Providing VCR Functionality in a Constant Quality Video-On-Demand Transportation Service

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Abstract

Bandwidth smoothing techniques for the delivery of prerecorded compressed video have been shown to be effective in reducing the network bandwidth required for video playback, however, can limit the ability of the user to interactively modify the playback in the manner familiar from VCR operations. In this paper, we examine the impacts that VCR functions have on the smoothed delivery of stored video. We introduce the notion of VCR-window, which allows users to have full VCR functionality in a limited window while not requiring increases in the bandwidth reservations. In addition, we introduce a resource reservation scheme that can be used with the VCR-window for the delivery of stored video. To test the applicability of the VCR-window in video-on-demand systems, we have digitized 15 full-length movies for experimental data. Our results indicate that time-limited VCR functionality can be provided while retaining a fairly high network utilization.

1. Introduction

The delivery of constant-quality compressed video requires that the network adapt to large fluctuations in bandwidth. Bandwidth smoothing techniques have been shown to be effective in removing burstiness, making network resource scheduling simpler, but at the expense of added delay and requiring additional buffering [10,15,16]. For live video applications, the benefits of smoothing are constrained by the requirement that latency remain low between video capture and video playback. Stored video applications, on the other hand, have two major advantages over live video network scheduling. First, a priori knowledge can be used to smooth out the stream to the extent that the buffer will allow, trading buffer bandwidth for network bandwidth. Second, the scheduling of the network bandwidth can be done well in advance of the playback of video. The use of advance reservations in such schemes, however, has implications for the ability to provide users with familiar video cassette recorder (VCR) functionality such as stop, rewind, and fast forward.

For constant quality video delivery, the video bandwidth requirements can be smoothed by prefetching data into a buffer, shifting bursts of large frames forward in time. Depending on the amount of buffering available, a frame may sit in the client’s smoothing buffer for a shorter or longer time before it is played back. Long buffer residency times are required to reduce high peak bandwidth requirements. Despite long buffer residency times, the rate of transmission and the rate of consumption remain coupled. Alterations in the consumption rate that occur with VCR functions require alteration in the video delivery plan, lest the buffer overflow or underflow. A video-on-demand (VOD) system must effectively handle the contradictory goals of smoothing versus responsiveness.

For VOD systems with little or no buffering, the clients and servers must be tightly coupled. Any change in consumption of video data from the client must be immediately and continuously handled by the server. With buffering, changes in consumption still require an adjustment by the server. These adjustments, however, need not be made instantaneously. Many operations can be performed without requiring the delivery of any new data from the server. Larger buffers allow greater latitude in handling these stops, starts, and rewinds. With excess buffering specifically used for handling variations in consumption rate, it is possible to further decrease the required disruptions of the server by combining the changes in consumption into a few requests. The number of disruptions that the servers must handle will be proportional to the buffer size used. If a majority of the rate changes can be handled by the client machine, then the network and servers can devote their resources to the handling the special cases that may arise instead of handling cases that can be taken care of with appropriate buffering.

In this paper, we present a framework for providing...
VCR functionality and advance reservations of bandwidth within a bandwidth-smoothing, stored-video environment. We introduce the notion of VCR-window, the set of buffered frames within which, full-function VCR capabilities are available without requiring changes to the bandwidth reservations made. The size of the VCR-window is determined by the size of the client buffer. We expect that for reasonable buffer sizes a large proportion of VCR operations can be handled from the VCR-window, with the remainder requiring more involved client and server interactions. The VCR-window affects the way in-advance reservations can be handled. We discuss the impact of providing VCR functionality on a priori bandwidth reservations and present a reservation system for interactive VOD systems. Our results show that the VCR-window can be effectively implemented with a small amount of additional buffering and result in high bandwidth utilizations.

In the next section, we present some background material, along with further motivation for investigating the problem of providing VCR functionality in bandwidth smoothing environments. In Section 3, we describe the VCR-window and a resource reservation scheme for stored video applications. In Section 4, we present our experimental results based on the 15 digitized movies, along with a videotaped one-hour seminar. We finish with some conclusions and directions for future work.

2. Background and Motivation

2.1. A Basic Video-On-Demand Architecture

Our basic VOD system architecture consists of three main components: video servers, a network, and clients (see Figure 1). A server typically handles large fast disks that deliver video to the clients [1,14,18]. These servers may also be part of a hierarchical video distribution system where less frequently requested video data is served from a tertiary archival server consisting of low cost storage devices, such as tape or optical jukeboxes [7]. The network provides the pathway between the video servers and their clients. The only assumption we make about the network is that it can provide network resource guarantees based on either some rate-based or real-time channel approach [2,23]. We also assume that the network provides some mechanism for in-advance reservations of bandwidth [5,13,22]. The clients consist of either desktop computers with support for digital video or a set-top-box devoted solely for viewing compressed video. We assume that clients have buffering available (either disk or RAM) for smoothing of network bandwidth requirements.

2.2. Bandwidth Smoothing Techniques

Bandwidth smoothing techniques fall into two broad categories: window-based and unlimited-lookahead bandwidth smoothing. Window-based smoothing techniques result in smoothing that occurs over some fixed interval [16,15]. Because the bandwidth smoothing is constrained to a fixed interval, these techniques are useful for systems where the delay between the transmission and playback of a frame must adhere to some maximum delay requirement. Thus, window-based smoothing is particularly suitable for use in live video-conferencing applications because they result in a maximum delay equal to the window size. For prerecorded video, however, one need not be restricted to smoothing within a fixed window.

Unlimited-lookahead smoothing techniques, such as the Critical Bandwidth Allocation (CBA) algorithm [9,10], smooth bandwidth requirements based on the a priori knowledge available about videos in stored video applications. The CBA algorithm constructs a bandwidth allocation plan that consists of runs, each with a constant bandwidth allocation requirement. The CBA results in plans for the continuous playback of video that have (1) the minimum number of bandwidth increases, (2) the smallest peak bandwidth requirements, and (3) the largest minimum bandwidth requirements. The Optimal Bandwidth Allocation (OBA) algorithm creates bandwidth plans for the delivery of stored video that, in addition to the CBA properties, have the fewest number of bandwidth changes possible given the client-side buffer size[11]. For our discussions, we use the digitized movie Speed and a video we call Seminar. The Seminar video was recorded at a talk presented at our department. The video consists of the speaker standing next to an overhead projector presenting their work. As shown in Figure 2, the bandwidth allocation plans generated by the OBA result in very few required bandwidth changes for the playback of the videos. Note, the bandwidth plans generated by the CBA and OBA algorithms do not require any prefetching before the playback of the videos begin, hence, a high initial bandwidth may be required (as in the Seminar video). If the video request is made in advance, this initially high bandwidth requirement can be removed by prefetching data before the start of playback of the video.
Figure 2: Video Examples

It is important to note that the Seminar and Speed videos are Motion-JPEG encoded, thus, they do not take advantage of temporal similarities between frames. This results in rather conservative estimates of buffering and bandwidth requirements. In general, using MPEG encoded video streams instead of Motion-JPEG encoded video streams results in smaller buffer requirements or in greater buffer occupancy times. The amount of buffering required to achieve the same amount of smoothing for MPEG encodings using B and P frame types can be expected to be 4 to 10 times smaller.

2.3. Buffering Versus Delay

Using the CBA or OBA bandwidth smoothing techniques results in a trade-off between buffering and delay. To smooth large frame-size peaks such as those found at the end of the Seminar video (see Figure 2), the data in the burst must be prefetched before the peak is played back. As a result, the buffer residency times (the time that a frame sits in the buffer) can be fairly substantial. The buffer residency times for the videos Speed and Seminar using the OBA plans from Figure 2 are shown in Figure 3. The buffer residency times are correlated to the amount of buffering used for smoothing. That is, the larger the buffer used, the higher the buffer residency times tend to be. The amount of time a frame spends in the buffer can be on the order of half a minute to a minute for a 20 MB buffer. For the Speed video, a larger variation in frame sizes throughout the movie results in buffer residency times that also vary more. For the Seminar video, the stream consists of roughly the same size frames except at the end where a larger bursts of frames occur. As a result, large buffer residency times are required to smooth out the large frame sizes at the end of the video. Incidentally, the end of the Seminar video consists of the lights turning on, a panning of the speaker toward the center of the room, and a short question and answer session that included the first row of listeners.

The large buffer residency times introduced by unlimited-lookahead smoothing techniques have a direct impact on the ability to provide users with VCR capabilities. If changes in consumption rate are allowed (while keeping the video quality constant), the network may have to contend with a large burst in the bandwidth required above that originally allocated. This large burst of extra bandwidth may be needed to make up for the absence of buffering (and delay) that ordinarily reduce the bandwidth requirements. Thus, providing VCR capabilities in a bandwidth smoothing environment can be a difficult task.

3. A Constant Quality VOD Service

Any VOD system must bring together several interrelated issues such as disk scheduling at the server, reserving underlying network bandwidth, and charging users for network usage. In systems that deliver constant quality video using bandwidth smoothing to reduce peak bandwidths, changes in consumption rate have the potential to cause buffer overflow or underflow. Yet frequent adjustments in
bandwidth allocations are undesirable. In this section, we describe a VOD service that has several key features: constant quality video delivery, VCR functionality (the VCR-window), and reservations in advance.

3.1. VCR Interactivity

In a bandwidth-smoothing VOD system, limited network resources may make it impossible to exercise unconstrained full-function VCR capabilities without incurring significant delays. By looking at the expected interactions during the playback of video, however, the VOD system can be designed to take advantage of the expected interactions. We believe that VOD users typically change the access pattern during the playback of a video that fall into one of the four categories:

- *Pause/Stop* - user stops the movies for a short time to answer a phone call, etc.
- *Rewind* - user rewinds the video to play back part of the video that they did not understand
- *Examine* - user stops the VCR to examine more closely a portion of the video. As an example, a user may be watching a football game and wants to see a certain play a couple of times in slow motion to see why it did or didn’t work.
- *Fast forward scan* - user scans past parts of the video such as commercials in the program.

We believe that users may want all of these functions from a VOD system, although the actual distribution of access patterns within these categories may change. For example, consider the operation fast-forward scan, which is frequently used to fast-forward through commercials. If all users are going to fast-forward through commercials, then it would defeat their purpose. We would expect that in such an environment that commercial messages may become a service, whereby, the video providers allow users to access commercials by companies on demand. While operations such as fast-forward will require more complex interactions, we expect that many of the accesses will be in a localized area within the video, therefore, providing a limited window of full function VCR capabilities may suffice for most applications. As a result, using the client’s local buffer to service a majority of the interactions results in bandwidth requirements that need not be altered, while minimizing the number interactions with the server and the network.

3.2. The VCR-Window

To allow for VCR functionality, we propose a different model of video delivery, which allows users to have full function VCR controls in a limited window called the VCR window. In our model of video transfer, we allow all VCR functions to occur at anytime within the course of playback but limit the range of accessible data without renegotiating the reserved bandwidth. We define the point of play (POP) to be the furthest frame in the video that has been viewed by the user and the point of transmission (POT) as the furthest frame in the video that resides in the client buffer. Our model then consists of viewing the buffer as a circular buffer, in which, the POP and POT traverse the circumference in a clock-wise manner (see Figure 4). During the delivery of video to the client, the POT will always be ahead of the POP. In addition, the distance the POT is ahead of the POP will be the amount of buffer space used for prefetching. The remaining part of the circumference, the rewind area, is the amount of data that has been played back and is still in the buffer. Thus, when the buffer is nearly full, the rewind area will be very small. Note, if the POT ever passes the POP or the POP passes the POT, we have buffer overflow and buffer underflow, respectively.

Using these definitions, we make the observation that we can allow the user to have full function VCR capabilities in the area that the POP leads the POT without changing the bandwidth reservation level. One major drawback of this method is that when the buffer is nearly full the POP will not lead the POT by any significant amount. To ensure that the rewind area has some minimum amount of data, we define the rewind buffer to be the closest distance that the POT can approach the POP (see Figure 5). For clarity, we continue to refer to the distance that the POP leads the POT as the rewind area (or the VCR-window). Figure 5 shows the resulting two cases when the buffer is full and when the buffer is empty.

Formally, we define the amount of available data in the rewind area on the ith frame, \( RBS(i) \), as

\[
RBS(i) = MaxBuff - \sum_{j=0}^{i} (BwAlloc(j) - Frame(j))
\]

where,

- *MaxBuff* is the maximum buffer size including the rewind buffer.
\begin{itemize}
\item $BwAlloc(k)$ is the bandwidth allocation on frame $k$. Note, we assume that the bandwidth allocation plan is allocated in bytes/frame.
\item $Frame(k)$ is the size of the $k$th frame.
\end{itemize}

This equation takes the difference between the total bandwidth received and the total bandwidth played back (i.e., the amount of data in the buffer) and subtracts it from the amount of buffering available. This equation does not, however, calculate the amount of video that is actually available but calculates its aggregate compressed size. We can calculate the amount of rewind buffer needed to have $T$ frames available in the buffer on the $i$th frame as

$$AddBuffReq(i, T) = \sum_{k = \max(0, i - T)}^{i} Frame(k) - RewBuffSize(i)$$

This equation is essentially the size of the $T$ frames needed in the rewind area with the amount of data already in the rewind area subtracted. If the user requires that 100% of the time the buffer has $T$ frames in it, then the additional amount of buffering needed is simply the maximum $AddBuffReq(i)$ over all frames within the movie. That is, to ensure the buffer always has $T$ frames in the minimum buffer requirement $MinBuffReq(T)$ is:

$$MinBuffReq(T) = \max_{T \leq j \leq N} AddBuffReq(j, T)$$

Note that since the video is stored, these calculations can be calculated off-line.

To allow for VCR capabilities, when a user starts moving in the rewind area, the data flow from the server is stopped. The flow is then restarted only when the playback point reaches the POP. Thus, only two interactions to the server and network are required to support the VCR-window, one to stop the data flow, and one to start the data flow again. Because the delivery of bandwidth starts at exactly the same point in which the data was stopped, no changes in the bandwidth reservation level will be necessary while allowing for a small window of full function VCR capabilities. For long term bandwidth reservations, the only modification necessary will be the extension of the bandwidth requirement by the amount of time that was spent in the rewind area. Using this model for VCR functionality, the operations stop/pause, rewind, and examine can be provided to users. As an example, consider the bandwidth allocation plan shown in Figure 6. At time $t$, the user decides to stop the playback and examine the video that was just played. Suppose that the total time it takes for the user to examine the video and get back to time $t$ is $t'$ time units. We then simply move all bandwidth allocations after the time $t$ in the original bandwidth allocation plan to start at time $t'$, the time at which playback started again. Note, by shifting the bandwidth allocation plan after time $t$ by $t'$ time units, the resultant bandwidth reservation has been modified and can be accounted for with appropriate bandwidth reservations as will be discussed later.

3.3. Access Outside the VCR-Window

Scans to points outside the VCR-window require renegotiations with the network and server. For long fast-forwards, the consumption rate originally anticipated may now be compressed in time, resulting in the need for more bandwidth than was originally reserved. These interactions may not occur very frequently, nonetheless, they should not be disallowed. For the renegotiation of bandwidth reservations in these cases, contingency channels which save part of the network bandwidth for renegotiation purposes are useful [4]. In addition, the application of the CBA techniques can help determine the minimum bandwidth required from the contingency channel for renegotiation. Because the VCR-window filters many of the interactions that are required through buffering, the contingency channels can be more efficiently allocated to handling the special cases that may arise.

3.4. A VOD Resource Reservation Scheme

Resource reservations are important for network management for both in-advance and on the fly reservations because the network can then accurately track expected bandwidth requirements. For stored VOD services, the ability to provide reservations of bandwidth in advance can make the job of resource allocation easier[17]. Resource reservation schemes have two key components that are necessary for resource reservations: the bandwidth requirement (level) and the duration that the bandwidth requirement is needed [13,5,22]. Without providing these, resource reservations in-advance then becomes a difficult task. In addition, as Ferrari, Gupta, and Ventre have pointed out, scheduling of bandwidth based on some fixed interval reduces the fragmentation with which the reservation scheme has to contend[13]. Finally, it is commonly agreed upon that advance reservations consist of two distinct phases, an admission control phase where the reservation is admitted and an enforcement phase where the bandwidth allocation is enforced.

Our in-advance reservation model is a slotted reservation scheme in which bandwidth is reserved in 30 second slots. The client creates a bandwidth allocation plan based
on the slot boundaries and then passes this plan to the server and network for admission control. The network managers then compare the bandwidth requirements of the new channel and compare it to the available bandwidth allocation plan offered by the user. The example in Figure 7 shows sample requests that may be sent to the network manager. By using 30 second bandwidth allocation periods, the network manager only needs to evaluate 180 slots for a 90 minute video, reducing the complexity of the admission control algorithm. The network manager then allocates the available resources to the new channel if available. If the available bandwidth does not exist, then the network manager might either offer a new starting time which can satisfy the bandwidth allocation plan or find a different network path that can satisfy the request. Handling of these conditions is beyond the scope of this paper.

Passing bandwidth plans to the network manager as part of admission control creates rigid schedules. To allow VCR-window functionality, the resource reservation system must reserve bandwidth based on the maximum amount of “VCR-time” to be introduced by the viewer. The total time that the video can be delayed must be declared at admission control. The actual amount of VCR-time delay reserved depends on the guarantees that the user expects and the quality of service expected if the delay bounds are exceeded. The amount of VCR-time reserved may be also determined by economic factors (i.e. how much users are willing to pay for bandwidth that they may not use). For now, we assume the worst case for this delay, in that, all of the delay can occur at any interval. Therefore, in the calculation of the bandwidth allocation plan used for admission control, we create a bandwidth allocation plan that reserves the data such that at each point within the movie the video can be stopped for the maximum delay. Figure 8 shows a sample bandwidth allocation plan calculation that has the expected VCR-induced delay built into the bandwidth allocation plan.

4. Experimentation

The success of the VCR-window concept depends on how much data is available in the rewind area at a given time as well as the amount of buffering required for use as the rewind buffer. As the amount of buffering devoted to the rewind buffer increases, the amount of smoothing available diminishes. The success of the reservation system will depend on the effectiveness of the VOD system to utilize its bandwidth. In order to fully understand the impact of buffering on the VCR-window and the associated in-advance reservation system, we have digitized 15 full-length movies and the video we have called Seminar. Due to space constraints, we present only 10 of the videos here. A more in-depth discussion about the testbed used to capture the video and the experimental results that these produced can be found in our technical report [12]. The Motion-JPEG compressed videos generally had an encoding of 2 to 3 Mbits/second.

4.1. VCR-Window Experimentation

Using the CBA or OBA algorithms with a reasonably large buffer, the number of times when the buffer is full (and therefore limiting the rewind area) tends to be small. Thus, very little additional buffering for use as a rewind buffer may be required.

Figure 9 shows for an amount of time, x, the probability that the rewind area has x amount of video in it for a 25 and 50 Mbyte buffer with the rewind buffer size set to 0. Adding more buffer for smoothing bandwidth requirements stretches the probability curve further in time, while the addition of buffer specifically as a rewind buffer shifts the entire curve to the right. For the Speed video, using a 25 MByte buffer results in having over half a minute of video in the rewind area 53% of the time while using a 50 MByte buffer results in having over half a minute of video in the rewind area 75% of the time. In addition, 15 seconds of video is available 74% and 91% of the time for the 25 and 50 Mbyte buffers. As shown in Figure 10, the percentage of time that the rewind area contains more than 30 seconds of video for the rest of the video data exhibit similar numbers as well. Typically, the 25 and 50 MB buffers result in the rewind area having 30 seconds of video 45-60% and 75-90% of the time, respectively.

The addition of a rewind buffer shifts the histograms of buffer rewind times to the right, thus increasing the amount
of time that is available in the rewind area. Figure 11 shows, the amount of buffering needed for the rewind buffer size in order to have the rewind area contain a certain percentage of video in the rewind buffer greater than 15 and 30 seconds. Note, these buffer rewind sizes are in addition to the 25 and 50 MByte buffers used for the smoothing of bandwidth requirements. The lines for the same time (15 and 30 seconds) approach the same required rewind buffer size because this buffer size is determined by

the same point within the video. In addition, the amount of required rewind buffer space decreases as the size of the smoothing buffer increases. This is mainly due to the larger buffer sizes having more rewind area on average. In order to achieve at least 15 seconds of video in the rewind area 95% of the time for the movie Speed, only 4 and 2 MBytes of rewind buffer were required for the 25 and 50 MByte smoothing buffers, respectively. The Seminar video approaches the 100% line faster than the Speed video, due to its smaller (and more constant) average bit rate.

Figure 10 shows the percentage of time that 30 seconds of movie is available when using an 8 MByte rewind buffer. The smallest bit rate videos (E.T and Crocodile Dundee) result in the highest percentage of rewind times. This suggests that the rewind size is roughly correlated to the average bit rate of the encoded movie. Thus, we expect that the use of tighter encoding schemes such as MPEG with B and P frames to reduce the overall requirement of the rewind buffer size.

4.2. Bandwidth Reservations

For bandwidth reservations, one of the main concerns is the actual network utilization versus the amount of bandwidth that was allocated. Because of the relatively long constant bandwidth allocations, the OBA algorithm (with prefetching on the first run) yields plans that utilize nearly all the bandwidth reserved based on 30 second slots and
Figure 12: Reservation Utilization

Figure 12 shows the bandwidth utilizations for plans that have 5 minutes of VCR-time built into the reservation plans. As shown by the graph, even with the 5 minutes of VCR-time built into the plans (as in Figure 8), all the movies result in utilizations greater than 90% for a 30-second periodic bandwidth reservation. To establish a “lower bound” on the expected network utilization for individual plans, we modified the bandwidth allocation plans to have both the peak bandwidth reservation for the entire video with the 5-minutes of expected VCR induced delay and no additional rewind buffer. Thus, the peak bandwidth allocation makes the reservation for the entire movie as one constant bandwidth reservation. We then graphed the expected bandwidth utilization based on these peak bandwidth allocations instead of the bandwidth reservations. As shown by Figure 12, the bandwidth utilization drops from the utilizations based on the periodic scheduling boundaries. For bandwidth plans that use a 25 MByte smoothing buffer, no rewind buffer, and have an extra 5 minutes of delay in the bandwidth reservations, the movie Speed has a utilization of 90.7% while the Seminar video has a utilization of 92.7%. Thus, even for peak bandwidth reservations with 5 extra minutes reserved, we expect that the bandwidth utilization can be held fairly high. The peak bandwidth reservations do not affect the Seminar video as much as the Speed video because it has less variation between frame sizes resulting in smaller peaks when then occur. The 25MB buffers are affected more because they cannot remove the peak burstiness as much as with a 50 MB buffer. Nonetheless, they exhibit fairly good utilizations. The video Beauty and the Beast video is affected the most by using a peak bandwidth reservation. The reason this occurred is that a peak of very large frame sizes could not be overcome with smoothing in a small area within the movie. We expect that these singular peaks can easily fit into the valleys of other bandwidth allocation reservations. Some movies exhibit no change in utilization from the reservation utilization to the peak reservation utilization. In these cases, the amount of buffering in the reservation utilization is enough to remove almost all of the burstiness and thus does not get affected as much by using the peak bandwidth requirement. In general, however, the overall expected bandwidth utilization of the network can be expected to be fairly high.

5. Conclusion

In this paper, we have introduced the notion of VCR-window, which allows a user to have full function VCR capabilities within a constrained region by adjusting the bandwidth allocation in advance. We have also shown that providing 30 seconds of video available for 90% of the time can be implemented with a small amount of additional buffering, even for loosely encoded Motion-JPEG video. We expect that the majority of interactions that occur during the playback of video can be accounted for by using this technique. For users who want a guarantee of some amount of video always available in the rewind area, the required rewind buffer size is determined by a few frames within the movie. For users who are willing to settle for lesser guarantees during the examine or scan phases, the VCR functionality can always be provided by the server which can fit the required video into the reserved channel capacity. Work on supporting scan operations from the server can be found in [3,6,21], while modifying compressed video to fit within a specified channel capacity can be found in [20].

We have also presented a slotted, in-advance resource reservation scheme to be used in conjunction with the VCR-window. The OBA algorithm results in very high network bandwidth utilization even under slotted scheduling boundaries. This is mainly due to the OBA algorithm minimizing the number of bandwidth changes as well as the peak required bandwidth. Using the advance reservation scheme in conjunction with the optimal bandwidth allocation algorithm, allowing users 5 to 10 minutes of “VCR-time” can be provided with a fairly high network utilization. We can expect that the lower bound for network utilization will be at least 80 percent.

In the event more “random” access patterns are required such as jumps or scans of more than a couple of minutes in the video, renegotiation of bandwidth will most likely be required or the reservation of bandwidth higher than actually used. For random accesses, it is probably more beneficial for the underlying network services to use approaches
found in live-video applications or reserve part of the bandwidth for contingency channels that are used in the “difficult” cases. The size and magnitude of these contingency channels will depend on the percentage of times that the users in the video-on-demand system stray from the VCR-window. While we expect that the frequency of these occurrences will be quite small, the video-on-demand system should provide this flexibility. Finally, for random accesses, the use of indexing schemes to allow access at distinct points within a video may allow the bandwidth requirements to be handled in a more efficient manner for accesses outside the VCR-window.

6. References


