VIDEO ON DEMAND: IS IT FEASIBLE?

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ABSTRACT

This short paper examines the technological feasibility of a "video on demand" service that is provided from a centralized location over a digital network. The video on demand service is considered to be a service similar to the currently popular video-tape rental services. The problem is divided into two parts: communications and database access. It is argued that the incremental communications cost is small, as long as one assumes that there is already a network with sufficient bandwidth to the customer. A solution to the database access problem is presented which could be implemented with technology available in no more than 10 years.

1. Introduction

Video on demand is a service many people currently believe cannot be economically provided over a digital network. This paper takes a qualitative look at a scenario in which a video on demand service similar to that provided by videotape rental stores today is provided from a central location. The paper is divided into several parts. First, the service is defined. Next, the technological assumptions are given. Finally, arguments are given for solving the communications problem (delivering the video to the customer from a centralized location), and the database problem (how do we store, copy, and access a large set of video files).

2. The Video On Demand Service

We will assume that the video on demand service is a relatively simple one. It is provided from a centralized location like the local central office. A customer can signal the network to select a movie, and the network will start transmission within a reasonable time. The customer can stop and continue the transmission. A coarse (non-visual) rewind and fast forward can also be provided, i.e. the customer could signal the network to rapidly move forward or backward some number of basic time units. All customers could choose to watch the same movie, with each customer having an independent "phase-shift" (i.e. each person is watching a different part of the movie). Alternatively, all customers could be watching different movies. Most combinations of numerous customers watching numerous movies with independent phase shifts are possible.

3. Technological Assumptions

There are a number of technological assumptions necessary to determine the technological feasibility of the video on demand service. The most important of these assumptions is the rate at which the video material is coded. Since technical advances in video coding are occurring at a high rate, it is difficult to make a single assumption which will hold true for a long period. However, some insight may be gleaned by observing the bandwidth of some standard digital network channels. Current North American telephony systems have a common digital rate of 1.544 Mbps. Recent advances suggest that it will be possible to extend this rate into the loop plant. In the broadband arena, SONET has emerged as a standard, with a basic channel rate of 51.84 Mbps. For examples in the remainder of the paper, we will assume two coding rates: NTSC video encoded into a 1.5 Mbps channel, and HDTV encoded into a 50 Mbps channel [1,3]. For numerical examples that are a function of the coding rate, we will give the NTSC and HDTV assumptions separated by a '/', i.e. the video coding rate is 1.5/50 Mbps.

In all cases, we are making the assumptions by extrapolating various technology trends no more than 10 years into the future. Thus, one can imagine this service being possible sometime before the year 2000.

3.1 The network

We assume that there is an installed base of customers, each with a connection to his home, and a television (possibly HDTV) which can be connected to the network. For the 1.5 Mbps NTSC service, the loop plant can be assumed to be an upgraded copper technology, while the HDTV scenario assumes a BISDN fiber loop. The fiber loop plant is assumed to be in a double star configuration, with a non-shared fiber running from the customer premise to a remote concentrator, and then some shared fibers running between the concentrator and the local central office. The central office switch in both cases is an ATM-based packet switch with multicast capability, and the centralized video database is connected to the local central office with a large number of loops [5]. The video database thus is either in the central office, or in a nearby facility that has a large amount of dedicated fiber bandwidth to the central office.

3.2 The video material

The video material is assumed to consist of a large number of movies, with a length of about 100 minutes each. The video may be stored on analog tape or video disk, but is converted into a digital stream at a constant rate of 1.5/50 Mbps. Lowering this rate due to coding advances is permissible, and it will reduce the cost of the system. The video is transmitted to the customer in digital form, and the customer is responsible for conversion from digital to display on his television.

As will be explained in the next section, a three-level memory hierarchy will be used to store the video database. The levels are: (1) a very large, long access, low transfer rate *library*; (2) a medium size fast quantized access *copier memory*; and (3) a per-user *stop-start buffer*.

The *library* sub-system can be thought of as a "video jukebox" which holds several thousand reels of tape or video disks, each containing a single movie.[1] The tapes can be loaded

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into a number of tape players that will output a digital stream at 1.5/50 Mbps. The jukebox would load tapes on demand into an available player. This could be done either with existing mechanical technology, or a group of operators who physically load and unload tapes as in large computer centers today. We also assume that the access time to a given tape that is not in a drive is reasonably short, no more than a couple of minutes. Tapes each contain 100 minutes of video material. This may vary, but for simplification is assumed to be constant in the rest of the paper.

The *copier memory* could be implemented as a group of digital read/write disk memories. We assume that a disk is large enough to store a significant fraction of a 100 minute movie, which holds 1.125/37.5 gigabytes (GB) or 100 minutes at 1.5/50Mbps. The other important parameter of the copier memory is its transfer rate. Section 4.1 will discuss the operation of the copier memory in detail, but for now let us arbitrarily require a transfer rate of 20 times the coding rate, or 30/1000 Mbps. For the HDTV example, this transfer rate will have to be achieved by operating the disk heads in parallel. If a disk has at least 20 heads, and a transfer rate of at least 50 Mbps per head, a constant transfer rate of 1000 Mbps can be produced.

The one gigabyte disks (for the NTSC implementation) with transfer rates of 30 Mbps are possible today, and indeed are offered commercially. The availability (for the HDTV implementation) of a magnetic 37 GB disk with a per head transfer rate of 50 Mbps can be predicted by extrapolating from recent technology trends. In 1980, the largest disk drive one could purchase was about 200 MB. In 1988, we could purchase disks holding approximately 2 GB, an annual increase of 33%. Extrapolating this trend would predict a 35 GB disk by 1998. The transfer rate (which is controlled by the linear bit density and rotational speed) of a single head is approximately 20 Mbps today. If we assume half of the increasing disk density comes from increasing the linear bit density, while the other half comes from increasing the radial density, and no change in rotational speed, then a 35 GB disk will have a per head transfer rate of 83 Mbps.

The *stop-start buffer* is a small FIFO buffer holding the amount of data that is under 2 heads of the copier memory. Assuming a 20 head copier memory, the stop-start buffer would need to hold 112.5/3750 megabytes (MB). It must also have a transfer rate of twice the coding rate, or 3/100 Mbps. Increasing the number of heads per movie on the copier memory would reduce in inverse proportion the size of the stop-start buffer. Thus, a 100 head copier memory (one 1.125/37.5 GB disk with 100 heads, or 5 0.225/7.5 GB disks each with 20 heads) would require a copy memory of 22.5/750 MB. At some point, as the number of heads in the copier memory becomes large, and the amount of video material under each head diminishes, the stop-start buffer may no longer be needed. The exact size and technology of the stop-start buffer would have to be determined at system implementation time, but it might be semiconductor RAM or a small disk.

3.3 The central office switch

Let us assume for the moment that the video database is attached to a single central office, which serves a region with 10,000 customers. Let us further assume that each one of them is watching a different video stream coded at 1.5/50 Mbps. This would require a switch capacity of 15/500 Gbps. Bellcore is currently constructing a 38.4 Gbps switching fabric (256 lines at 150 Mbps per line). Figure 1 shows a diagram of the 3-D packaging scheme for this switch, which is based on the Batcher-banyan technology [2,6]. This switch, with appropriate multiplexing extensions, could handle the NTSC application. Figure 2 shows a conceptual design of a 2,457 Gbps switch made up of 256 of the 38.4 Gbps switching modules. This switch has 16,384 bi-directional I/O lines operating at 150 Mbps per line, more than enough for our 10,000 customer HDTV central office. With the addition of a copying capability, this switch could operate at several places within the video database [5].

In summary, the technical requirements for the NTSC application are within our reach today. The HDTV application exceeds the capabilities of current storage and switch technology, but extrapolations of these technologies predict technical feasibility in less than 10 years.

4. System Architecture

The system architecture is shown in figure 3. The library, copier, and stop-start buffer are all connected to a central office switch, along with the customer loops and trunks. The library, being a read-only memory, can only transmit to the switch (it does receive control information from the switch). The copier has many more output lines than input, the ratio being determined by the number of heads per movie. Each copier disk has a single input, which would come from one of the library tape players. It has one output per head, thus a disk with 20 heads would have 20 outputs and one input. The stop-start buffers each have one input and one output. Inputs and outputs would probably be multiplexed up to the switch rate, which is likely to operate on a per line speed of 150 Mbps or higher.

Let us explain the operation of the video service by walking through a number of scenarios of increasing complexity. The first would be a single customer watching a movie that no other customer is viewing concurrently. The customer signals the network with his movie selection. The network signals the library to retrieve the appropriate tape, and insert it into a player. When the tape starts playing, the switch sets up a connection directly from the tape player to the customer loop. When he wishes to stop, reverse, or fast forward the movie, his signal is simply passed through the network to the appropriate tape player. This scenario is by far the simplest, since it is merely a centralized shared tape player. It is appropriate, however, for movies that are unpopular and have at most one person viewing them at a time.

Now, let us complicate the situation. Our customer (let's call him $customer_1$) selects a movie that is a little more popular. The system, knowing that there is a high probability of another customer overlapping $customer_1$'s viewing of the movie, decides to cache the movie in the copier memory. The network allocates a copier disk to this movie, and also signals the library to load the tape. The network then sets up a multicast connection, from the library tape to the copier disk and also to the customer. Our $customer_1$ is unaware that "his" movie is also being loaded onto a disk.[2]

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1. The decision on tape vs. video disk is not pertinent to the rest of this paper, and can be deferred until the system is implemented. For the rest of this paper, we will use the term "tape" to mean either analog video tape, digital video tape, or some video disk technology. If the recording technology is analog, we will assume it includes an encoder that produces a digital stream at 1.5/50 Mbps.

2. This isn't strictly true, since $customer_1$ can no longer fast forward the tape player. However, if we assume that a movie is read from a copier disk many more times than it is written, the number of people in $customer_1$'s situation is small. Alternatively, we can assume that information is moved into the copier memory in an off-line fashion (which could result in some blocking).

4.1 The copier memory

At this point, we must digress and explain the operation of the disks in the copier memory. For the HDTV case, let us assume each disk holds exactly one movie (37.5 GB), and has 20 heads operating in parallel at 50 Mbps each (exactly the coding rate of the HDTV information). The relative positions of all the disk heads are fixed, i.e. it is not possible to read two arbitrary parts of the disk simultaneously. The disk heads are moved, however, in a repetitive pattern, with the first head constantly reading the first 5 minutes of the movie, the second head reading the second 5 minutes of the movie, etc. Thus, the motion of the arm holding the disk heads (let us assume one head per surface), would be a slow spiral from the outside towards the center of the disk, taking exactly 5 minutes. When the head reaches the center of the disk, the arm moves rapidly to the outside of the disk and repeats. Each time the disk seeks back to the outside, the relative positions of the outputs are switched in a circular fashion: i.e. if $output_1$ was reading from $head_1$, it now reads from $head_2$. In general, if $output_i$ is connected to $head_j$ before the seek motion, it will be connected to $head_{(j+1) mod\ 20}$ after the seek. We also assume that there is a small smoothing buffer connected to each output, which prevents an interruption in the data stream during seeks. Thus, a disk with 20 heads is producing 20 different versions of the same movie, each with a 5 minute phase offset. The size of the phase offset can be controlled by adjusting the number of heads per movie. This could be accomplished either by changing the physical disk design, or by spreading the movie across more disks, each with a smaller capacity.

The NTSC case, because of the vastly different ratio between the per-head transfer rate and the coding rate, would require a slightly different layout. As an example, one disk currently marketed has a capacity of 637 MB, with a sustained transfer rate of 81.6 Mbps (this is done with 4 heads operating in parallel). If a movie was stored on two drives, a sustained transfer rate of 163.2 Mbps would be available. At 1.5 Mbps per channel, 108 different channels could be read simultaneously (this requires a 108-way interleaving of the information on the disk). With the addition of some smoothing buffers, we would have the equivalent of 108 heads per movie, with the phase difference between heads of only 56 seconds. The heads would sweep each disk every 56 seconds.

Back to our customer scenario. Some time after $customer_1$ requests the more popular movie, $customer_2$ requests the same movie. There is an arbitrary phase relationship between $customer_1$ and $customer_2$. Since the disks are constrained to have a fixed phase relationship between the heads, we must ask $customer_2$ to wait. $Customer_2$ will wait until the next time the disk holding his movie switches heads.[3] At this time there will be a head over the exact beginning of the movie, and $customer_2$ will be connected via the switch to the appropriate head on the disk playing his movie. If $customer_3$ also requests a connection at about the same time, the network simply sets up a multicast connecting $customer_2$ and $customer_3$ to the same head.

Using just the library and copier, we now have a rough service that can supply movies to a large number of customers (limited only by the number of disks and the size of the switch). The customers, however, must be brought into a fixed phase relationship, with the granularity controlled by the number of heads per movie, in our examples 56 seconds or 5 minutes. If the movie is completely on a disk, customers could even fast forward or rewind, in increments of the phase difference between heads, by signaling the network to connect them to another head. Any number of customers could be connected to a single head, limited only by the physical dimensions of the switch.

4.2 The stop-start buffer

The stop-start buffer is used to allow the phase relationship between various customers, initially fixed at the start of a movie, to change during the course of a movie due to the customer requesting a pause in the presentation. Suppose our $customer_2$ above requests the network to stop presentation, and then a short time (relative to the phase difference between heads) later requests that the movie continue from where it left off. At the time the movie is stopped, the network selects an idle stop-start buffer from a pool attached to the switch, and directs the transmission from the disk into this buffer. Then, when $customer_2$ restarts the movie, his transmission will now come from the head of the stop-start buffer, while transmission from the disk continues into the tail end. The stop-start buffer is now operating as a FIFO queue, of the proper length to achieve the desired phase shift between $customer_2$ and the disk heads. Pauses longer than twice the head phase difference can be handled with a combination of the stop-start buffer and a head change. The stop-start buffer could also allow the customer a limited visual rewind or fast forward. The maximum size for the stop-start buffer is fixed at twice the head phase difference, 112/600 seconds or 21/3750 MB in our examples. Note also that the bandwidth required of the stop-start buffer is twice the coding rate of the channel, or 3/100 Mbps in our examples.

The stop-start buffers must be allocated on a per-user basis, and under worst case conditions might gain little from existing as a shared pool. They also use considerable amounts of switch bandwidth. It is therefore reasonable to consider placing the buffer in the customer's television or digital decoder.

5. System Tradeoffs

The preceding sections have given a very qualitative discussion of a video on demand system. Quantitative studies will require considerably more information on the costs and performance of the various technologies involved, as well as the statistics of customers' viewing habits. However, in this section we would like to point out some of the tradeoffs that might be possible.

One tradeoff not previously discussed is the placement in the network of the video on demand system. The system is capable of supporting a very large number of users, assuming that there is a large commonality in the movies they would select, i.e. that there is a limited set of movies that many people would watch simultaneously. Consider for a moment placing the video on demand system at a central point in a LATA rather than at each class 5 office. If we assume some average statistics for a LATA: 625,000 customer homes per LATA, 60 class 5 offices per LATA, 2000 movies available, then an interesting tradeoff becomes possible. Suppose we eliminate the library and stop-start buffers, and simply keep all 2000 movies on disk. If we assume a $10,000 cost per disk, the cost of the video database would come out to $32 per customer home (loop), a small fraction of the cost of the fiber loop and loop electronics[4] .

3. Alternatively, each disk could contain a "leader" track that would contain a video sequence of a clock counting down the time to the beginning of the movie. Since a customer will not mind missing some of the count down, the network could simply connect him to the head playing the leader at the time he requests the movie. Our customer will then see a count down that starts at some arbitrary point, in our 20 head example between 0 and 5 minutes. Appropriate muzak might also be played, or some advertising inserted.

To this would be added the increased cost of transmitting from the centralized site (probably a tandem office) to the class 5 offices. Assume as a worst case that every phase of every movie is multicast to every class 5 office in the LATA. This would require a maximum of 324/2,000 Gbps transmission installed in a star fashion from the tandem to each class 5 office.[5] If the fiber is not shared, this number would probably be reduced by at least a factor of four, since there are only about 10,000 customer homes per class 5 office, but 216,000/40,000 independent phases coming out of the disks. Thus we might see a increase of 15/500 Gbps transmission bandwidth to each class 5 office. The switching bandwidth would be increased in the tandem office, but would remain unchanged in the end office. The tandem office would require some 216,000/40,000 inputs at 1.5/50 Mbps each, and 937.5/31,250 Gbps of output bandwidth, consisting entirely of multiple copies of the inputs (this assumes no copying in the class 5 offices). While this is a large switch, it is by no means impossible in the 10 year time frame.

One of the interesting points would be to examine the cost of providing a broadcast TV service in addition to the tandem video on demand service described in the last paragraph. Broadcast TV could be thought of as simply another 10-100 channels added to the thousands of channels provided from the copier memory system. This addition would have a negligible impact on the total system cost.

6. Conclusions

In this memo we have tried to make a case for the technical possibility of a video on demand HDTV system which could be provided from a central location like a class 5 or tandem office in the BISDN network. Assuming a video coding rate of 50 Mbps, we may require the availability of 37.5 GB disk drives, multi-terabit (1Tb = 1,000 Gb) switching systems with copy capabilities, and inexpensive buffers with about 4GB of capacity. It may be possible to supply a relatively large portion of the country with a video on demand service from as few as 100 installations. While the performance required of some components may seem excessive, extrapolation from current technology trends suggests their availability around the year 2000. Quantitative economic studies should be performed to determine the economic feasibility of such a system.

If we assume a video coding rate for NTSC of 1.5 Mbps, the requirements on the disk drives (1.1 GB), switching systems (15 Gbps), and buffers (22 MB) are well within today's capabilities. It should be possible to construct a laboratory prototype today.

4. And not much different from the cost of joining a video rental club today.

5. It might be possible to use a broadcast WDM system to distribute the information to the class 5 offices.

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3D Network

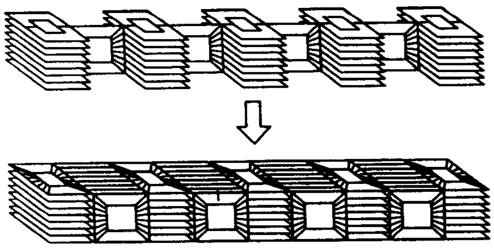

Figure 1

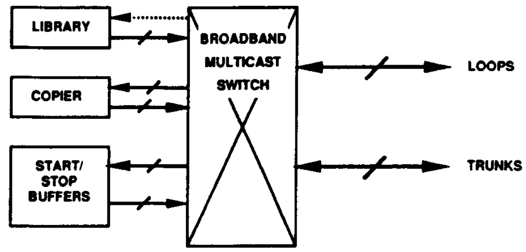

Figure 3

Broadband Packet Central Office

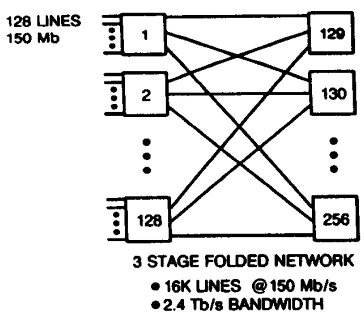

Figure 2