L41: Lab 5 - TCP Latency and Bandwidth

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The goals of this lab are to:

- Learn to draw TCP time-bandwidth and time–sequence-number diagrams.
- Evaluate the effects of latency on effective TCP bandwidth.
- Evaluate the effects of socket-buffer size on effective TCP bandwidth.

Lab 5 builds on the investigation started in Lab 4, and uses the same TCP benchmark.

Background: TCP, latency, and bandwidth

The Transmission Control Protocol (TCP) layers an reliable, ordered, octet-stream service over the Internet Protocol (IP). As explored in the previous lab, TCP goes through complex setup and shutdown procedures, but (ideally) spends the majority of its time in the `ESTABLISHED` state, in which stream data can be transmitted to the remote endpoint. TCP specifies two rate-control mechanisms:

Flow control allows a receiver to limit the amount of unacknowledged data transmitted by the remote sender, preventing receiver buffers from being overflowed. This is implemented via *window advertisements* sent via acknowledgments back to the sender. When using the sockets API, the advertised window size is based on available space in the *receive socket buffer*, meaning that it will be sensitive to both the size configured by the application (using socket options) and the rate at which the application reads data from the buffer.

Contemporary TCP implementations *auto-resize* socket buffers if a specific size has not been requested by the application, avoiding use of a constant default size that may substantially limit overall performance (as the sender may not be able to fully fill the *bandwidth-delay product* of the network)[1]. Note that this requirement for large buffer sizes is in tension with local performance behaviour explored in prior IPC labs.

Congestion control allows the sender to avoid overfilling the network path to the receiving host, avoiding unnecessary packet loss and negative impacting on other traffic on the network (*fairness*). This is implemented via a variety of congestion-detection techniques, depending on the specific algorithm and implementation – but most frequently, interpretation of packet-loss events as a congestion indicator. When a receiver notices a gap in the received sequence-number series, it will return a *duplicate ACK*, which hints to the sender that a packet has been lost and should be retransmitted[2].

TCP congestion control maintains a *congestion window* on the sender – similar in effect to the flow-control window, in that it limits the amount of unacknowledged data a sender can place into the network. When a connection first opens, and also following a timeout after significant loss, the sender will enter *slow start*, in which the window is 'opened' gradually as available bandwidth is probed. The name 'slow start' is initially confusing as it is actually an exponential ramp-up. However, it is in fact slow compared to the original TCP algorithm, which had no notion of congestion and overfilled the network immediately!

When congestion is detected (i.e., because the congestion window has gotten above available bandwidth triggering a loss), a cycle of congestion recovery and avoidance is entered. The congestion window will be reduced, and then the window will be more slowly reopened, causing the congestion window to continually

[1] Bandwidth (bits/s) * Round Trip Time (s)

[2] This is one reason why it is important that underlying network substrates retain packet ordering for TCP flows: misordering may be interpreted as packet loss, triggering unnecessary retransmission.

(gently) probe for additional available bandwidth, (gently) falling back when it re-exceeds the limit. In the event a true timeout is experienced – i.e., significant packet loss – then the congestion window will be cut substantially and slow start will be re-entered.

The steady state of TCP is therefore responsive to the continual arrival and departure of other flows, as well as changes in routes or path bandwidth, as it detects newly available bandwidth, and reduces use as congestion is experienced due to over utilisation.

TCP composes these two windows by taking the minimum: it will neither send too much data for the remote host, nor for the network itself. One limit is directly visible in the packets themselves (the advertised window from the receiver), but the other must either be intuited from wire traffic, or more preferably, monitored using end-host instrumentation. Two further informal definitions will be useful:

Latency is the time it takes a packet to get from one endpoint to another. TCP implementations measure *Round-Trip Time (RTT)* in order to tune timeouts detecting packet loss. More subtlely, RTT also limits the rate at which TCP will grow the congestion window, especially during slow start: the window can grow only as data is acknowledged, which requires round-trip times as ACKs are received.

Bandwidth is the throughput capacity of a link (or network path) to carry data, typically measured in bits or bytes per second. TCP attempts to discover the available bandwidth by iteratively expanding the congestion-control window until congestion is experienced, and then backing off. While bandwidth and latency are notionally independent of one another, they are entangled in TCP as the protocol relies on acknowledgments to control the rate at which the congestion window is expanded, which is dependent upon round-trip time.

Background: Plotting TCP connections

For this lab, you will prepare two types of TCP graphs:

TCP time-bandwidth graphs plot time on a linear X axis, and bandwidth achieved by TCP on a linear or log Y axis. Bandwidth may be usefully calculated as the change in sequence number (i.e., bytes) over a window of time – e.g., a second. Care should be taken to handle wrapping in the 32-bit sequence space; for shorter measurements this might be accomplished by dropping traces from experimental runs in which sequence numbers wrap.

TCP time–sequence-number graphs are a useful means of exploring protocol-level behaviour, making a number of important network and protocol properties easy to understand visually. Figure 1 illustrates a somewhat abstracted graph with real time on a linear X axis, and the TCP sequence space on a linear Y axis – your graphs will be more concrete (e.g., include actual sequence numbers and times!). The graph displays properties of a single communication direction in TCP (e.g., from server to client), but incorporates data from both data segments and their acknowledgments. Sender-originated data consists of the range of bytes in a particular TCP segment, starting with the transmitted sequence number and continuing through the sequence number plus packet length. Receiver-originated data consists of the acknowledged sequence number and the advertised window (which is added to the acknowledged sequence number to calculate the highest sequence number the sender is, at that point, allowed to transmit).

Both graphs may benefit from overlaying of additional time-based data, such as specific annotation of trace events from the congestion-control implementation, such as packet-loss detection or a transition out of slow start. Rather than directly overlaying, which can be visually confusing, a better option may be to "stack" the graphs: place them on the same X axis (time), horizontally aligned but vertically stacked. Possible additional data points (and Y axes) might include advertised and congestion-window sizes in bytes. Bandwidth graphs are suitable for plotting quite long periods of protocol operation, but time–sequence-number graphs will primarily be used when investigating specific local behaviour in TCP (e.g., around the transition from slow start to steady state).

The benchmark

This lab uses the same IPC benchmark as prior labs. You will run the benchmark both with, and without, setting the socket-buffer size, allowing you to explore the effects of manual versus automatic socket-buffer tuning.

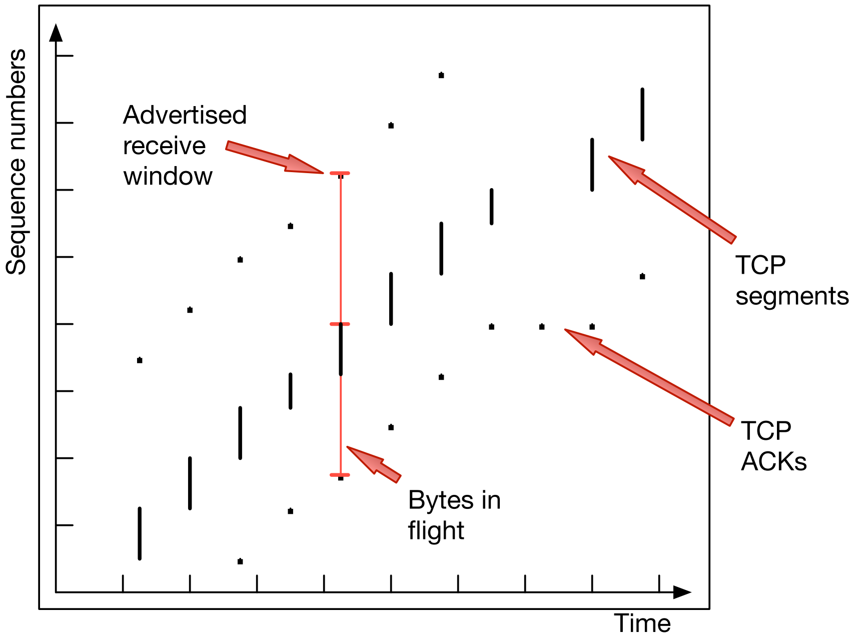

Figure 1: TCP time–sequence-number plot: linear X axis representing real time, and linear Y axis representing the TCP sequence-number space. TCP segment data is based on the sequence number and segment length from the sender, and acknowledgement and advertised window based is from the receiver.

The benchmark continues to send its data on the accepted server-side socket on port `10141`. This means that data segments carrying benchmark data from the sender to the receiver will have a *source port* of `10141`, and acknowledgements from the receiver to the sender will have a *destination port* of `10141`. Do ensure that, as in Lab 2, you have increased the kernel's maximum socket-buffer size.

DTrace probes

As in Lab 4, you will utilise the `tcp_do_segment` FBT probe to track TCP input. However, you will now take advantage of access to the TCP control block (`tcpcb` structure – `args[3]` to the `tcp_do_segment` FBT probe) to gain additional insight into TCP behaviour. The following fields may be of interest:

snd_wnd On the sender, the last received advertised flow-control window.

snd_cwnd On the sender, the current calculated congestion-control window.

snd_ssthresh On the sender, the current *slow-start threshold* – if `snd_cwnd` is less than or equal to `snd_ssthresh`, then the connection is in slow start; otherwise, it is in congestion avoidance.

When writing DTrace scripts to analyse a flow in a particular direction, you can use the port fields in the TCP header to narrow analysis to only the packets of interest. For example, when instrumenting `tcp_do_segment` to analyse received acknowledgments, it will be desirable to use a predicate of `/args[1]->th_dport == htons(10141)/` to select only packets being sent to the server port (e.g., ACKs), and the similar (but subtly different) `/args[1]->th_sport == htons(10141)/` to select only packets being sent from the server port (e.g., data). Note that you will wish to take care to ensure that you are reading fields from within the `tcpcb` at the correct end of the connection – the 'send' values, such as last received advertised window and congestion window, are properties of the server, and not client, side of this benchmark, and hence can only be accessed from instances of `tcp_do_segment` that are processing server-side packets.

To calculate the length of a segment in the probe, you can use the `tcp:::send` probe to trace the `ip_length` field in the `ipinfo_t` structure (`args[2]`):

```
typedef struct ipinfo {
        uint8_t ip_ver;                 /* IP version (4, 6) */
        uint16_t ip_plength;            /* payload length */
        string ip_saddr;                /* source address */
        string ip_daddr;                /* destination address */
} ipinfo_t;
```

As is noted in the DTrace documentation for this probe this `ip_plength` is the expected IP payload length so no further corrections need be applied.

Data for the two types of graphs described above is typically gathered at (or close to) one endpoint in order to provide timeline consistency – i.e., the viewpoint of just the client or the server, not some blend of the two time lines. As we will be measuring not just data from packet headers, but also from the TCP implementation itself, we recommend gathering most data close to the sender. As described here, it may seem natural to collect information on data-carrying segments on the receiver (where they are processed by `tcp_do_segment`), and to collect information on ACKs on the server (where they are similarly processes). However, given a significant latency between client and server, and a desire to plot points coherently on a unified real-time X axis, capturing both at the same endpoint will make this easier.

It is similarly worth noting that `tcp_do_segment`'s entry FBT probe is invoked before the ACK or data segment has been processed – so access to the `tcpcb` will take into account only state prior to the packet that is now being processed, not that data itself. For example, if the received packet is an ACK, then printed `tcpcb` fields will not take that ACK into account.

Flushing the TCP host cache

FreeBSD implements a *host cache* that stores sampled round-trip times, bandwidth estimates, and other information to be used across different TCP connections to the same remote host. Normally, this feature allows improved performance as, for example, by allowing past estimates of bandwidth to trigger a transition from slow start to steady state without 'overshooting', potentially triggering significant loss. However, in the context of this lab, carrying of state between connections reduces the independence of our experimental runs. As such, we recommend issuing the following command (as root) between runs of the IPC benchmark:

```
sysctl net.inet.tcp.hostcache.purgenow=1
```

This will flush all entries from the host cache, preventing information that may affect congestion-control decisions from being carried between runs.

Experimental questions (part 2)

These questions supplement the experimental questions in the Lab 4 handout. Configure the benchmark as follows:

- To use the statically linked version: `ipc-static`
- To use TCP: `-i tcp`
- To use a 2-thread configuration: `2thread`
- To use a fixed 1MB buffer `-b 1048576`
- To set (or not set) the socket-buffer size: `-s`
- To use only I/O-loop analysis
- Flush the TCP host cache between all benchmark runs

Explore the following experimental questions, which consider only the TCP steady state, and not the three-way handshake or connection close:

- Plot DUMMYNET-imposed latency (0ms .. 40ms in 5ms intervals) on the X axis and effective bandwidth on the Y axis, considering both the case where the socket-buffer size is set versus allowing it to be auto-resized. Is the relationship between round-trip latency and bandwidth linear? How does socket-buffer auto-resizing help, hurt, or fail to affect performance as latency varies?
- Plot a time–bandwidth graph comparing the effects of setting the socket-buffer size versus allowing it to be auto-resized by the stack. Stack additional graphs showing the sender last received advertised window and congestion window on the same X axis. How does socket-buffer auto-resizing affect overall performance, as explained in terms of the effect of window sizes?
- Plot a time–sequence-number graph for two new TCP connections through a few packets past the end of slow start for each of the runs, one with a 10ms round-trip time, and another with a 20ms round-trip time. How has latency affected the time required to enter the steady state? What is the resulting effect on bandwidth for the two connections over the same period?

Ensure that your final lab report answers all of the experimental questions in both labs 4 and 5.