinguished from that of its component *objects*.

8.2.1 Differentiating Single Object and Page Delays

The point is illustrated by Figure 8.1 on the next page, which shows three simple cases of page downloads and the effects that delayed objects might have on overall times. In Sub-figure (a) Object B is delayed, but with no effect on overall page download time. Objects D – J are delayed as only a single connection is available, but not by the magnitude of the Object B delay; this will be noticeable in a browser which renders objects as they are received.

In Sub-figure 8.1(b) Object B is delayed beyond the download time of the container document, and hence adds to the overall page download time. Objects C – I are delayed as in Sub-figure 8.1(a). Object J is also delayed, but adds nothing to the delay in overall time already contributed by Object B. Although the overall page download time has been extended, it is only the rendering of two objects which is significantly delayed.



(a) Page download with object B delayed — the whole page download is not delayed

(b) Page download with objects B and J delayed — the whole page download is delayed

(c) Page download with objects B and D delayed — the whole page download is delayed

Note: Each single horizontal line represents the period of a TCP connection from the client's SYN, and the superimposed boxes the period between HTTP request and the last data packet of the response. In each figure Object A is an HTML document and Objects B – J might be small in-line image objects. The x-axis represents elapsed time, and the y-axis the order in which connections are opened and the objects requested. Typical browser behaviour is represented in which the root document is downloaded on one connection, and a maximum of two concurrently open connections is maintained for the download of subsidiary objects. The arrowed letter following each connection line indicates the connection which follows its closure.

Figure 8.1: **The contribution of single object delays to overall page download time when using non-persistent connections**

Sub-figure 8.1(c) also shows a download in which two objects are delayed. In this case the downloads of six of the remaining objects are also significantly delayed resulting in late receipt of eight of the nine images contained in the page.

It will be appreciated that the typical Web page will probably contain many more objects than in the simple examples shown, and that, while individual object delays of the general pattern shown in Sub-figures 8.1(a) and 8.1(b) may serve only to introduce minor delays in the presentation of a whole page, there is also the possibility that delays occurring in patterns similar to that shown in Sub-figure 8.1(c) may result in very a significant cumulative degradation in performance.

8.2.2 Assessing the Degree of Delay

Whole page delay may be defined as the difference between the time when delivery of the last object of a page completes and the corresponding time had there been no delays in the delivery of individual objects. Calculation of this delay therefore depends upon establishing the notional download time without delay.

In order to calculate the duration of the delay-free page download three steps are required:

Establishment of an accurate model: A model of the set of TCP connections and HTTP transactions involved is derived using the reconstruction techniques described in Section 7.3.

Calculation of object PDTs in the absence of delay: The delay-free PDT for each individual object is calculated using the accurate connection simulations described in Section 5.6 on page 133. Because the technique draws upon fine-grained detail of TCP, application, and network-level activity provided by the activity model, downloads can be simulated in the total absence of loss, or as a set of what if scenarios (e.g. with only a certain category of packet loss[1], with a differing probability of loss, with modified browser/server latencies, or if persistent connections or pipelining were used).

Reconstruction of the page download based upon the modified constituent download times: The original download will be traversed by a *critical path* through its constituent concurrent connections and transactions. Reconstruction of the download may make the original critical path obsolete, but it is not necessary to use network analysis techniques to identify or calculate the duration of either the original, or the new, path — both are inherent in the reconstruction of the download.

Even with the relatively rich set of data provided by `Nprobe` traces it is not entirely simple to derive a model of an equivalent, non-delayed, set of downloads for a page. It can be difficult to ascertain the target number of concurrently open TCP connections: browsers are often inconsistent — even within a single page, the point of connection closure recognised by browsers may also vary (the completion of the full TCP 4-way close, the transmission of the

[1] In some cases where timings are to be calculated with the removal of an easily identified and quantified category of loss (e.g. `SYN` loss) it is possible to do so without traversing a simulation.

browser's FIN packet, the receipt of the server's FIN packet on a non-persistent connection, etc.), the opening of new connections may be delayed by the browser, and account must be taken of the delay between causative and consequent events as seen by the probe.

A frequency analysis of the number of connections currently open, as each fresh connection opens, is calculated on the basis of the various possible criteria which a browser may use. This gives an indication of the criterion used by the browser and its concurrency target.

The whole page download is reconstructed by taking the set of connections used, discarding any which did not establish a full connection or succeed in obtaining a server response, and adjusting the PDTs of the remainder using the desired scenario. The modified open and 'close' times can then be calculated for each successive connection on the basis of the timings of the preceding connections, and the browser's concurrency criterion and target. It is assumed that any inconsistencies in the browser's observed pattern of connection concurrency would also apply to the recalculated set of download connections[2], and in calculating when each connection would open, the number of currently open connections at the point of opening are used in order to maintain any such inconsistencies. It is also assumed that any delays in the server remain constant despite changes in the pattern of requests over time, and similarly that any browser-introduced delays remain constant. Because the relationship between the links contained in the root document and object downloads is known, it can be ensured that modified connection timings do not cause an object to be requested before the browser would have seen the corresponding link.

Chapter 6 describes the techniques used to estimate server and client delays together with the pRTTs between probe/host/probe which establish the time lag between causative and consequent events, but for the purposes of this calculation such techniques are not considered necessary if it is assumed that client/server delays and network transit times remain unchanged (and unless these are modified as part of a what if scenario). These assumptions are considered reasonable, as the new model of the set of downloads without delays does not in general produce major changes to either patterns of network or server activity. Any variations which break these assumptions are also likely to be at least two orders of magnitude smaller than the phenomena of interest.

8.2.3 The Distribution of Object Delay within a Page Download

From the subjective perspective of the user it is not just the overall page download time which is important, but also the distribution of any object delays within the download period. The delays shown in Figure 8.1(c) would probably be perceived as more annoying than those shown in Figure 8.1(b), although both pages may be completed in the same times. It is assumed that, in the general case, in-line objects are fetched in the order that the browser's HTML parser encounters the relevant links, and that this order reflects the significance and rendering order of the objects.

In the current analysis the distribution of individual object delays is characterised using a simple metric — a *cumulative object delay* (*cod*) for a page of N objects calculated as follows:

[2] There appears to be no correlation between unsuccessful or delayed connections and such inconsistencies.

$$cod = \left(\sum_{n=1}^{n=N} (D_n - U_n) \right) \times \frac{1}{N}$$

where:

N is the number of objects in the page,
D_n is the delivery completion time of object n
and
U_n is the notional delivery completion time of object n in the absence of delay

As an illustration of the effect of object delays and distribution on the *cod*, Table 8.1 summarises the downloads shown in Figure 8.1, giving the *cod* for each case, assuming the container document downloads in 100 time units and that each image object would download in 10 time units if not delayed. It is stressed that the *cod* represents a measure of the distribution of delay; while it is intuitive that delay early in the download of a page is subjectively less acceptable than delay affecting only the later components, assessment of user dissatisfaction is not within this field of study. This metric, however, together with the accurate calculation of overall download time and delay, would provide a constructive basis for any such investigation.

Table 8.1: **Summary of delays and cumulative object delays for the page downloads illustrated in Figure 8.1.**

Fig.	Individual object delays				Cumulative delay	Page Download Time		*cod*
	Object	Delay	Object	Delay		Delayed	Undelayed	
(a)	B	50	-	-	100	100	100	10
(b)	B	130	J	90	310	180	100	31
(c)	B	130	D	60	670	150	100	67

Note: Although the total individual object delays, and the overall page download time, are higher in (b) than in (c), the distribution of object delays results in a higher *cod* for (c).

8.3 The Effect of Early Packet Loss on Page Download Time

In the initial stages of a TCP connection neither client nor server has seen enough packets to establish a usable round trip time estimation. In the case of packet loss, retransmission will therefore take place only after a default timeout period (typically in the order of 3 seconds, increasing exponentially for each repeat). Packet losses during this period are henceforth referred to as *early* packet loss. Such delays in individual connections have been noted by the WAWM Project [Barford99a].

This context gives rise to a serious implication for the use of many short-lived TCP connections delivering single objects. While long delays may be introduced by early packet loss on any connection, the page downloads using non-persistent connections are particularly vulnerable — most or all activity taking place in conditions of potential early packet loss. From here onwards in this chapter 'delay' will refer to delay arising as a result of early packet loss unless otherwise stated.

Whereas the delay contribution to page download times due to connection setup latency, or to packet loss on an established connection, are likely to comprise a small number of RTTs — in the order of some tens or hundreds of milliseconds — those due to early packet loss contribute delays in the order of seconds, and which, when occurring in patterns similar to that illustrated in Figure 8.1(c) may cumulatively reach the order of tens or even hundreds of seconds. It is also inherent in this stage of a connection's lifetime that fast-retransmit mechanisms will not be operative. It is worth noting that in the context of many short-lived connections, default retransmission values based upon shared routing metrics are also unlikely to be available to individual connections.

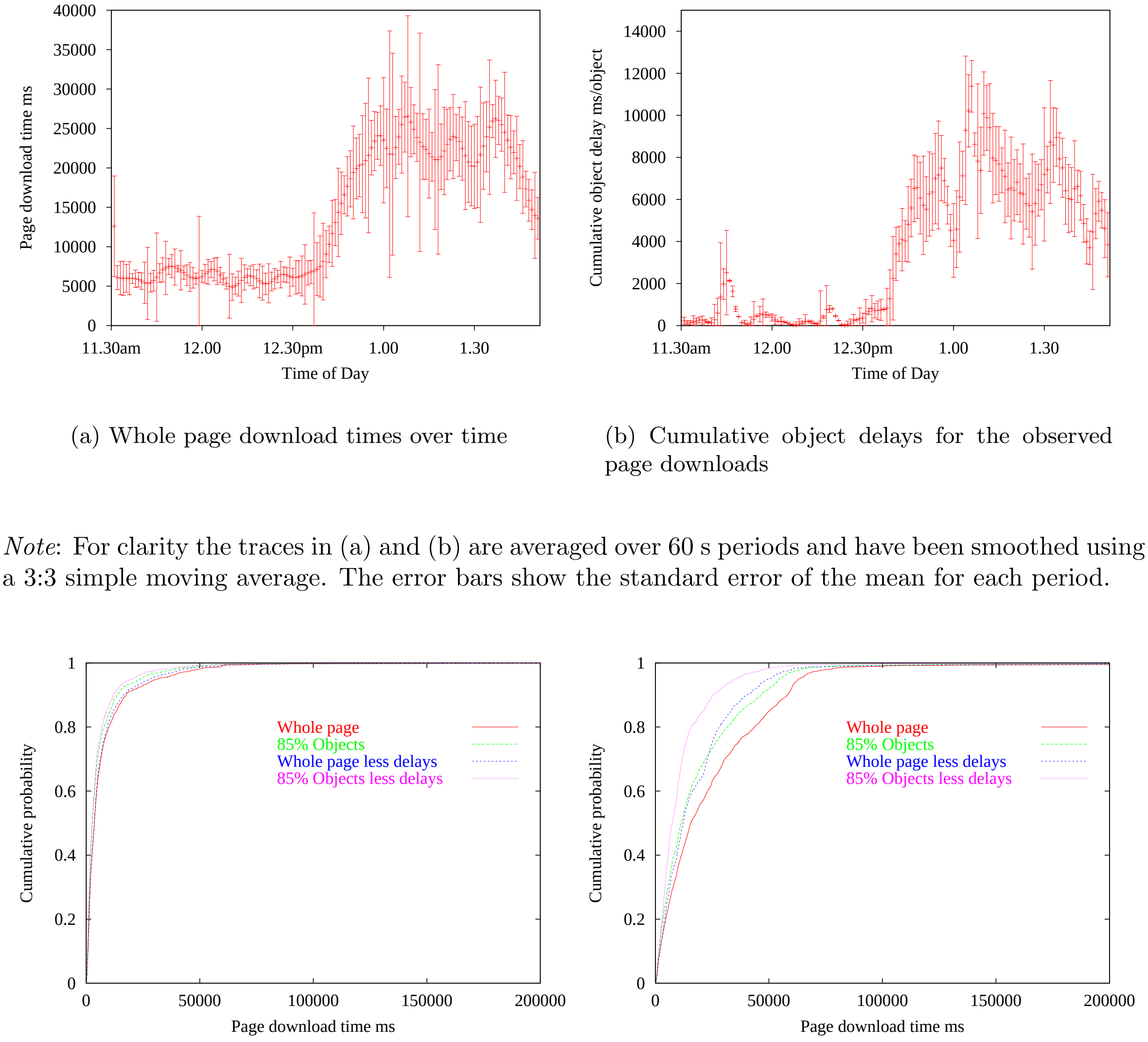
On an individual connection early packet losses will manifest themselves as:

- Loss of client's `SYN` packets(s) causing one or more `SYN` retransmissions.
- Loss of server's `SYN-ACK` causing one or more `SYN` retransmissions.
- Loss of client's request causing one or more retransmissions.
- Loss of server's `ACK` to the request causing one or more retransmissions.
- Loss of server's response.

Such losses may occur on both persistent and non-persistent connections, but in the persistent case losses of requests/responses after the first will normally cause retransmits based upon established RTT values or fast-retransmit mechanisms. The case where a client's first request is lost can be distinguished from that where the server merely exhibits a long delay before responding by the receipt of an `ACK` for the segment carrying the request.

8.4 Delay in Downloading from a Site with Massive Early Packet Loss

Users of a popular British news Web site frequently experience long and frustrating delays in downloading pages. Traffic between this site and the UCCS network was monitored for a period of 24 hours to obtain the trace first introduced in Section 6.4. Analysis of the trace revealed that downloads from the site suffered a high incidence of exactly the delays due to early packet loss discussed in Section 8.3, and that the delivery of many pages was thereby considerably delayed.



(a) Whole page download times over time

(b) Cumulative object delays for the observed page downloads

Note: For clarity the traces in (a) and (b) are averaged over 60 s periods and have been smoothed using a 3:3 simple moving average. The error bars show the standard error of the mean for each period.

(c) CDF of page download times: 11.30am – 12.40pm. Times for the entire page delivery and 85% of its content are shown, both for the observed downloads, and as calculated for the same downloads with delays due to *early* loss removed.

(d) CDF of page download times: 12.40pm – 1.50pm. Times for the entire page delivery and 85% of its content are shown, both for the observed downloads, and as calculated for the same downloads with delays due to *early* loss removed.

Figure 8.2: **News server: whole page download times.**

This section concentrates upon an analysis of the trace for the period between approximately 11.30am and 1.50pm, which is of particular interest as it spans the beginning of the lunch hour, when the server load may be expected to increase as people visit the site during their break. The trace and analysis results are summarised in Table 8.4 on page 191.

Figure 8.2 summarises the results of the trace analysis. In Sub-figure (a) a dramatic rise in page download times can clearly be seen between approximately 12.30pm and 1.00pm as load increases. At the higher page download times the error bars show a corresponding increase in the standard error: the difference in download times between delayed and non-delayed pages becomes more marked due to the magnitude of the delays. Sub-figure (b) shows the *cods* for the page downloads, and demonstrates a corresponding increase in magnitude.

The download times for the observed pages, but with the contribution of early loss removed, were calculated as described in Section 8.2.2. The CDFs of page download times for the first and second periods of the trace are shown in Sub-figures (c) and (d); comparison of the two again clearly show the increase in download times during the lunch break. Times for download of 85% of page content, and the calculated loss-free equivalents are also shown.

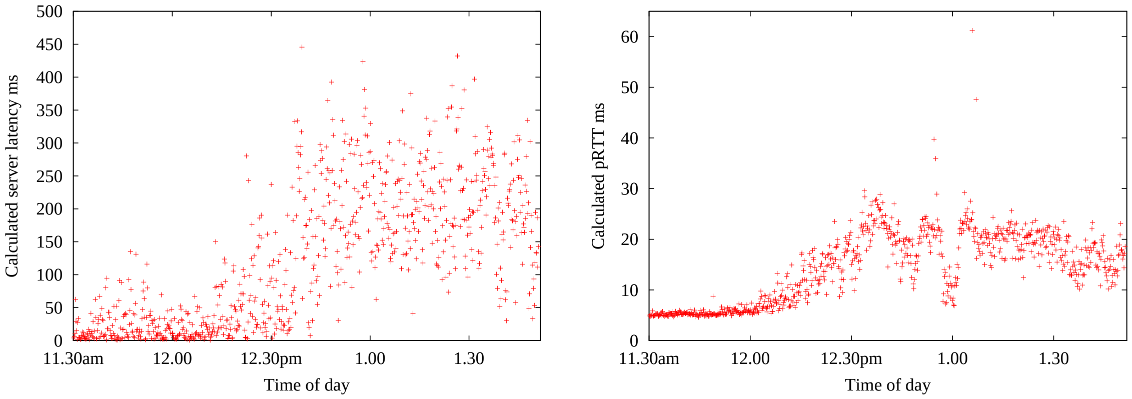
Table 8.2 summarises page download times for the 75th and 90th percentiles of complete and 85% downloads, showing for comparison the results calculated with delay removed. It can be seen that, for instance, early-loss delays contribute only approximately 1 second to 90% of downloads during the early period of the trace, but that the corresponding contribution during the second period is approximately 20 seconds (i.e. an increase of approximately 50% in download time).

Table 8.2: **75th and 90th percentiles of news site page download times in seconds for whole pages and 85% of content**

Period	**75th percentile**		**90th percentile**	
	Page	**85%**	**Page**	**85%**
11.30 – 12.40	8.2	6.3	18.1	14.2
Without delays	7.6	5.5	16.9	12.2
12.40 – 1.50	35.6	26.4	58.0	46.6
Without delays	25.0	12.6	37.9	25.0

In order to compare the effects of early loss on the observed page download times with other contributory factors as load increases, Figure 8.3(a) and (b) reproduce Figure 6.7, and show how server latency and pRTT vary over the period of the trace. The increase in latency is an order of magnitude larger than that of pRTTs and, in the case of non-persistent connections, its contribution to increasing download times is secondary only to that of early delays.

Sub-figure 8.4(a) presents the probability of either SYN or data packet retransmission on an individual TCP connection. The probability that data packets will be retransmitted due to network loss rises slightly from approximately 12.00pm onwards as (by inference) traffic levels increase. It is suggested that the contrasting very sharp rise in the probability of SYN retransmission at approximately 12.40pm is due to connection refusal by the server as load increases. Figure 8.3(a) shows that from 12.40pm onwards server latency remains approximately constant, although higher and more dispersed than during the earlier period of lower demand, and that this time therefore represents the point at which the server becomes saturated and is, in effect, exercising admission control through connection limiting. It is the sharp rise in 'lost' SYNs that is the principal cause of the corresponding jump in page download times.

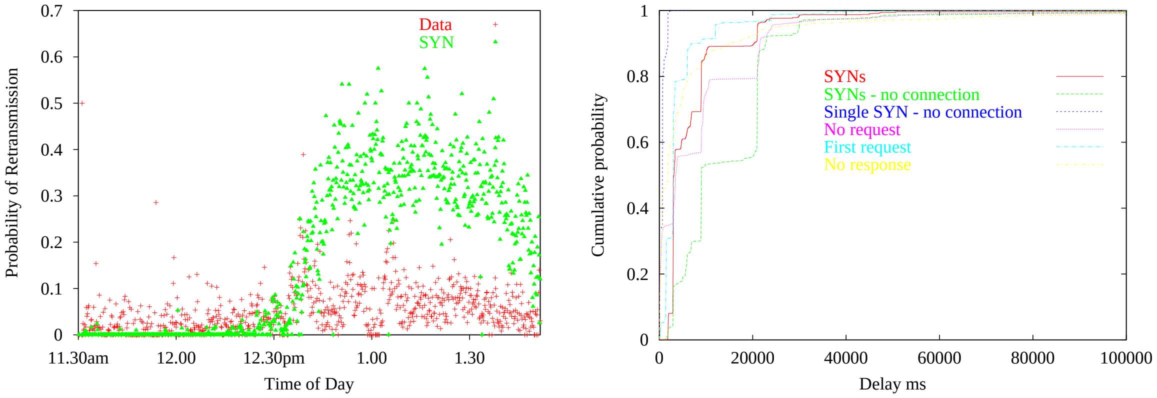


(a) Server response latency

(b) pRTTs between monitor and server

Note: For clarity the values shown are averaged over 10 second intervals.

Figure 8.3: **News server: server latency and pRTTs over time**



(a) Averaged probability of SYN and data packet retransmission on connections to the news server, averaged over 10 second intervals

(b) The factors contributing to delay: CDF of delays contributed by retransmissions of SYNs and first requests, no request on connection, or no response from connected server

Figure 8.4: **News server: components of early-loss delay.**

The contribution made to individual object download times by early loss in each category, when it occurs, is summarised by the CDFs shown in Figure 8.4(b). Note that, with the exception of delays caused by single SYNs not receiving a response, or connections upon which the client issued no request — in neither case is packet retransmission involved — the reliance of retransmission on default values is very clearly seen from the distinct steps at 3, 6, 9... seconds. It is surmised that many of the large delays introduced by connections on which SYNs were retransmitted, and which did not result in a connection (greater than 21 seconds in approximately 45% of cases), and connections upon which no request was made (greater than 21 seconds in approximately 20% of cases), represent the situation of the user cancelling, or recommencing, an apparently stalled download.

8.5 Comparison with a General Traffic Sample

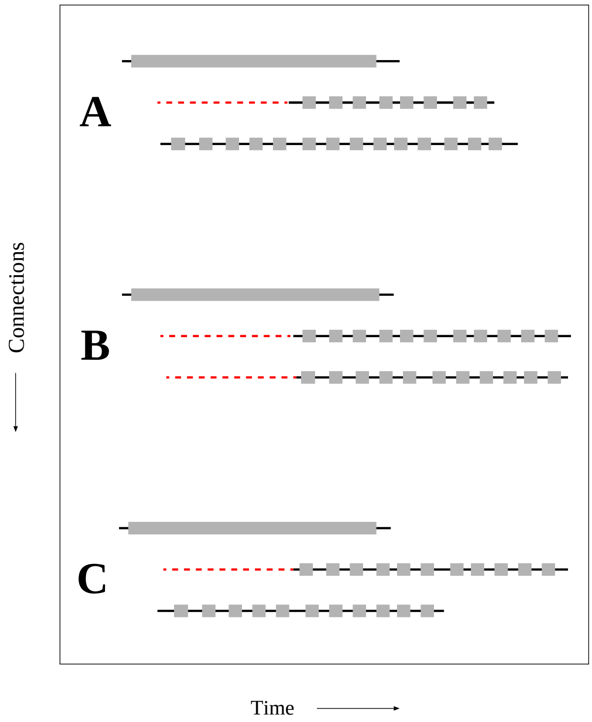
The high rate of SYN loss observed in the traces of traffic to the news site is fortunately not typical of the majority of page downloads. Table 8.5 on page 192 present summaries of three traces (Traces 2 – 4), each of approximately two hours duration, collected at the same monitoring point and at the same time of day. Traffic to the news site has been excluded from the analysis upon which these tables are based.

Comparison with Table 8.4 on page 191 shows that approximately 7.4% of connections in the general samples suffer from early loss (as opposed to approximately 14.4% in the case of the news server); similar proportions for the number of pages visited are 2.7% and 18.82%. Although the incidence of early delay is markedly less in the general sample, the potential magnitude of the delay which can be caused in page-download time may be subjectively annoying to the user in the instances where it occurs. In view of the high incidence of long delay enshrined in 'Web lore' it may be surmised that page requests from the University site contains a higher ratio of visits to well-provisioned servers than that of the general population.

8.6 Implications of Early Packet Loss for Persistent Connections

When non-persistent connections are used to download pages, early loss on one of the concurrent connections used to fetch components does not necessarily lead to serious delay — as shown in Figures 8.1(a) and (b), progress can continue using other connections. The download only becomes completely stalled when the browser's entire 'allowance' of concurrent connections are delayed, as illustrated in Figure 8.1(c). When *persistent* connections are employed, the effects of early loss can cause a different pattern of delay. If a connection is stalled through early loss, *all* requests using that connection will be delayed, but once a connection has been established no further such delays will occur.

Figure 8.5 on the next page shows a typical pattern of page download activity using persistent connections: the container document is requested on an initial connection, and component objects are downloaded on concurrent persistent connections. In the download shown at **A**,



Note: The dotted lines indicate an initial delay on the connection. In the case of page **A** one connection suffers delay while object downloads proceed on the other. All progress is initially stalled in the case of page **B**. Naïve behaviour is demonstrated by the browser downloading page **C**.

Figure 8.5: **The contribution of early delay to page-downloads using persistent connections**

one connection is subject to delay, but activity can continue on the other; objects downloaded on the first connection, once established, are all subject to the initial delay. In the case of page download **B**, both connections are initially stalled, and no progress can be made. In either case, object downloads are not postponed for longer than would have been the case if one, or both, of the initial pair of non-persistent connections of a similar download had been delayed. However, once the persistent connections have been established there is no opportunity for further delay to be introduced by subsequent early loss (assuming that the connections do not remain unused for any period sufficiently long to cause a reversion to slow-start mode).

It is interesting to know how the set of page downloads represented by the news server trace would have performed if persistent connections had been used, and how the high rate of `SYN` loss would have affected them. The downloads were therefore simulated using this scenario, both with early loss, and in its absence. The observed server latencies, network transit times, probability of loss (both early and later) and browser sinking capacity prevalent at the time of each download were used in the simulation.

A set of key assumptions must underlie such simulation:

- That the different pattern of data transfer would not significantly alter network characteristics (i.e. transit times and loss rates)

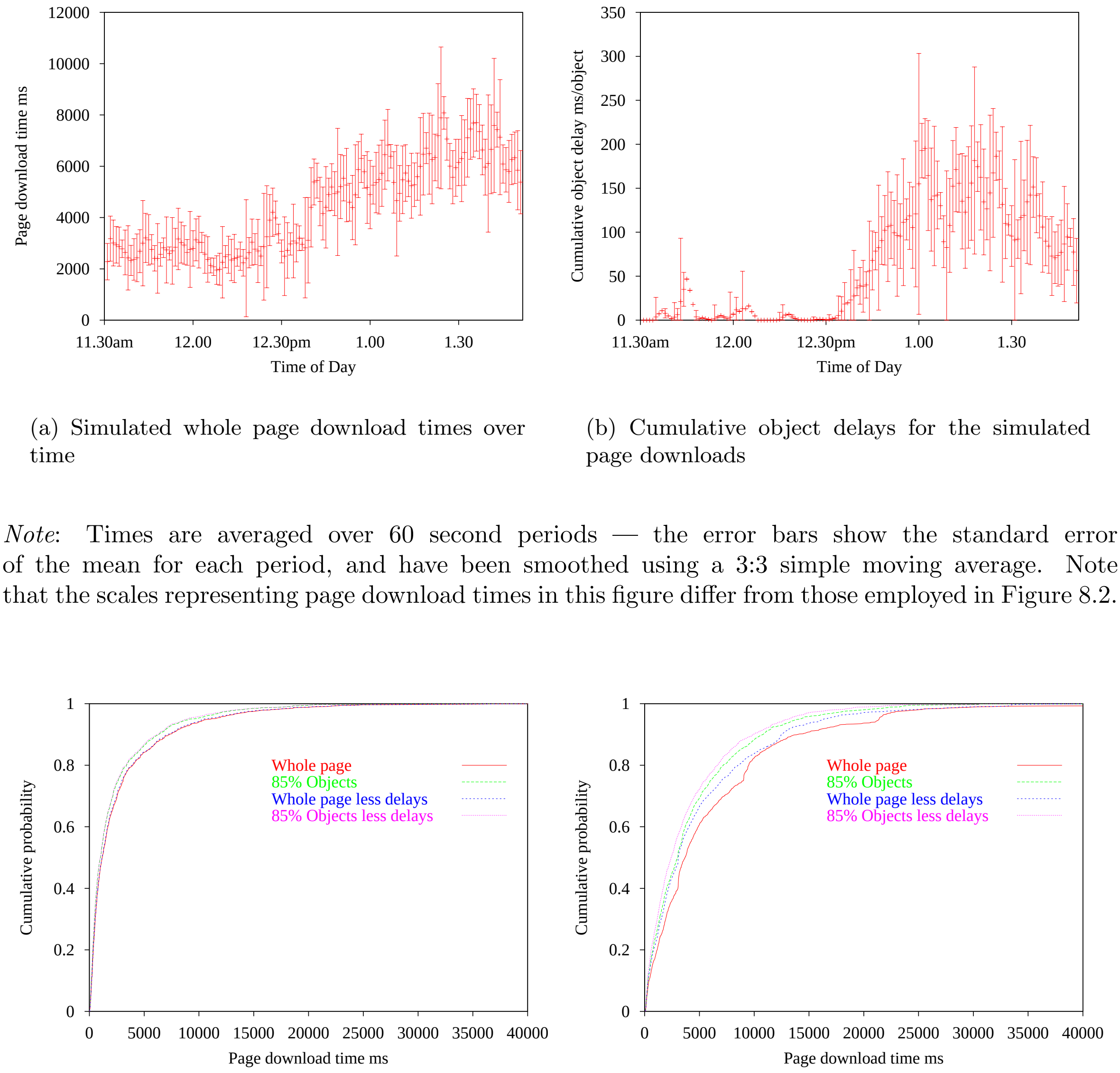
- That the more bursty requests would not appreciably raise server latency (or alternatively that the decreased number of connections to be serviced would not increase the server's work rate)
- That the browser would keep pace with higher data arrival rates
- That the service latency for subsequent requests remains that of the initial request on each connection

The simulation of each page download follows the typical pattern of one connection used to request the container document, and two concurrent persistent connections upon which subsidiary components are requested, shown in Figure 8.5. When one of the two secondary connections are subject to initial delay, requests are channelled to the active connection until a connection is established, and thereafter each request is made on the first connection to become available. The naïve browser behaviour shown at **C** in Figure 8.5, in which requests are equally divided amongst connections, would result in undue delay. Care is taken that requests are not issued before the browser would have seen the corresponding link in the container document. The University site is connected to that of the news server by a well-provisioned network, and the requirement of good connectivity stipulated in [Heidemann97b] would apply to the simulated connections. A conservative assumption of 10 Mbps links is employed in calculating serialization delays in the simulation's operation.

Figure 8.6(a) shows the page download times calculated by the simulation. Comparison with Figure 8.2(a) on page 182 (which shows the actual observed times) shows that the times are considerably less, although they do follow approximately the same trend over the period of the trace, and that the proportionate increase over the lunch period is reduced by a factor of approximately 1.7. It is noticeable that there is a great deal more variation between averaging periods, and that shorter-term trends are much less identifiable; the pattern of activity and delay when using non-persistent connections is smoothed by the constantly shifting juxtaposition of delayed and non-delayed connections during a page download, in the case of persistent connections delay is 'all or nothing' and download times consequently vary to a much greater degree.

The improvement in performance that would have been gained by using persistent connection is underlined by comparing the *cods* shown in Figure 8.6(b) with the observed values of Figure 8.2(b): although the proportionate increase as the server becomes busy is maintained, the averaged values of the *cods* are reduced by two orders of magnitude. It is interesting to note that while the average *cod* for the real traffic is approximately 25% of the average page download time, in the case of the simulated downloads this proportion falls to approximately 2.5%. This difference reflects the concentration of delay at the commencement of the persistent connections, and confirms that download performance when using persistent connections is more robust in the face of early loss.

Figures 8.6(c) and (d) show the CDFs of simulated page downloads corresponding to the observed values shown in Figures 8.2(c) and (d). The reduction in the overall magnitudes of the download times are accompanied by a lesser difference in the distributions for 85% of the



(a) Simulated whole page download times over time

(b) Cumulative object delays for the simulated page downloads

Note: Times are averaged over 60 second periods — the error bars show the standard error of the mean for each period, and have been smoothed using a 3:3 simple moving average. Note that the scales representing page download times in this figure differ from those employed in Figure 8.2.

(c) CDF of page download times: 11.30am – 12.40pm. Times for the entire page delivery and 85% of its content are shown, both for the observed downloads, and as calculated for the same downloads with delays due to *early* loss removed.

(d) CDF of page download times: 12.40pm – 1.50pm. Times for the entire page delivery and 85% of its content are shown, both for the observed downloads, and as calculated for the same downloads with delays due to *early* loss removed.

Figure 8.6: **Page download times for the pages downloaded from the news site using simulated persistent connections**

content and the delay-free download times. The greater robustness of persistent connections in the presence of early loss is demonstrated by the closer *lossy* and *lossless* distributions, and the absence of early loss once connections are established is reflected in the closer *whole page* and *85% of objects* distributions.

Table 8.3: **75th and 90th percentiles of news site page download times in seconds for whole pages and 85% of content, using simulated persistent connections**

Period	75th percentile		90th percentile	
	Page	85%	Page	85%
11.30 – 12.40	2.9	2.6	7.5	6.4
Without delays	2.8	2.5	7.2	6.2
12.40 – 1.50	10.0	5.9	14.6	10.9
Without delays	8.0	5.4	12.6	10.2

In conclusion, Table 8.3 summarises the simulated page download times for the 75th and 90th percentiles of complete and 85% downloads, with and without early loss. Comparison with Table 8.2 on page 183 reinforces the comment already made about the better performance realised by persistent connections, and the very much greater degree of robustness that this mechanism displays in the presence of early loss.

8.7 Summary

This chapter has drawn together the matter of the previous chapters to consider the phenomenon of delay in downloading Web pages. The page download reconstruction techniques introduced in Chapter 7 have been used to identify the sets of object downloads forming the overall download and the relationships between them, and the modelling and simulation techniques described in Chapter 5 used to investigate the same page downloads using the scenario of the exclusive use of persistent TCP/HTTP connections. The simulations encompass the discrimination of application-level latency and network transit times described in Chapter 6; none of these techniques would be feasible without the protocol-spanning data collected by `Nprobe`, and the sophisticated analysis involved has been developed and run using the post-collection analysis toolkit described in Chapter 4.

It has been shown in this chapter that component object delays may contribute to delays in page downloads, but that the overall effect can only be assessed in the context of the whole page, the relationship between objects, and the interaction between components. Such an assessment must rely upon data contained in a range of protocols. Techniques for assessing the degree of delay, based upon a delay-free reconstruction of the page download, and its distribution over the period of the download, based upon simulation and calculation of delay-free component downloads, have been introduced.

The potentially large delays introduced by packet loss before the establishment of TCP's RTT estimate have been considered, and illustrated by the analysis of downloads from a site over a period where the phenomenon was experienced with growing demand upon the server. Finally a simulation of the same page downloads, but using persistent TCP/HTTP connections, investigated the effects of such loss upon downloads using this mechanism. It is demonstrated that the use of persistent connections is not only more robust in the face of early loss, but that the distribution of delay is considerably more favourable. The trace-driven simulations used, and the page download reconstructions based upon them, would, again, not have been possible without the powerful analytic tools provided by the Nprobe monitoring and analysis systems.

Web browsing is probably the most common computer-based activity currently experienced by the non-specialist, and certainly their most common interaction with the Internet. Download delays are a common, and subjectively irritating experience, yet their investigation has been hampered by the restriction of research to the investigation of single-object delays, due to the limitations of the prevalent data collection and analysis technologies. By making the study of whole-page downloads possible, based upon more powerful and comprehensive data collection and analysis techniques, the work described in this chapter has made a new and significant contribution to this important area of research.

Table 8.4: **News site: summary of trace and delays**

	Number of						**% Persistent**
Period	**Clients**	**Servers**	**Conns.**	**Trans.**	**URLs**	**Pages**	**connections**
1130 – 1350	732	29	89195	113901	1570	10232	0.52
1130 – 1240	407	18	43377	55734	835	4908	0.70
1240 – 1350	470	24	45818	58167	1098	5327	0.36

(a) The total numbers of clients, servers, connections, transactions, distinct URLs, and page downloads seen. The final column indicates the proportion of persistent connections upon which multiple requests were made.

	% Delayed			**% Later packet loss**	
Period	**Conns.**	**Pages**	**Servers**	**Client**	**Server**
1130 – 1350	14.39	18.82	34.48	0.12	2.32
1130 – 1240	2.64	5.03	33.33	0.09	2.25
1240 – 1350	25.52	31.31	41.67	0.15	2.38

(b) The proportion of connections, distinct pages, and servers subject to delay through early packet loss. For purposes of comparison the last two columns indicate the proportion of later packets lost from each host.

	% of connections subject to early loss					**% Early**	
	Client		**Other**			**packet loss**	
Period	**SYN**	**Req.**	**No Req..**	**No Rep.**	**No conn.**	**SYN**	**Req.**
1130 – 1350	13.18	0.86	1.39	1.62	1.07	119.42	16.67
1130 – 1240	2.05	0.35	0.26	0.39	0.14	102.50	4.77
1240 – 1350	23.73	1.35	2.46	2.79	1.94	135.22	27.78

(c) The proportion of connections subject to early packet loss, and its category; note that the categories are not mutually exclusive. The last two columns show SYNs and requests retransmitted as a proportion of the number of connections suffering early loss — multiple retransmissions account for percentages in excess of one hundred.

Note: The topmost entry describes the entire trace for the period of interest, the sub-periods 11.30am – 12.40pm and 12.40 –1.50pm are shown below.

Table 8.5: **Summary of trace and delays: Traces 2 – 4 (general Web traffic)**

	Number of						% Persistent
Trace	**Clients**	**Servers**	**Conns.**	**Trans.**	**URLs**	**Pages**	**connections**
2	19077	10820	983921	1608944	157146	368774	14.41
3	18510	13592	1177208	1788477	212412	572355	12.83
4	10804	7877	386891	661562	90432	169697	17.64

(a) The total numbers of clients, servers, connections, transactions, distinct URLs, and page downloads seen. The final column indicates the proportion of persistent connections upon which multiple requests were made.

	% Delayed			% Later packet loss	
Trace	**Conns.**	**Pages**	**Servers**	**Client**	**Server**
2	9.03	3.84	8.48	0.42	21.14
3	5.85	1.48	7.43	0.42	21.25
4	7.38	2.85	7.21	0.63	23.13

(b) The proportion of connections, distinct pages, and servers subject to delay through early packet loss. For purposes of comparison the last two columns indicate the proportion of later packets lost from each host.

	% of connections subject to early loss					% Early	
	Client		**Other**			**packet loss**	
Trace	**SYN**	**Req.**	**No Req..**	**No Rep.**	**No conn.**	**SYN**	**Req.**
2	4.51	0.42	5.29	7.92	4.54	72.36	6.24
3	3.72	0.43	4.59	4.65	3.71	68.40	6.78
4	3.43	0.75	4.77	4.76	3.76	65.64	8.32

(c) The proportion of connections subject to early packet loss, and its category; note that the categories are not mutually exclusive. The last two columns show `SYN`s and requests retransmitted as a proportion of the number of connections suffering early loss — multiple retransmissions account for percentages in excess of one hundred.

Chapter 9

Conclusions and Scope for Future Work

This final chapter of the dissertation summarises the work upon which it is based and assesses the original contribution of the work. The closing section describes continuing development of the `Nprobe` monitor and post-collection analysis, and indicates the scope for future work.

9.1 Summary

As the volume of traffic carried by networks continues to increase, and the bandwidths employed rise, passive monitoring is faced with a dual challenge: to keep pace with the observed traffic, and to store and manage the potentially very large volume of data collected. Although there is a body of research dedicated to monitoring ever-faster network technologies, the common approach to these challenges is to limit capture to TCP/IP headers — hence bounding both computational expense and volume, or to sub-sample. Packet capture continues to rely principally on packet-filter–based mechanisms which may also be used selectively, but which impose a coarse-grained data discard policy.

Such an approach has the great disadvantage that activity at higher levels of the protocol stack cannot be directly observed, and, crucially, that the facility to examine the interaction between higher and lower level protocols is severely limited. As a consequence, research based upon passive monitoring has often been shaped by the limitations of the available tools.

Chapter 1 introduces the concept of a monitor designed to keep pace with higher bandwidths and which captures data simultaneously from the whole of a range of protocols of interest, and discusses the attributes desirable in pursuit of this goal. In particular, it is suggested that the design should minimise data bulk through extraction, abstraction, and storage of only the data of interest — leading in turn to integration of data over disparate protocol data units and the need to maintain state. The design should be scalable: by striping packets across multiple processors, possibly in a cluster of monitoring machines, to accommodate high traffic volume; and through modularity, to allow the addition and tailoring of data collection mechanisms to varying experimental demands. Such a monitor should also be efficient, minimising data copying and control overheads.

A considerable body of research has been founded upon passive network monitoring and Chapter 2 outlines a selection of the most relevant work. It is seen that the two themes — of monitoring higher bandwidths, and of monitoring a wider range of protocols — have not significantly come together in any single project or wide deployment of monitoring effort. The few projects which have extended the range of protocols monitored (e.g. Windmill [Malan98b], IPSE [Internet Security96], BLT [Feldmann00]) have either not been designed to monitor high bandwidths (Windmill, IPSE) or have been designed only to study an integrated but limited range of protocols (BLT). Other studies which integrate data from higher protocol levels have relied upon a combination of TCP/IP-level traces augmented by server instrumentation (Balakrishnan *et al.* [Balakrishnan98]), server logs (Allman [Allman00]), or data gathered using active techniques (WAWM [Barford99a][Barford99b]).

Chapter 3 describes the design and implementation of a unique monitor — `Nprobe` — which constitutes the major single item of work described in this dissertation. The probe infrastructure, common to all protocols monitored, is described, together with the protocol-specific data extraction modules implemented to date.

Traces collected with existing monitoring tools are likely to consist of verbatim copies of whole or partial packets; the required data can be extracted using knowledge of the contained protocols' syntax and semantics — trivially in the case of those protocols (e.g. TCP, IP, RPC, or NFS) where the verbatim copy mirrors defined C language structures. `Nprobe`-collected traces, on the other hand, contain data which is not only already extracted but may be abstracted or coded, and which is variable in nature and format as determined by experimental requirements; a common interface for data retrieval is required. The relatively rich and complex data contained in `Nprobe` traces, moreover, will be collected for the purpose of, and subject to, commensurately more complex and sophisticated post-collection analysis. An early decision was therefore made that the `Nprobe` design would be incomplete without an accompanying post-collection analysis infrastructure.

Chapter 4 describes the post-collection analysis of `Nprobe` traces based upon an analysis toolkit which provides a data-retrieval interface generated automatically from the data structure definitions contained in the `Nprobe` data extraction modules, a library of standard analytical methods for the protocols so far incorporated, and an analysis development environment. Visualisation tools are also provided to present trace data in a summarized and readily comprehensible form, and to assist in identifying and reasoning about the interrelationships between the activities represented by it. An analysis definition and control infrastructure defines the analysis to be carried out and accumulates the data generated, while an analysis summary tool presents the, possibly high, volume of results and an analysis log. The data generated may be examined using the toolkit's own plotting tool, which, together with the summary tool, is integrated with the analysis modules to allow the derivation of any result to be re-run and examined in detail. Analysis code may also be modified and re-run under close scrutiny during the analysis process, hence supporting iterative design. The potentially large volumes of trace data to be analysed dictate that mechanisms should also be provided to allow partitioning of analysis, and that confidence in results should be supported by the facility to follow an audit trail based upon the data's derivation.

The possession of data from multiple protocols allows analysis to examine activity at any protocol level with an accurate knowledge of events at other levels. Chapter 5 presents an activity model of TCP behaviour which differentiates and quantifies the effects of the network, TCP itself, and application-level processes. The detailed information provided by the model may, in turn, be used as the basis for trace-driven simulations which, by varying the known parameters of the observed connections, can be used to investigate *what if* scenarios and, for instance, to assess the exact effects of loss, RTT variation, or changes in server latencies.

Use of the activity model is illustrated in Chapter 6 in a case study of Web server latency. Traffic carrying artificial server loads is observed to assess the accuracy of the modelling technique, and the changing latency of a busy server examined as load increases.

The investigation of Web page downloads based upon passive monitoring has, because of the limited data gathered by existing tools, been largely confined to the study of the download of individual page components. Chapter 7 explains how the comprehensive data collected by `Nprobe` can be used to accurately reconstruct the total activity involved in the download of whole pages, hence allowing the relationships between HTTP transactions and the TCP connections carrying them to be examined in full context, and the download to be analysed as a complete system of activity.

Finally, Chapter 8 draws together the work described in earlier chapters in a case study of delay in Web page downloads. It is demonstrated that whole page delays are not simply the sum of component delays; the technique of page download reconstruction is used to assess the download times of pages observed in traffic to a popular news site, with particular emphasis on major delays caused by packet loss occurring before the establishment of TCP RTTs . The connection modelling and simulation techniques introduced in Chapter 5 are then used to examine the implications of early packet loss on the observed page downloads had persistent HTTP connections been exclusively used.

9.2 Assessment

This section of the dissertation measures the work described in the previous chapters against the thesis and hypothesis stated in Chapter 1, and assesses its original contribution to the field of passive network monitoring.

> “The thesis of this dissertation may be summarised thus: observation of the network and the study of its functioning have relied upon tools which, largely for practical reasons, are of limited capability. Research relying upon these tools may in consequence be restricted in its scope or accuracy, or even determined, by the bounded set of data which they can make available. New tools and techniques are needed which, by providing a richer set of data, will contribute to enhanced understanding of application performance and the system as a whole, its constituent components, and in particular the interaction of the sub-systems represented by the network protocol stack.
>
> The hypothesis follows that such improved tools are feasible, and is tested by

> the design and implementation of a new monitoring architecture — *Nprobe* which is then used in two case studies which would not have been possible without such a tool.”

9.2.1 Conclusion

Chapter 2 draws attention to the paucity of research based upon examination of activity at all levels of the network protocol stack, and shows that when such research has been conducted, it has rarely drawn all of its data from passive monitoring of the network. A small body of research has been based upon data gathered from levels above TCP/IP, but has been based upon monitoring systems designed for a single protocol set, or has not addressed the parallel challenge of keeping pace with contemporary network bandwidths. Current work in monitoring high-speed network technologies has, conversely, limited itself to the traditional collection of a verbatim copy of a limited set of lower-level protocol headers.

It is axiomatic that any research based upon gathered data must be shaped by the scope of that data. All inter-computer communications are based upon complex systems of interrelated and interacting components and protocols, yet current tools fail to exploit the breadth and scope of the data available through passive monitoring, and as a consequence, research is largely limited to investigation of sub-systems of the whole. The limitation is manifest in two ways: at the granularity of a single connection only a subset of the protocols are studied, and at the larger granularities often implicit in application activity, the set of connections used may not be accurately identified and associated with that activity. In both cases the study of application-level activity is inhibited, and the interactions between system components may not be manifest, identifiable, or quantifiable.

A passive network monitor has been designed and implemented which successfully circumvents the limitations of existing tools of the genre. By extracting only the data of interest from passing traffic the bulk to be stored is reduced, and data from the whole range of contributing protocols can be captured. Careful attention to efficiency of operation, and to achieving a data-reduction ratio which balances computational expense against storage volume, enables the design to keep pace with relatively high bandwidths. Extensibility in terms of the protocols studied is ensured by the provision of a common infrastructure and protocol-centric data extraction modules, which also provide the capacity to tailor data collection to specific needs. The extensibility required to keep pace with higher traffic bandwidths is provided by partitioning data processing between multiple processors, possibly located in clusters of monitoring machines.

A more comprehensive set of gathered data suggests the potential for post-collection analysis employing a variety of more sophisticated techniques, particularly as the interplay of activity inherent in examination of a greater range of subsystems is captured. The richer nature of the data, moreover, also suggests that, for any data set, the range of analysis that can be carried out is wider and more varied. There is consequently a danger that the full informational potential of the data gathered will not be realised if analysis tasks are designed in an ad-hoc manner: an environment is called for where analysis tasks can be designed and executed with minimal time expenditure; which supports a common data retrieval interface, reuse of analysis components, and investigative analysis design; and reflects the bulk and complexity of the data. The analysis infrastructure and toolkit accompanying the Nprobe monitor meet this requirement, and represent a foundation upon which the new analysis techniques presented in this dissertation are constructed.

New and powerful analysis techniques — the TCP activity model, Web server latency measurement, Web page download reconstruction and delay assessment, the investigation of early packet loss effects, both as observed and as assessed using accurate trace-driven simulation — demonstrate the greater understanding of application-level behaviour and system component interactions which can be contributed by gathering a more complete set of data from the network, and which would not be possible without it. Some of these analysis techniques are general, others are directed towards specific protocols or tasks, but all can be generalised.

In summary — a new and more powerful passive monitoring design has been implemented and used to gather a considerable amount of data from a range of network protocols. New analysis techniques have been developed which exploit the comprehensive contents of the data and have demonstrated the ability to investigate and understand behaviour at network, transport and application levels of the protocol stack. The utility of the monitor, and of the enhanced analysis of the gathered data have thus been demonstrated.

9.2.2 The Original Contribution of this Dissertation

The proposition that passively monitored data would contribute to more comprehensive research if the data were to be gathered from a wider range of network protocols is hardly new. The requirement for probes to keep pace with increases in network bandwidths is well recognised and such probes are the subject of ongoing development. It is then, perhaps, rather surprising that so few probes have been designed to gather data from protocols beyond TCP/IP[1], and that no probe has yet been developed for use by the network research community which directly addresses both needs.

The Nprobe design, therefore, makes a new and powerful contribution to the field of computer network research based upon passively monitored and gathered data. For the first time the three requirements of multi-protocol data capture, capacity to monitor high bandwidths, and general applicability (i.e. the capacity to extend and tailor data gathering to the requirements of a specific study) have been addressed in a single probe implementation. The probe is therefore not only capable, but highly flexible.

The implications for future research based upon such a tool are considerable: application-level activity can not only be observed directly, but can be related to lower-level activity; events hitherto studied at the granularity of a single connection can be aggregated into the multiples associated with higher-level activity; and the interactions of components at all levels and granularities can be studied. Probe placements are not (as) limited to low-volume (and hence possibly unrepresentative) links, and data reduction allows for longer traces to be gathered

[1] Probes based upon the packet filter and its variants can, of course, do so, simply by capturing a greater packet length, but are largely discounted because of the data copy overheads and the infeasibly high volume of the resulting capture.

for any set traffic volume and mix.

Neither is the association of data collection and analysis into a single system entirely new: Coral Reef [Keys01], `netflow` [Cisco-Netflow], and NIMI [Paxson98][Paxson00], for instance, all provide standard analysis and report mechanisms. These mechanisms are, however, essentially static: set measurements are performed and subject to one or more standard analyses. `Nprobe` breaks new ground in providing an analysis toolkit and environment designed to support not only the execution of post-collection analysis tasks, but their fast design and development; the richness and complexity of the data gathered must be matched by equally sophisticated analysis methods.

The variable and extensible nature of the data collected has required the development of a unique, automatically generated, data retrieval interface which can be used by any analysis task. The principle is extended into an innovative framework of standard analysis control, data collection, and analysis summary tools accompanied by a library of reusable analysis classes. Full advantage is taken of the object-oriented software model to ensure that the infrastructure and analysis classes can be rapidly modified through sub-typing and composed to meet the requirements of specific tasks. Two new visualisation techniques also introduce novel features: a TCP connection visualisation tool, and a Web download visualisation tool, present not only a summary of trace data but also the results of the analysis carried out on it. The relationships within the data are made more easily identifiable, and confidence is promoted by the explicit connection between original and generated data which is displayed. The design and testing of complex analysis would be very much more difficult without such tools.

The provision of a fully integrated and extensible analysis toolkit also enables the incorporation of other novel features: both the analysis summary tool and a dedicated data plotter employ callback mechanisms which allow the derivation of individual or multiple results to be examined in detail and the appropriate visualisations instantiated. Thus development and confidence are both supported.

The TCP activity model represents a new technique for the examination of individual TCP connections and the discrimination of activity determined by the separate components at network, TCP and application-levels. The model is also innovative in its independence of probe position and ability to interpret TCP-level activity without *a priori* knowledge of the participating implementations.

Another new and far reaching technique that has been introduced is that of Web page download reconstruction, enabling downloads to be studied as a whole, and the contribution and interaction of all components assessed. Such a technique is particularly valuable as it represents the ability to accurately investigate communications involving multiple connections, where previously they would have to be studied individually, and their relationships inferred.

The two case studies which have been presented, investigations into Web server latencies and Web page download times, represent original and unique research into Web activity. This area was chosen to demonstrate `Nprobe` capabilities because, although the protocols and principles involved are relatively well understood, it is also a field where the accurate investigation of certain fundamental phenomena — those involved in whole page downloads

— have been beyond reach without the range of data gathered by `Nprobe` and the analysis techniques which depend upon it. The study presented in Chapter 8, in particular, represents unique work in its assessment of individual transactions' contribution to overall page download times, the investigation of early loss, and the accuracy of the simulations used in assessing an alternative download scenario.

Although the case studies are included primarily as examples of the power of the `Nprobe` monitor, and the analysis techniques which it makes possible, they stand as original research in their own right. It is important to note that the underlying analysis makes use of the common analysis infrastructure and TCP analysis classes, which could contribute equally to the investigation of other protocol sets. The elements of analysis specific to HTTP and HTML would contribute equally to wider analysis of these protocols, but, more importantly, establish principles and techniques which can be generalised to the study of further protocols.

The potential of the monitor, and the breadth of new research which it makes feasible, are recognised by the establishment of two new projects which are based upon it. The Computer Laboratory's Gridprobe project will build upon the work described here to continue `Nprobe` development, with the aim of increasing capture rates and extending the range of protocols and tools. The Intel Cambridge Laboratory's Scope project [Hamilton03] will collaboratively pursue the same aims.

9.3 Scope for Future Work

It is convenient to present discussion of the scope for future work under the heads of further investigation into Web traffic and continuing `Nprobe` development.

9.3.1 Further Analysis of Web Activity

Although the exemplary studies presented here have concentrated upon the assessment of delay due to early packet loss, it will be little more than a triviality to extend the work to assess the impact of download delay due to all causes, and the contributions made by both server and browser. In particular, initial investigations indicate that browsers may sometimes behave in a less than optimal manner, and this may prove a fruitful field for further investigation. It is hoped that future probe placements will present the opportunity to observe a more representative sample of traffic than that so far encountered, and that this may be used to establish up to date traffic characterisations, which will be more valuable than those hitherto available because they will be page, rather than object, based.

It is remarked that the Web traffic gathered to date provides almost an embarrassment of information that might be extracted by widening existing analysis methods, but that further examples of possible research include extension of the HTTP data extraction module to gather object lifetime, freshness, and caching data to study cache behaviour and effectiveness. It is also noted, for instance, that a high proportion of `GET` requests are conditional, and that of these a very high proportion receive `not modified` responses; it may be that those responsible are unduly pessimistic about object lifetimes, and that considerable unnecessary traffic is therefore generated. Informal observation suggests that the number of individual pages drawing content from multiple servers appears to be growing, particularly where partial content (e.g. that from *ad-servers* or CDNs) is independent of the main content. It would be interesting to know whether such multiple sourcing has deleterious effects upon performance.

In some cases analysis of the collected data reveals that full understanding of the phenomena seen can only be achieved through further observation, or data gathering by other means. Section 7.4.3, for example, refers to aborts of apparently healthy TCP connections as indicators of aborted page downloads. While this situation can be inferred from currently gathered data, accurate identification of aborted or recommenced downloads, and their correlation with delay, must depend upon the dependable recognition of user behaviour based upon patterns established using mechanisms such as instrumented browsers, or the observation of browsing sessions set up for the purpose.

9.3.2 Nprobe Development

Current work is concentrating on benchmarking `Nprobe` performance — no probe placement has so far provided traffic volumes sufficient to test its capabilities — and increasing potential capture rates. The capabilities of the available NICs are being investigated, together with improvements to their drivers to allow higher degrees of interrupt coalescence. The use of more powerful NICs, such as the DAG cards, may also be investigated. Work is also required to optimise the way in which workload is shared across multiple processors, particularly dual core architectures.

Because `Nprobe` is designed to allow the simple addition of further protocol-based data extraction modules, the scope for further work using it is very wide — the existence and availability of a more powerful tool leads to further research, and ease of analysis development encourages innovative studies. There are currently plans to add a Border Gateway Protocol (BGP) module to investigate routing convergence and stability, and further modules designed to observe streamed media traffic. Future work may include investigations of real and user-perceived Quality of Service, denial-of–service attack detection, traffic engineering issues, and extension into observation of new Grid traffic types.

The use of `Nprobe` is not, of course, limited to the observation of established protocols and application activity: its unique capabilities may make it a valuable tool in the development of new protocols, and of distributed systems.

Appendix A

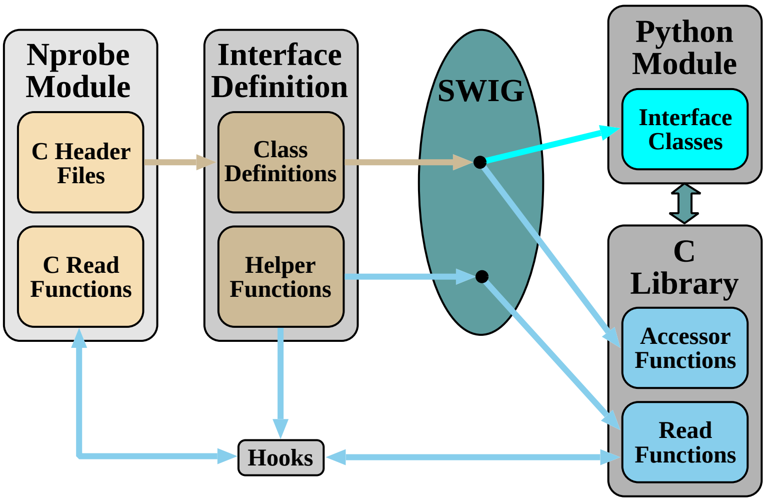
Class Generation with SWIG

Figure A.1 on the following page illustrates the generation of the data retrieval interface by SWIG. Input, in the form of the relevant C header files, is converted into a Python module — the data retrieval interface — defining a series of Python classes, each analogous to one of the C structures in which data is stored and dumped by `Nprobe`, and having *data attributes* corresponding to the *fields* of the C structure. SWIG output consists of the Python module containing the class definitions, a C file containing the class implementations, and an (optional) documentation file. The class definitions include initialization and destructor methods for the class, together with a set of *accessor* methods for the data attributes. The C implementation file is compiled into a library which is imported into the Python interface module.

A.1 Interface Definition

SWIG operation and module generation are specified in an *interface definition* file which lists the header files upon which class generation is to be based, and also those which must be included in the C interface implementation file. Any changes in the header files are incorporated into the interface by regenerating it under the control of the normal `make` dependency hierarchy.

The SWIG interface definition file allows considerable flexibility in the generation of the desired module. Additional C structures may be defined, generating further classes for inclusion in the module, and C function prototypes may be included which will generate *module-level functions* implemented by C code, also included in the interface file, and which is copied verbatim into the C interface implementation file. Such C code may be specified as implementing further methods (*helper functions*) for each of the classes generated. Defining methods for the interface classes in this way can lead to efficiency gains in certain circumstances: automatically generated accessor methods for nested classes (structures) will call an accessor method for each level of nesting whereas a helper function can return the desired value in a single method (function) call, and where manipulation of the underlying C structure is required, this can be implemented directly by helper functions.



Note: The interface definition lists the `Nprobe` module header files from which Python classes are to be generated, and includes verbatim C functions which provide hooks into the modules' data retrieval code, and fast accessor and data manipulation functions. SWIG generates a Python module defining the required interface classes and C source which is compiled into a library implementing them. Hooks may also be provided for other data manipulation functions provided by the `Nprobe` modules.

Figure A.1: **SWIG Trace file interface generation.**

A.2 Tailoring Data Representation in the Interface

SWIG helper functions, providing methods for the generated Python interface classes, have one further, and central, role — their use as *hooks* by which further functions can be called. The `Nprobe` modules must provide not only the definition of data structures, but also the functions which can interpret record formats, and hence read the data from trace files; these functions are made available to the interface through the hooks provided for each class.

A sub-set of the C preprocessor constructs are understood by SWIG which, additionally, can be invoked with a set of defined constants. Class generation can therefore be based upon a sub-set of the definitions contained in C header files by appropriate use of the `#ifdef` and similar directives. The same mechanism can also be used to modify the content of the `Nprobe` module data structures to a more appropriate form in the retrieval interface where appropriate.

Reference to Figures 3.3 and 3.4 on pages 59 and 70 respectively will show, for instance, the way in which data and state may be nested within `Nprobe`, but that only the data is dumped to file, and that nested data is *serialized* as it is dumped — state does not need to be saved, and nested data may or may not be present, hence it would be potentially wasteful of file and disc space to dump nested data structures. Although the components of state relevant to data extraction are not required in the analysis data representation, those locating and associating data (e.g. links to chained or subsidiary SSUs) are; data nesting also associates data, and should be reflected in the analysis representation. Conditional inclusion is therefore used in the relevant structure definitions in order to create appropriately nested classes which include only the state fields required to associate and link SSUs and recreate data nesting. Serialized data structures are retrieved into the original nested form.

Appendix B

An Example of Trace File Data Retrieval

Section 4.2.2 on page 87 explains the role of automatically generated Python retrieval classes and utility module functions, provided by the analysis infrastructure, when reading trace file data. The examples in this Appendix demonstrate the use of the infrastructure during the analysis process.

B.1 A Typical Data-Reading Function

The Code Example in this section shows how a `get_data` function[1] retrieves selected data from an `Nprobe` trace file.

```
#
# Retrieve TCP connection and HTTP transaction data
#    from Nprobe trace files:
#  - argument file_list is list of trace files
#  - returns data as list of connection/transaction list tuples
#

from np_file_util import get_files, EOF
from np_http_util import allocate_http_reusable_objects
from np_http_util import get_http_rec_and_trans
from np_TCPConn import TCPConn
from np_HTTPTrans import HTTPTrans
from nprobe import REC_TCP_HTTP

def get_data(file_list):
```

[1] The example shows a function called by a data analysis *script*, but it could equally well be a *method* of an analysis *object*. Whether to drive analysis through function calls made by a script, or method invocations of an analysis object will depend upon which is the more appropriate for the analysis task in hand.

```
    # check and open trace files, aggregate meta-data
    openfilelist, counters = get_files(file_list)

    #
    # instantiate a reusable TCP connection data retrieval
    # object with list of HTTP transaction retrieval objects
    #
    connrec, tlist = allocate_http_reusable_objects()

    # a list to return the data in
    data = []

    #
    # main loop
    #
    for file in openfilelist:

        while TRUE:

            # position at next TCP/HTTP record
            try:
                file.next_type_rec(REC_TCP_HTTP)
            except EOF:
                break

            # get the data into the retrieval objects
            ntrans = get_http_rec_and_trans(file, connrec, tlist)

            # instantiate higher-level protocol class objects
            conn = TCPConn(connrec)
            translist = []

            for t in tlist[:ntrans]:
                translist.append(HTTPTrans(t))

            # accumulate data for this connection and its
               transactions
            data.append((conn, translist))

    #
    # return the data
    #
    return data
```

Example B.1: **An example of trace-file data retrieval. The function steps through the specified files, selecting from each the records of the desired type. A class utility function — get_http_rec_and_trans — uses the retrieval objects connrec and tlist to read data from the record. The retrieval records are passed as arguments to the instantiation of the higher level class objects of type TCPConn and HTTPTrans. The higher-level classes' constructor functions will use the retrieval objects' accessor functions to select the data values required, and will call its own conversion functions to map data types or reduce relative time**

stamps to a common base.

In Code Example B.1 lines 9 – 11 import the utility functions required by the get_data function, and lines 12 – 13 import the higher-level DAU classes. Note that the retrieval objects returned by the call to the utility function allocate_http_reusable_objects are instantiated only once, and are reused for each record read. The inner loop commencing at line 35 uses the next_type_rec method of the current file (an object of type TraceFile) to position the file at the data part of the next record of the required type (REC_TCP_HTTP); an EOF exception is caught at the end of each file.

The retrieval records are populated with data from the record in line 44 by the utility function get_http_rec_and_trans which invokes their read methods; the number of transactions actually carried by the TCP connection is returned (as the list of transaction data retrieval objects is pre-allocated and is long enough to hold an arbitrary maximum number of objects, the number actually populated with data is required). Lines 47 and 51 instantiate the higher level classes TCPConn and HTTPTrans which will be used in the data analysis itself.

All of the utility functions called are part of the standard analysis infrastructure, as are the SWIG-generated retrieval classes and the higher-level protocol classes. The entire data retrieval process has been implemented in exactly 17 lines of code (excluding comments and import statements).

B.2 Use of Retrieval Interface Classes

Figure 4.2 on page 86 illustrates the use of retrieval interface objects to read data from trace files, and Code Example B.1 in Section B.1 demonstrates their use in a typical trace file reading function. In the function shown reusable retrieval objects of types tcp_conn and http_trans are instantiated by a call to the utility function allocate_http_reusable_objects and populated with data using a call to the function get_http_rec_and_trans — both provided by the utility module np_http_util. Code Example B.2 is an excerpt from that module showing the two functions.

```
from nprobe import tcp_conn, http_trans, MAX_NTRANS

#
# Return a tcp_conn object and maximum list of http_trans
#  objects for repeated use
#

def allocate_http_reusable_objects():

    # instantiate a TCP retrieval class object
    tc = tcp_conn()
    # provide it with a packet header data buffer
    tc.tcp_alloc_hdrbuffs()

    tl = []
```

```
17      # provide a list of HTTP transaction retrieval class objects
18      for i in range(MAX_NTRANS):
19          tr = http_trans()
20          # provide each with a buffer to hold link data
21          tr.http_links_buf_alloc()
22          tl.append(tr)

24      # return the objects
25      return (tc, tl)

27  #
28  # Given an Nprobe rec file lined up at the next TCP/HTTP tconn
        record,
29  # a pre-allocated tcp_conn object and list of http_trans objects,
30  # read the data from file into the objects
31  #

33  def get_http_rec_and_trans(file, connrec, translist):

35      # get tconn record data
36      connrec.read(file)

38      #
39      # build the transaction list
40      #  - first find out how many transactions

42      ntrans = connrec.get_ntrans() # accessor method
43      i = 0
44      while i < ntrans:
45          # get the transaction data for each
46          translist[i].read(file)
47          i += 1

49      return ntrans
```

Example B.2: **Instantiation and reuse of retrieval interface classes. An excerpt from the `np_http_util` utility module showing the functions provided to instantiate the retrieval interface classes which read TCP and HTTP transaction data from trace files, and to populate the class objects with data by invoking their `read` methods.**

Line 2 of Code Example B.2 imports the retrieval classes `tcp_conn` and `http_trans` from the automatically generated retrieval interface module `nprobe.py`. Note the imported *constant* `MAX_NTRANS`[2] — SWIG understands the `#define` C preprocessor construct (in the case of constants so defined) and generates module level 'constant' variables with the corresponding names and values.

[2] Although there is no theoretical limit on the number of transactions that may be carried by a TCP connection a finite (but adequate) upper bound is imposed in practice in order to avoid depletion of `Nprobe` HTTP SSUs in the case of a 'runaway' connection.

The function `get_http_rec_and_trans` at line 9 instantiates a single `tcp_conn` object and a list of `MAX_NTRANS` `http_trans` objects. Lines 14 and 21 equip the objects with buffers into which they can read TCP packet header and HTML links data respectively — as the retrieval objects are to be re-used it would be inefficient to allocate these buffers on the fly as required by individual record instances.

`get_http_rec_and_trans` at line 33 is called as each record is encountered in order to populate the retrieval classes with data from the trace file, taking as its arguments the current `TraceFile` object (positioned to read the record data) and the retrieval objects. The `read` method of the `tcp_conn` object is invoked at line 36 and its `get_ntrans()` accessor method at line 42 in order to establish the number of transactions present. The loop at line 44 reads the required number of transaction records serially from the file, each being populated by the `read` method of the corresponding `http_trans` in the list.

B.3 Using the FileRec Class to Minimize Memory Use

Data association during analysis may exceed the available memory capacity if all data is stored. The `FileRec` class is used to store the *location* of the associated trace file records during a preliminary pass through the file(s) and then, during full analysis of the associated data, to retrieve data from file and instantiate an analysis object of the appropriate type. Code Example B.3 illustrates the association of data using FileRec objects.

```
  from np_file_util import get_files, EOF from nprobe import
      tcp_conn,
  REC_TCP_HTTP from np_filerec import FileRec, WEBCLIENT

#
# Use an initial pass through the trace to associate TCP/HTTP data
# on a per-client basis using the FileRec class
#

def first_pass(file_list):

    # check and open trace files, aggregate meta-data
    openfilelist, counters = get_files(file_list)

    #
    # instantiate a reusable TCP connection data retrieval object
    #
    connrec = tcp_conn()

    # a dictionary in which to store the associated data (as
        FileRecs)
    clients = {}

    #
    # main loop
    #
    for file in openfilelist:

        while TRUE:

            # position at next TCP/HTTP record
            try:
                file.next_type_rec(REC_TCP_HTTP)
            except EOF:
                break

            # get the file offset
            off = file.curr_offset # get before read advances

            # get the data into the retrieval object
            connrec.read(file)

            client = connrec.client() # accessor method

            if clients.has_key(client):
                #
                # a FileRec for this client exists
                # - add this record to it
                #
                clients[client].add_rec((REC_TCP_HTTP, file,
                   offset))
            else:
                #
                # create a new FileRec with this record initially
                # - the analysis object to be constructed will be
                #   of class WebClient
                #
                clients[client] = FileRec(WEBCLIENT, REC_TCP_HTTP
                   , file, offset)

    #
    # return the associated data
    #
    return clients

#
# Now analyse the associated data - clients is a dictionary
# of FileRecs associated by client
#

def analyse(clients):

    for c in clients.values():
        # create a WebClient analysis object
        client = c.reconstruct()

        # call the object's analysis methods
        c.build_page_downloads()
```

```
77              c.first_analysis_task()

79              .
80              .
81              .

83          return
```

Example B.3: **Minimizing memory use by storing record locations. TCP/HTTP data pertaining to individual clients is associated by client during an initial pass through the trace. The data itself is not stored — objects of the `FileRec` class accumulate a list of the relevant record locations. During full analysis objects of the `WebClient` class are instantiated and populated using the `FileRec` objects' `reconstruct` method.**

Data association (in this case the activity associated with individual Web clients) is carried out during the first pass through the trace file(s) by the function `first_pass` at line 11. The opening of the listed files at line 14 and the main loop at line 27 are substantially equivalent to the similar operations shown in Code Example B.1, but in this case protocol class objects are not instantiated. A re-used data retrieval object reads the record from file at line 41, the only data accessed being the address of the TCP connection client. If the client has already been encountered (the `if` statement at line 45) the record's type and location are added to the client's existing `FileRec` object's list of records at line 45. Otherwise a new `FileRec` object is created, initially populated with the location of this first record encountered, and entered into the `clients` dictionary at line 57.

Analysis of the associated data is carried out in the `analyse` function at line 69 which steps through the entries in the `clients` dictionary instantiating `WebClient` analysis objects at line 73 by invoking the `reconstruct` method of the `FileRec` object forming the data part of each dictionary client entry. The `WebClient's` analysis methods are then called from line 76 onwards.

Appendix C

Inter-Arrival Times Observed During Web Server Latency Tests

Chapter 6 describes a technique, based upon the activity model of TCP connections, which can be used to distinguish and quantify network and application-level time components of TCP connections. Sections 6.3.1 – 6.3.3 describe a series of experiments conducted to evaluate the technique and present the results in Figures 6.1 to 6.4 on pages 145–150. This Appendix examines the results of these experiments in the context of the request and response inter-arrival times observed at the monitor.

C.1 Interpretation of Request and Response Inter-Arrival Times

Figures C.1 and C.2 show the distribution of inter-arrival times for requests and responses in each of the typical experiments. As the monitoring point was immediately adjacent to the clients the request distribution shown is known to be minimally effected by variations in network transit times and therefore reliably represents intervals at the client.

The distribution of response inter-arrival times may assume a different shape to that of requests due to one or more of three factors:

- Variations in the processing time of individual requests
- Request queueing at the server
- Variations in network pRTTs between monitor and server

As care was taken to ensure that all requests could be satisfied from the server cache, and because demands upon the server were constant during each loading interval, variations in the processing time of individual requests should not materially effect the distribution of response inter-arrival times. In the case of the local server pRTTs are typically less than 0.05 per cent of the minimum inter-arrival periods observed, and therefore can not materially effect their distribution.

Although pRTTs were of the same order of magnitude as inter-arrival periods in the experiments conducted with a distant server, examination of Figures 6.3(c) and 6.4(c) on pages 148 and 150 shows that variations in pRTT are less than the significant inter-arrival periods and that (for each averaging period) the standard error of the mean is generally less than 1 ms. It is unlikely, therefore, that pRTT variations contribute significantly to the distributions observed in these experiments. Reference to Figures C.2 (a) – (b) and (d) – (e) additionally shows that response inter-arrival periods remain consistent for the proportion of responses expected to occur regularly, and also suggests that pRTT variation does not materially affect the distributions seen.

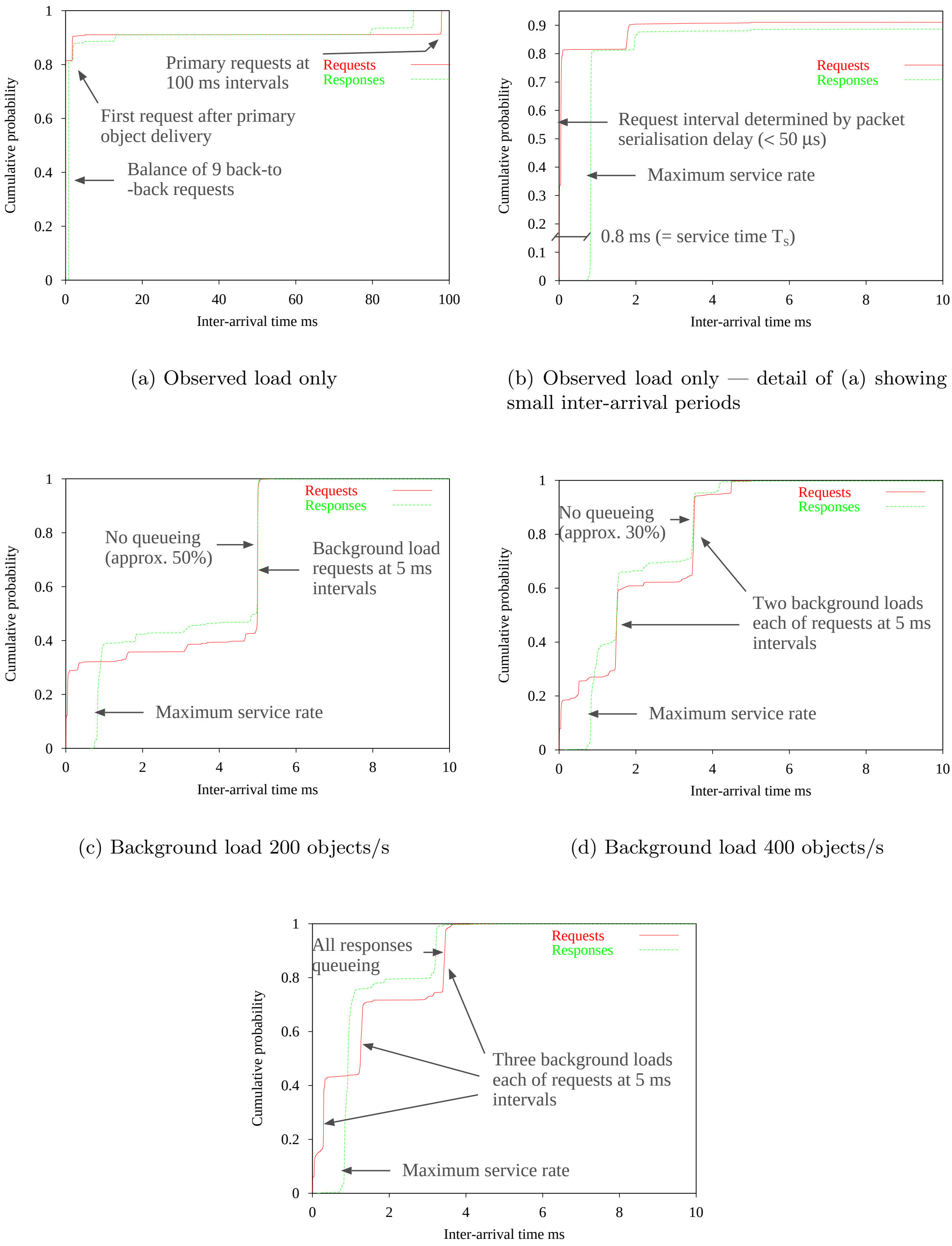
It is concluded, therefore, that differences seen between the distributions for requests and responses accurately reflects queueing behaviour at the server. Where a section of the response inter-arrival time distribution is displaced from the corresponding section of the request distribution, and both refer *to the same set of requests/responses*, the offset represents either a minimum possible server response time or the delay due to queueing.

C.2 Inter-Arrival Times for Client and Local Server with Small Round Trip Times

Figure C.1 shows the distribution of inter-arrival times for the typical experiment using a local server, and with small RTTs, for the range of four background loads employed (0, 200, 400 and 600 objects per second, Sub-figures (a) and (c) – (e)). In all cases the proportion of inter-arrival times attributable to each part of the observed and background loads is clearly identifiable, and is annotated appropriately. As background loads are added, shown in (c) – (e), the features due solely to the observed load, shown in (a) become less significant, and contribute a correspondingly lower probability to the distribution.

Figure C.1(b) presents a detail of the small inter-arrival time distribution at zero background load showing the contribution of the burst of back-to-back requests which forms part of the observed load. It is clear that the server has a maximum service rate, represented by a minimum latency of 0.8 ms (i.e. service time T_S), which is present at all background loads, and which will contribute an accumulative queueing delay of this magnitude to each response to requests arriving back-to-back. It is exactly this accumulative delay which is seen in Figure 6.1(b) on page 145, and confirms the figures calculated by the activity model; it also conforms reasonably to the service time of 0.836 ms predicted by the zero-background–load model of server activity.

Sub figures (c) – (e) show that, at background loads of 200 and 400 requests per second the server response is sufficiently fast to avoid queueing for the majority of the requests, but at a background load of 600 requests per second all requests are queued. The distinct steps introduced into the distribution by the successively added background loads suggest that the requests generated by the loading machines were (as might be expected) neither in phase,



(a) Observed load only

(b) Observed load only — detail of (a) showing small inter-arrival periods

(c) Background load 200 objects/s

(d) Background load 400 objects/s

(e) Background load 600 objects/s

Note: The observed load is one request for a 1 kB object, followed by a burst of 10 concurrent requests for a 512 byte object, every 100 ms. The three incremental background loads each consist of a request for a single 1 kB object every 5 ms.

Figure C.1: **Local server: distribution of response and request inter-arrival times for *all* loads**

nor were their phases evenly distributed — although the *average* request arrival interval (approximately 1.4 ms at the highest load) is never less than the server's minimum response latency the phasing of the requests makes it inevitable that some queueing will result.

C.3 Inter-Arrival Times for Client and Distant Server with Larger Round Trip Times

Figure C.2 shows the distribution of inter-arrival times for the typical experiments using a local server with small RTTs on non-persistent and persistent pipelined connections, for the range of four background loads employed (0, 100 and 200 objects per second, sub figures (a) – (c) and (d) – (f)). Sub figures (b) and (e) show detail of the small inter-arrival time distribution at zero background load.

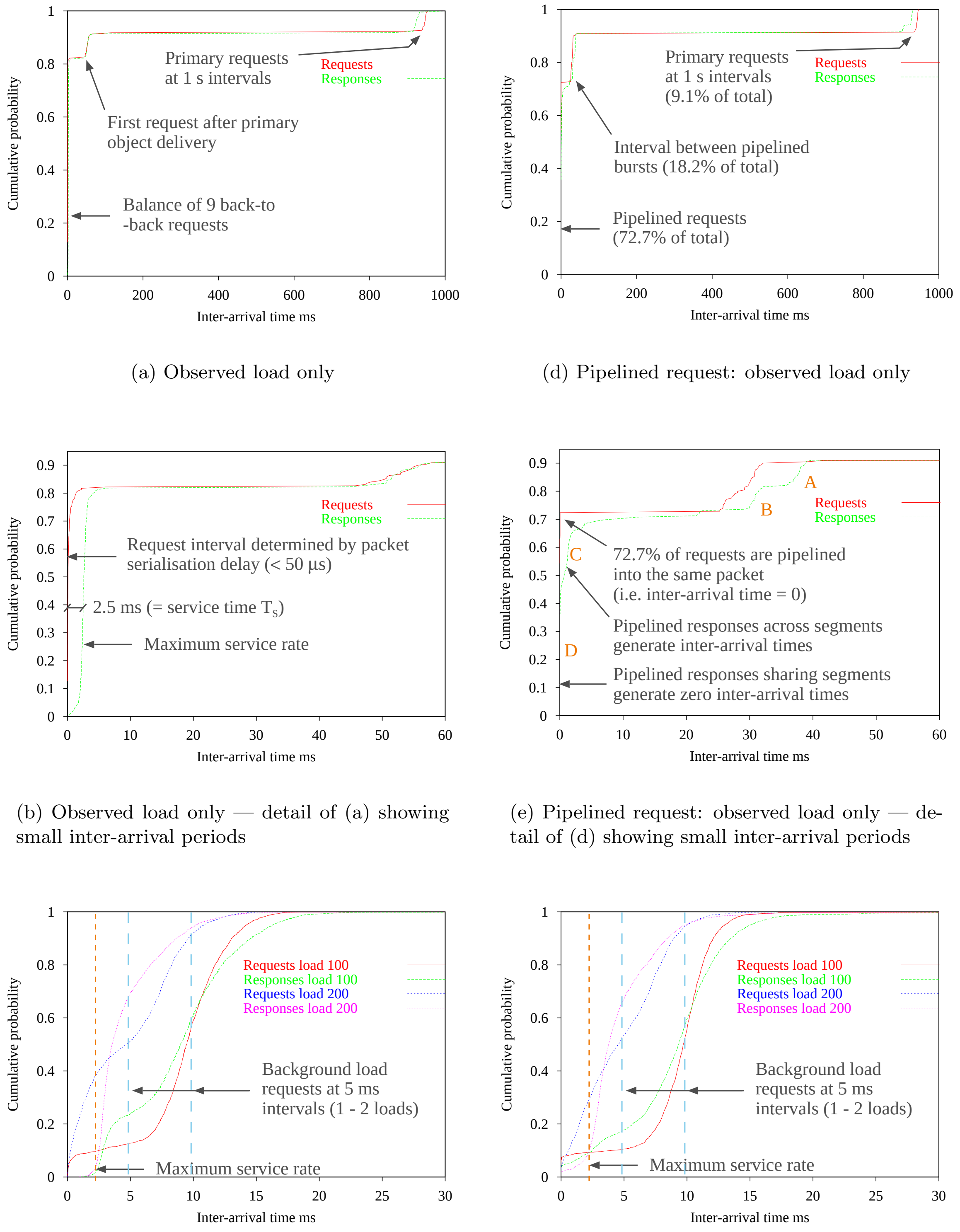
C.3.1 Using Non-Persistent Connections

The features of the zero-load inter-arrival times for the larger RTTs encountered in these tests, when using non-persistent connections (Figure C.2 (a) – (c)), are similar (although slightly less well defined) to those of the tests utilising a server with small round trip times. The less powerful server used reflects in a lower maximum service based upon a minimum latency of 2.5 ms, clearly seen in sub figure (b). This degree of latency again agrees closely with the accumulative queueing delays calculated by the activity model for this test, and which are shown in Figure 6.3(b) on page 148, and compares with a service time of 2.82 ms derived from the zero-background–load model.

The zero-load distribution features are not as well preserved by comparison, however, when background loads are added (sub figure (c)), and this probably reflects the higher proportionate load placed upon the machine's processor (compare Figures 6.1(d) and 6.3(d) on pages 145 and 148). The distribution of background load request inter-arrival times differs dramatically from the cleanly stepped distribution seen in the case of the local server. It is suggested that `Httperf's` request-scheduling policy underlies this difference: when called upon to generate a high request rate, `Httperf` schedules its activity by spinning between requests, hence achieving precise timings; at lower rates the `select` system call is used to schedule requests. The median values of background load request inter-arrival times are approximately 5 and 10 ms, as expected for loads of 100 and 200 requests per second, with a mean dispersion of approximately 2.5 ms — a typical, and expected, degree of precision when using the `select` mechanism.

C.3.2 Using Persistent Pipelined Connections

Zero-load inter-arrival time distributions for a typical test using persistent connections with pipelined requests are shown in Figure C.2 (d) and (e). Sub figure (d) demonstrates the division of request intervals into those between primary requests (approximately 9.1% of the



(a) Observed load only

(d) Pipelined request: observed load only

(b) Observed load only — detail of (a) showing small inter-arrival periods

(e) Pipelined request: observed load only — detail of (d) showing small inter-arrival periods

(c) Background loads 100 and 200 objects/s

(f) Pipelined request: background loads 100 and 200 objects/s

Note: The observed load is one request for a 1 kB object, followed by a burst of 10 concurrent requests for a 512 byte object, every second. The two incremental background loads each consist of a request for a single 512 byte object every 10 ms.

Figure C.2: **Distant server: distribution of response and request inter-arrival times for *all* loads**

total), between two bursts of pipelined requests (18.2%) and pipelined requests (72.7%). It is suggested, therefore, that the principal features exhibited by the distribution are determined by the pipelining behaviour of the requesting agent.

Sub-figure (e) shows the detail of (d) and is clarified by reference to Figure 6.5 on page 151, which shows the pattern of pipelining for request bursts and responses. The differing interval between the transmission of the primary response and the first response burst (approximately 32 ms) and the first and second response bursts (approximately 38 ms) are seen at **B** and **A**. The 45% of all responses whose initial octets share a segment with those of the preceding response result in zero inter-arrival times seen at **D**; 27 per cent of pipelined responses whose initial octets are carried in a subsequent segment are seen at **C**. It is clear that the principal features of the response inter-arrival time distribution are also determined largely by the pattern of pipelining. It is interesting to note, however, that the segments carrying responses #4 –#10 are not transmitted back to back[1], but are separated by approximately 1.5 ms (**C**). It *may* be that this interval represents a maximum service rate for pipelined responses, which is feasible compared with the 2.5 ms minimum latency exhibited for non-persistent and non-pipelined responses, where each involves the additional computational expense of creating and scheduling a separate server thread — the zero-background–load model of the server, however, does not support this supposition. The lower workload in the persistent/pipelined case *is* reflected in the lower CPU load factor seen in Figure 6.4(d).

The predominant features of the distributions with the addition of background load (Sub-figure C.2(f)) are dictated by the additional loadings, and are essentially similar to those in the case of non persistent connections shown in sub figure C.2(c). The different pattern of observed load is, however, reflected in the lower left-hand part of the two plots.

[1] The activity model assumes that these segments are transmitted back to back, and that the responses that they carry are, therefore, subject to *null* delays (see Section 6.3.3 on page 149). This will not introduce inaccuracy, but the model should be enhanced to recognise such delays between pipelined responses.

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