Design and Use of High-Speed Networks in Multimedia Applications

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ORL-91-2

Published in Proceedings of 3rd IFIP Conference on High Speed Networking Berlin, March '91

To appear 3rd IFIP Conference on High Speed Networking
Berlin March '91

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Abstract

This paper deals with architectures for networked multimedia systems. Such architectures are made up of both network components and multimedia device components. The networks include high speed switches and backbones for real-time stream applications as well as systems with lower capacity which provide additional facilities for different kinds of multimedia devices. The devices range from lightweight portable personal units to complex workstations. A report is given of experience from a multimedia experimental system called Pandora which places a camera on the desktop and allows many applications to be tried. An estimate of the bandwidth requirements for future systems is made by drawing on experience from the popular applications in Pandora and in the expectation of the much higher quality required by new multimedia applications.

1. NETWORKED MULTIMEDIA SYSTEMS

When considering multimedia systems it is important to look at both the different networks and different devices in use. The devices vary from simple portable units to high quality displays and provide different levels of quality of service to the user. A systems approach is required which combines optimum use of the networking infrastructures with the multimedia devices.

The future networking infrastructures will span many different systems. At the lowest speed range there may be infra-red systems operating between 9.6Kbps and 1Mbps. These have the property that transmissions can be localised because infra-red does not penetrate walls and other objects. Small cells can be used which do not require complex transmission scheduling. Infra-red is at present not regulated and it is possible to use cheap technology to make portable devices communicate at these lower speeds. At speeds between 128Kbps and 10 Mbps it seems likely that radio based systems will be popular. Radio waves have the property that they travel through most physical objects, although to some extent are attenuated by them, and the shape of cells is quite different from those used for infra-red. It is possible to use fast components and techniques such as spread spectrum to provide the higher bandwidth rates. These systems will consume more power than infra-red systems and thus are less suitable for portable applications [1,2].

At speeds from 10Mbps to 2Gbps, various kinds of LAN/MAN technology are possible. For example, rings operating at 50Mbps to 150Mbps are becoming commonplace and experimental systems at speeds up to 2Gbps are being developed. Such systems can be used as backbones for connecting conventional data traffic and also to carry real-time streams for audio and video related applications [3].

The most general networking approach is that of a switch as this can both provide high capacity and can be easily deployed in hierarchical structures. Low cost high capacity switches are being developed which will have throughput performance up to 10Gbps and higher [4]. Such switches can be used as core units and may to some extent replace the higher speed rings if appropriate. It is an attractive thought that all the networks described above could be implemented in the style of ATM and thus present a unified approach with the benefits of easy connection with minimum buffering (cut-through) to conventional and real-time systems.

Various computing devices make up the multimedia space. At the lowest end, the personal active badge is an object which can both transmit and receive at low data rates [5]. It can receive simple instructions or alarms and can also be used to communicate the position of the wearer to the computer system. A small portable computer system with a touch sensitive stylus may be the next type of device to become widely used. Ensuring that such devices have good communications features means they can be simple, and therefore light. This kind of tablet can be considered as a portable terminal with the computational tasks being sent off to remote (and powerful) servers.

The simplest non-portable device is a multimedia player. In this type of device, material is presented from a CD-ROM and the user can navigate through a world which contains graphics, audio and video. A more general purpose fixed device has a camera, microphone, and speaker attached. It has all the facilities of a player but, in addition, allows material to be generated. It can provide normal computing facilities as well and can be considered a multimedia workstation. Beyond this it is possible to envisage a high-end multimedia workstation which is able to handle very complex parallel real-time streams of quality comparable to HDTV. Finally, there may be very high capacity display devices such as video walls and others which require a large amount of information to be sent for best effect.

If the video devices and networks are shown on a graph, the space between them represents an applications area (Fig 1). The simplest applications are those which combine a personal active badge with a low speed network and include locating and paging systems. The tablet can use a high capacity radio link to provide facilities such as telefax, telephone or windows for pen based applications. The two devices can be combined to give a tablet which is aware of the location of people and other tablets.

For the multimedia player, a local CD-ROM can be used. However, a shared network could be advantageous because many users are likely to require access.

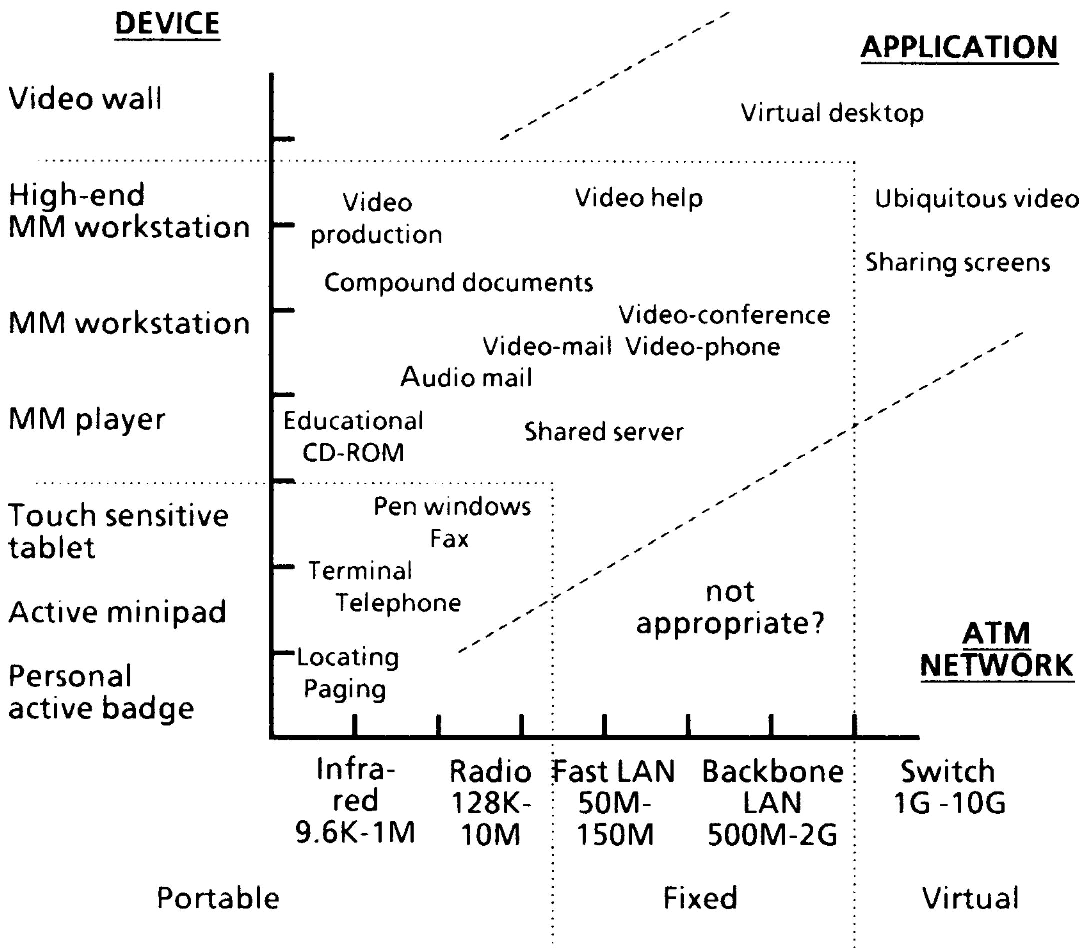

Figure 1. The multimedia space.

The speed of the network has to be high enough to support this sharing, and it has to handle both real-time and conventional streams. The multimedia workstation allows video mail and video phone applications to be provided. Video mail can be either spooled to a local disc and served from there or it can be delivered from a central server if the network can support this. If multiple real-time streams can be handled, then video conferencing becomes a possibility but in turn requires even more network capacity [6]. Such desktop video conferencing is quite different from conventional systems in use today because it does not require the participants to move away from their normal working positions. For high-end multimedia workstations, it is likely that at first various non-shared production applications will be available. Such facilities can be combined into more complex distributed systems which enable the handling of compound documents containing text, graphics, video and audio of high quality [7,8]. If very high speed networking is available then high quality video mail and video phones will be possible, or even screen sharing where any part of one screen can be mapped to any part of a set of other screens, no matter what the contents. However only with the highest network bandwidth can multiple and ubiquitous video applications be envisaged.

The traffic characteristics for the various networks described fall into a number of categories. The easiest to deal with is data, where conventional computer transactions are taking place. Such networks could also carry soft real-time traffic where time stamps of the type used in locating systems are being sent. When dealing with audio streams, the user requirements are much more severe and in particular when radio and other networks are communicating with portable devices, the handover from one base station to another must be jitter-free. For video, traffic can be divided into two categories: soft real-time and hard real-time. Video which is actually being watched by a human can be considered soft real-time because redundancy in the scene and compensation by the viewer enables it to withstand the occasional lost packet. However, if the video stream is being recorded or copied, then no packet loss is permissible, because the information would be lost forever. For one way real-time streams the jitter can be taken out using buffers, but if interactive or video telephony applications are being considered, the round trip delay must be controlled. For such applications it seems low audio delay is more important than accurate lip synchronisation.

It is likely that there will be many more portable devices used in the future, particularly ones based on high-speed low-range cellular networks. Many of these devices will require both audio and video features. For example, a portable touch sensitive tablet which has an attached TV camera and can display video and audio streams seems an attractive goal. The real-time traffic characteristics will have to be maintained as cells are crossed, and in modes where the radio and fixed networks are in use at the same time.

When considering network architectures for multimedia systems it is easy to assume that compression will reduce the amount of bandwidth required to lower levels. However, there is a tension between the compression factor and ease of manipulation of an image. In general, the more an image is compressed, the more difficult it is to perform manipulations on it. For example, if the image is represented as differences it may take considerable computation to unwind to the point where the original image is available and can be used. On the other hand if images remain in a form suitable for easy manipulation, the compression factors thus achieved are much reduced. The spectrum of these two extremes ranges from a compression factor of 10 for schemes which permit very easy manipulation to compression factors of 100-200 for schemes where manipulation is very difficult and picture quality degradation is permitted.

2. PANDORA

The research groups in Cambridge are aiming to explore the whole networked multimedia space described above. One part of this is reaching completion and deals with the generation and networking of audio and video using multimedia workstations. The Pandora project has placed a camera on the desktop of a number of users. As well as building a system, a number of new applications have been developed which provide insights into the way high speed networks may be used in the future [9].

The project has been in three stages. In the first a peripheral, Pandora's box, was designed. This box can be attached to a Unix workstation and provides multimedia facilities in X. From the user's point of view the normal workstation environment is maintained, but additional multimedia features are made available. In the second stage a number of systems were deployed amongst a community of systems developers and applications writers. This stage involved the development of a multimedia file server and a number of applications. In the third and final stage the experimental system is being used to evaluate the design and obtain experience of applications. Measurements of performance to help with the design of future network fabrics and interfaces are being made.

In order to avoid overloading the host workstation, a total subsystem approach was chosen. Pandora's box is a separate peripheral which can take control of the workstation screen. Pandora's box has a monochrome camera, a microphone, a loudspeaker and an ATM LAN attached. It is made up of a number of cards, each of which is controlled by a transputer. All data is represented digitally. There are no constraints on the number of streams within the box or network so that multiple video and audio streams can be used as required.

The real-time streams are handled inside Pandora's box and across the network as variable length segments. Each segment is carried by the underlying ATM network. Care is taken to ensure that no matter what form the contents of a segment take, the segment is mapped efficiently onto the underlying ATM mechanism. Characteristics of the most commonly used Pandora streams are summarised in Figure 2. There are three sizes of video stream sent across the

	size	rate	segment overhead	bandwidth	% CFR bandwidth
normal video	120x128x4	25	2%	1.56Mbps	3.7%
reduced video	120x128x4	12.5	2%	782Kbps	1.9%
small video	60x64x4	12.5	3.5%	199Kbps	0.5%
audio	8 bit μ-law	8K	40%	106Kbps	0.2%

Figure 2. Typical properties of Pandora streams.

network: normal, reduced and small. A normal stream requires two segments per frame and consists of 120x128 pixels encoded using DPCM in 4 bits and sent at 25 frames per second. A reduced stream is of the same size but sent at 12.5 frames per second. A small stream requires one segment per frame and consists of 60x64 pixels encoded in a similar way. There is a 68 byte overhead for each video segment. For display purposes the frames can be expanded locally by a factor of 4 using interpolation (thus making 3 sizes of image available). Audio streams are handled as 96 byte segments with a 36 byte overhead per segment. Because each byte represents 125µsecs, a sound segment spans 12ms.

Multiple streams can coexist and are controlled by applications. Incoming audio streams are mixed correctly and sent to a loudspeaker while video streams can be sent to different parts of the screen on a pixel-by-pixel basis. For example, in a video phone, audio and video streams are sent across the network between the participating workstations, and internal video streams are sent within Pandora to display on the local machine the image that is being sent to others. If a sender attempts to transmit at the full rate and a receiver is not able to keep up the data is thrown away. The frame rate can be controlled by the application and in general is reduced if a large number of video streams are being handled by one box. However, there is some difficulty with choosing arbitrary frame rates because of interference effects with the camera.

While the ATM LAN is used as the real-time stream carrier the Unix workstations are linked using ethernets in the conventional way. However, the ethernets are themselves connected using the ATM fabric which means that it carries both real-time and conventional data traffic. Other servers available on the network provide repository and Digital Audio Tape (DAT) back-up services, and bridging to further ATM and other networks.

3. PANDORA NETWORKING

Networking in the Pandora multimedia system is based on the Cambridge Fast Ring (CFR) [10]. This is a ring network operating at either 50 or 75 Mbps and which carries fixed size cells. An integrated low cost implementation has been developed. The hardware of the CFR was designed in a way which allows it to be used in either conventional address mode or in ATM mode.

The protocol which uses CFR cells is called Multi Service Data Link (MSDL) and implements lightweight virtual circuits with no hop-by-hop error recovery. This protocol was developed at the University of Cambridge Computer Laboratory as part of the Multi Service Network (MSN) and as well as being used in Pandora is used in conjunction with the Wanda micro-kernel on many machines [11]. Fragmentation and reassembly is on a per Virtual Circuit Identifier (VCI) basis. The circuits are set up using a protocol called MSNL which operates out of band from the MSDL stream. Figure 3 shows how MSN uses protocol stacks to implement the video, voice and other communication functions. Like ISO the MSN protocols are made up of layers, although above the data link layer they should be thought of as separate stacks according to function.

When operating in ATM mode the CFR uses a 4 + 32 format. The structure of each cell is shown in Figure 4. The 4 bit access control field is used to implement the empty slot protocol with slot release being done at the source. Next a 16 bit field identifies the VCI on which the cell is being sent. This is followed by a 16 bit reassembly field which starts with a 1 to indicate start of block. A 6 bit block identifier is used to indicate the block with which the cell is to be associated. An 8 bit sequence number is used to indicate the position of the cell in the block. For the first cell of a block the sequence number field

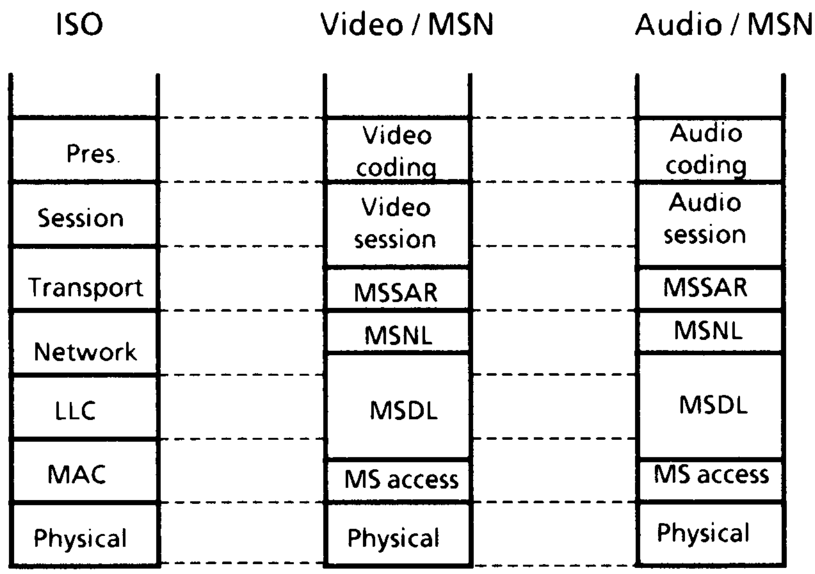

Figure 3. MSN protocol stack.

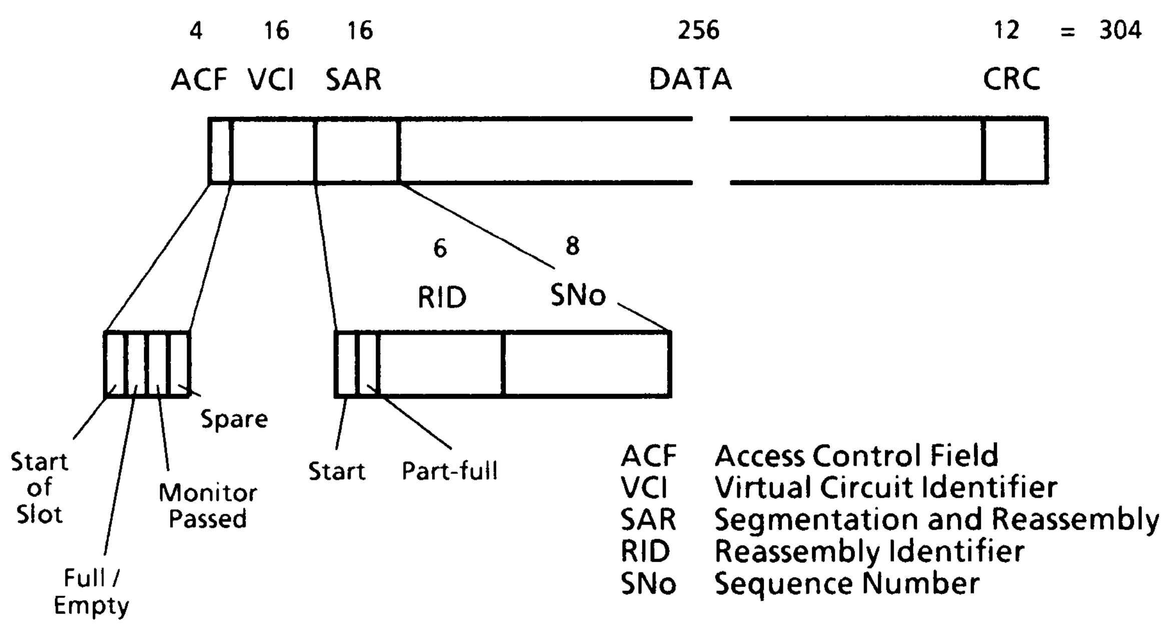

Figure 4. MSDL structure.

contains the length. The part-full bit is used to indicate that the last block contains less than 32 bytes.

Normally the MSNL connections are set up by sending out a cell on a well-known VCI. This call request quotes a return VCI. A reply is received which indicates the VCI on which a receiver is prepared to communicate using MSDL.

The network code is handled by a separate network processor residing within Pandora's box. This consists of two transputers one handling the CFR chip and acting as a high speed per-cell interrupt handler and the other controlling the per-block buffering of MSDL streams and other MSNL functions. Several MSDL streams can be multiplexed at once. Care is taken to make sure that Pandora segments fit MSDL blocks efficiently. Copying between Pandora's box and the network processor is faster than real-time and the major buffering takes place within Pandora's box itself. Buffering delay is minimised by careful overlap and fast copying. By maximising the number of cells per block throughput is improved while the favourable sharing properties of the CFR mean this does not cause contention for source access. The typical end-to-end delay between a camera on one box and the screen on another is about 50ms.

The CFR is designed to handle many simultaneous streams. About 20 Pandora's boxes are in use and the CFR operates with 7 slots. This gives a maximum theoretical point-to-point throughput of about 5Mbps per node and worst case throughput of about 3Mbps per node. The corresponding delays of a cell through the CFR are 50μsecs and 100μsecs. This means that even in the worst case when all Pandora's boxes decide to transmit, there is little performance loss for each connection and delays are dominated by packetisation, buffering and destination contention.

Figure 5 shows the measured load presented by one Pandora's box transmitting on the CFR as the number of real-time streams is increased. The amount of data each stream generates is a function of the image size and frame rate. Figure 5a shows how an audio stream and video streams of different types can be sent out by a single transmitting station. There is almost no source access contention and the station is able to go up to its current maximum transmission rate of about 2.3 Mbps. At a point close to the maximum the station continues transmitting but video quality degrades because segments are dropped haphazardly. There is little change to performance whether one large stream is being transmitted, several small ones, or a mixture. Similarly the limit on the number of sound streams that can be transmitted is set by the total bandwidth and not the number of such streams. The theoretical numbers shown in Figure 2 and the measured numbers in Fig 5a are in close agreement. Fig 5b shows the measured increase in total CFR traffic as more and more stations are added, each transmitting a single 1.56Mbps stream. Again there is an almost linear increase showing that the CFR slot mechanism is partitioning the bandwidth fairly. At present, the code is not optimised for speed and it is estimated that the station throughput could be doubled to about 4.6Mbps.

Figure 6 shows the reception of several streams by one destination. The upper curve of Figure 6a shows the actual traffic on the ring. The lower curve of Figure 6a shows the received data when a small video stream is being sent by each transmitter. The lower curve increases linearly to the current maximum at which a station can receive data (2.3Mbps). At the same time the total traffic on the ring increases considerably owing to destination contention. This causes a lot of

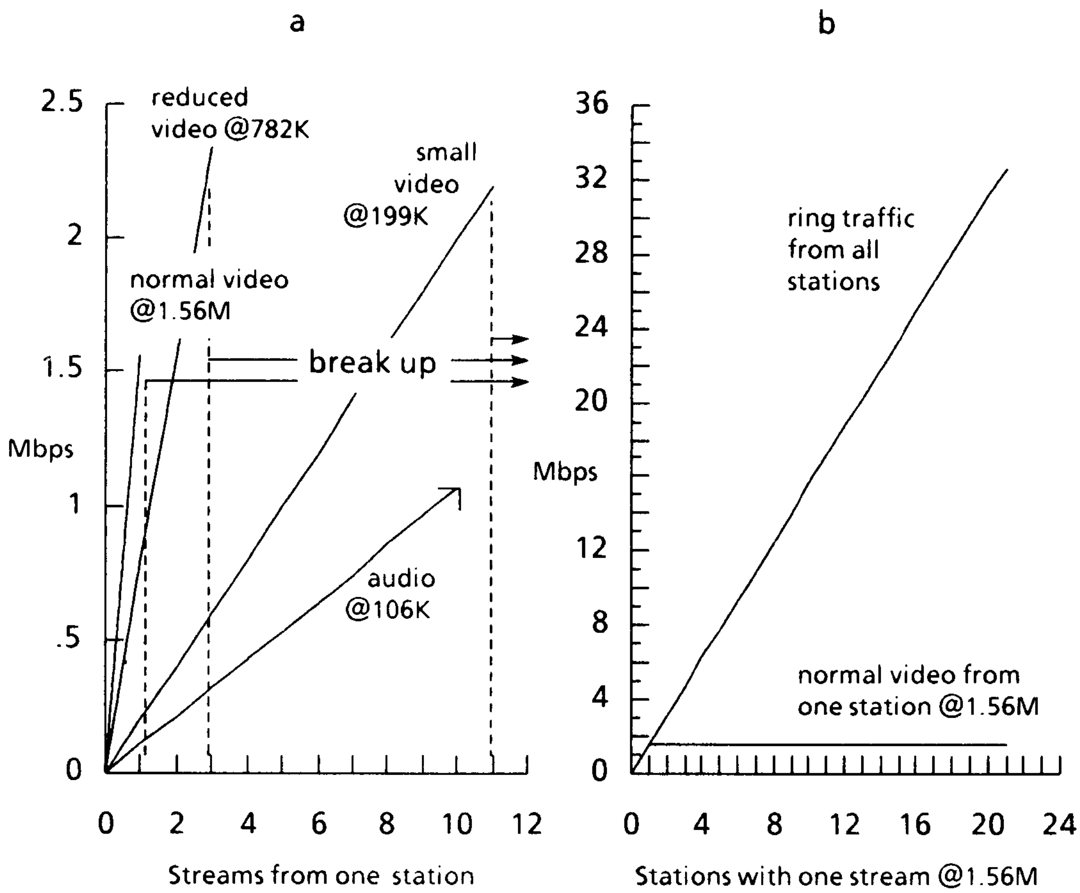

Figure 5. Transmission of streams.

cells to be retransmitted, both in hardware (max 3 attempts) and software (max 50 attempts). Fig 6b shows the same traffic pattern but with a higher bandwidth (reduced video) stream being attempted by each transmitting station. It can be seen that both receive throughput saturation and destination contention occur quickly; in this case picture break up is likely to be a problem with more than three streams.

Throughout the Pandora system incomplete segments (or blocks) are dropped and not retransmitted. We have found that by letting audio blocks take precedence when selecting the next item to be transmitted only video data is affected by congestion. Such low-level adaptation means that it is not always necessary to send error messages to the host under normal traffic conditions. However, congestion can occur at a destination and also within Pandora's box itself, when several streams are being received by one buffer. It is intended that eventually the error messages generated by these conditions will be passed on to the application which will be able to throttle back at the source. At present, however, it is up to the user to remove such congestion by making smaller or deleting a video window.

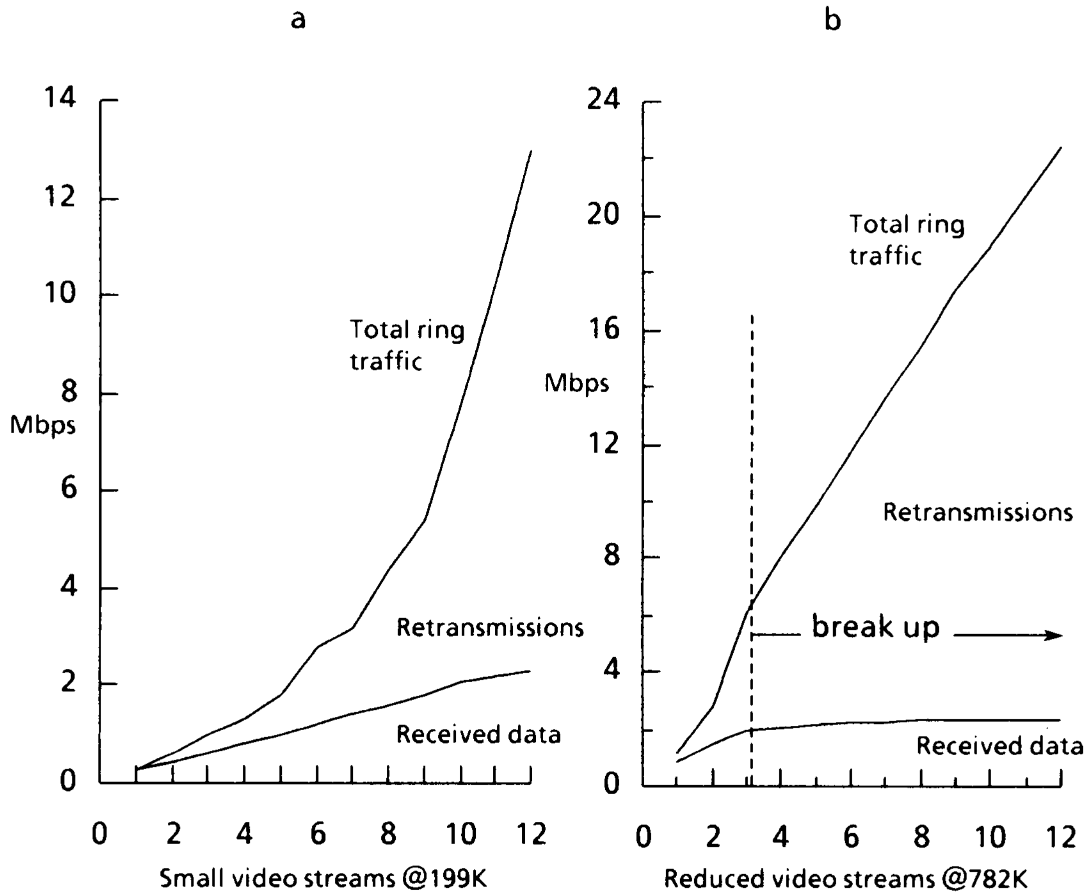

Figure 6. Reception of streams.

The CFR is also used as a bridge between ethernet networks at the sites using Pandora's boxes. The proportion of ethernet traffic is small. Since the Unix systems controlling Pandora's boxes exchange information, whether or not Pandora is sending real-time streams, this load is more or less constant. That this traffic does not affect the performance of the real time streams, seems to encourage the view that ATM is a unifying approach to networking.

4. APPLICATION IN USE

The Pandora system makes it possible quickly to put together and test multimedia applications on a group of users. One of the first observations made by a new user is that he or she is a little camera shy. This meant that there was very little take up of the Pandora system until the public machines were placed in sound proofed booths so that users could experiment without their mistakes being obvious to others. The second realisation is that a camera alongside a workstation screen shows a true image and not a mirror image, so that if one moves ones head to the right, the head on the screen moves the other way. Having overcome these two initial obstacles, users tend to find the use of audio and video very natural. This is particularly true for machines in private offices, which are also used for receiving e-mail, logging into computers, and other general purposes.

Amongst the first applications provided was reception of video streams from other boxes. A window on the screen indicates that a stream is being sent out by the workstation. It is possible to show the video from all cameras in one window, enabling a quick look round the whole system. While such facilities are good for demonstrations, in practice they are never used seriously. It was thought that to listen to another office was improper, and was disallowed from the outset.

One of the Pandora's boxes is attached to a TV, Radio and CD system. When users connect to this box they can select a live TV source, live Radio or CD music. Thus it is possible to watch TV or be entertained in some other way. It is rare that these facilities are used except at times of major news stories when most of the Pandora's boxes are seen to be sourcing the TV stream.

By setting up video and audio streams in two directions at once it is possible to implement desk top video phones. One window is normally used to show the local image so that the user can centre his head, and a large image of the other party is shown in another window. Hands-free microphones are used with frequency shifters to reduce feedback. It is thus possible to video phone somebody as easily as making a phone call. Based on a few months experience it seems that users find this worthwhile. Smoothly moving images of a lower quality are preferred to slow scan images of higher quality. It is possible to set up streams with several parties and therefore to arrange a desktop video conference. With four parties taking part the visual clues make it obvious who should speak next. With more than four images who should speak next is not obvious and explicit motions such as raising of the hand are necessary.

Another popular application is video mail. This enables a user to record a message on the file server and send it in the same way as electronic mail to somebody else. The multimedia file server can support several incoming and outgoing streams at once. Synchronisation of audio and video is done at the source end using time stamps. No special provision is made by the file server for handling large sequential files, but it is not used at the same time for storing normal data. The users who do not have desktop Pandora's boxes receive text mail telling them that there is a video mail message. Many hundreds of video mail messages have been sent. It seems that video mail is a form of communication which compliments others and makes it possible to convey information very quickly.

Figure 7a shows the lengths of video mail files seen recently on the multimedia file server. There is no technical or management constraint imposed on the amount of storage allocated to a user. Video (and accompanying audio) files fall into two categories: those that contain instructional or educational material and those that were used as video mail. Educational material tends to be several minutes long, is prepared carefully, and played many times. Video mail is in the range 5 seconds - 2 minutes with a mean of 30 seconds. While cut and join facilities are available only about 20% of the video mail messages used anything more than pause during recording. Because video mail messages are sometimes checked by the sender and because they can be sent to groups,

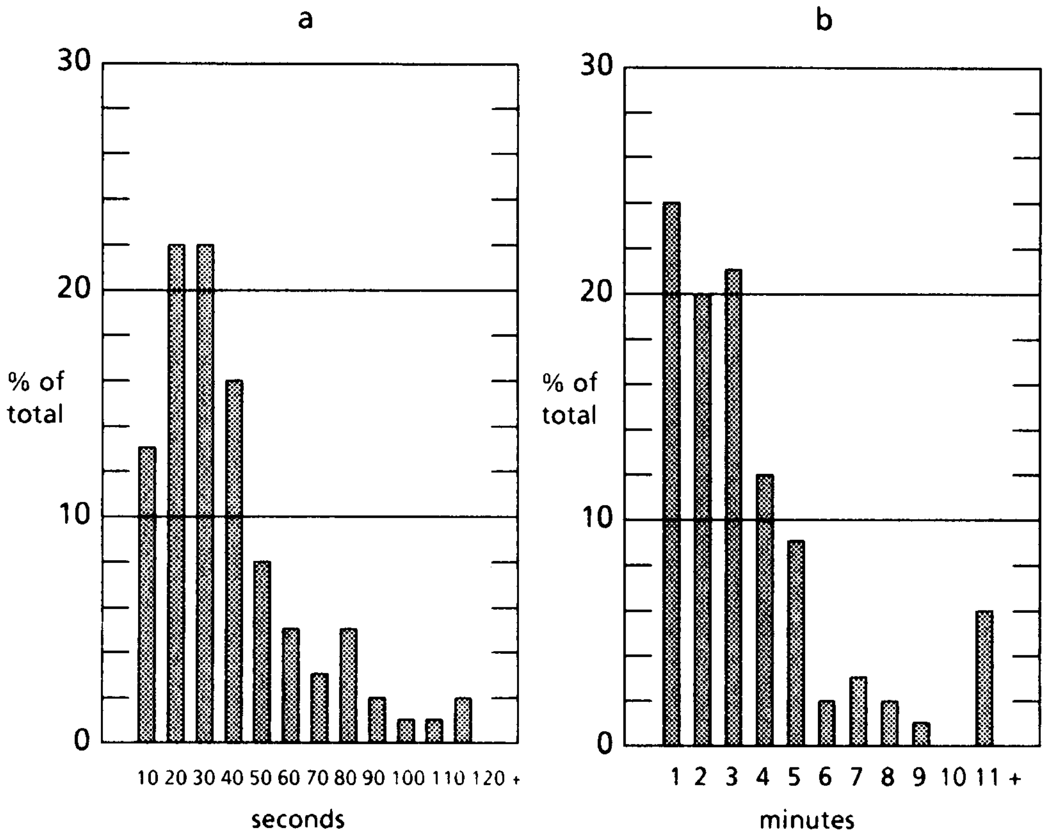

Figure 7. Pandora video mail and video phone statistics.

about 30% are looked at more than once. These are early figures and our experience is too short to judge if they will remain unchanged.

Figure 7b shows the distribution of video phone sessions. While the mean is about 2 - 3 minutes the tail is much longer than for video mail with some users habitually conversing for over 20 minutes. At present only about 5% of live video sessions are between 3 or more parties.

5. FUTURE SYSTEMS REQUIREMENTS

It has been possible to deploy the CFR on a scale which may indicate what traffic levels future networks supporting higher quality images may generate. A faster ATM network called the Cambridge Backbone Ring operating at 512 Mbps is currently in use linking Olivetti and the University of Cambridge Computer Laboratory [3].

Experience from the Pandora project is very encouraging, and a number of multimedia applications have proved very popular. It also shows that an ATM ring used in a simple way can provide a good transmission fabric. While the Pandora system uses monochrome, future systems will use colour and provide images of much higher quality. It is also likely that future workstations will provide more arbitrary mixing of video streams and will require many more streams in and out of each workstation. Compression technology has reached a point where chips giving a compression factor of about 20 are becoming available, while retaining the data in a form which allows easy manipulation [12]. Using this type of compression to send a 640x512x24 image at 25 frames per second, will generate about 10Mbps per stream. For a video phone application, a workstation network interface will have to support about 20Mbps continuously, as well as normal traffic. Current work suggests that it may be possible to build a simple scalable ATM interface which is based on a fast general purpose processor and which can support data rates from 30 Mbps for simple systems to 100Mbps with hardware assist [13]. The interface would be able to multiplex on a per-VCI basis, and also perform encryption if required. An efficient multicast facility, close to the network fabric, is important to permit applications like recording during video phone sessions.

Pandora experience suggests that in a large enough group, a user may use the two-way video phones 25 times in a 8 hour working day, with each call lasting an average of 3 minutes. For video mail applications it is likely that the same user will generate 25 video mail messages of 30 seconds each, and that these will be looked at an average of 35 times. This is slightly more than the average number of text mail files produced today but in comparison, video mail is considerably faster to generate (if not view). These numbers can be used to compute the maximum number of users that a 512 Mbps ring can support, assuming the incoming requests are independently distributed. This is highly dependent on the maximum utilisation the ring traffic is permitted to reach. If this is 256 Mbps (50%) then with 60 users capacity will be sufficient 98% of the time. Similarly, the number of users that can be supported by a file server interface can be estimated. If the interface can sustain 50Mbps continuously about 35 users can be supported, while if the interface can support 100 Mbps the number of users goes up to 85, assuming 98% availability. While these figures are not accurate, it does seem attractive to plan for about 50 high-end multimedia workstations per ring and per video file server.

For video mail applications further compression can be applied, if the files are to be sent to places where a high speed network is not available. It is interesting to note that, if we allow a user to retain 100 video mail files of high quality, the capacity of the file server is 1.2 Terabytes for the system under consideration. It may only be useful to do this if on line search techniques for video files are developed, which permit easy retrieval of video. In the mean time the size of the file server can be much reduced by using virtual memory techniques and mass storage like DAT.

The multimedia applications described above make it clear that the bandwidth being provided by new networks will have no difficulty in finding an application. It is interesting to speculate about how much real-time traffic will be carried on such networking infrastructures. The only time the traffic needs to be real-time is when there is a human listener or watcher in front of a multimedia device. If representations of images are being sent between computers, there is no requirement for real-time properties, and images can for example be sent faster than real time. As networked multimedia systems are developed it may be that networks continue to be dominated by conventional traffic of this type.

6. ACKNOWLEDGEMENTS

Many people have contributed to the CFR, CBN, Pandora and MSN projects, both at Olivetti Research and University of Cambridge Computer Laboratory. Of specific relevance to this paper Alan Jones, Dave Clarke and Gavin Starkey wrote most of the network and stream handling code on Pandora, Ian Wilson wrote the multimedia file server and C Ang carried out the performance measurements. Maurice Wilkes commented in detail on the manuscript.

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