5) If $C_B \geq C_B{}^o(\lambda)$ [or $C_B \geq C_B{}^h(\lambda)$], find the next singular λ using the current solution which corresponds to $C^o(\lambda)$ [or $C_B{}^h(\lambda)$]. Then, go to step 2.

6) If $M_T = \sum_{k=1}^{M} R_k(b_k^o) \leq C_M$ the set of all video streams can be supported by the video server, otherwise the set cannot be supported.

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This set is non-empty if ${b_k}^o + 1 \le q_k$. Also, define the set

$$M^I = \{k \in \{1, \dots M\} | S_k^I \ne \varnothing\}.$$

This defines the set of all resource relations for which an increase in bandwidth is possible. Then, the singular value

λ_1, which is necessarily the closest to λ from below is given in terms of λ by

$$\lambda_1 = \max\left\{ \frac{R_k({b_k}^o(\lambda)) - R_k(b_k)}{b_k - {b_k}^o(\lambda)} \middle| k \in M^I, b_k \in S_k^I \right\}.$$

Lemma 2: Let λ_2 be singular, $\lambda < \lambda_2$, and $\vec{B}^o(\lambda)$ a common solution associated with λ and λ_2. Define the set

$$S_k^D = \{p_k, \dots b_k^o - 1\}.$$

This set is non-empty if ${b_k}^o - 1 \ge p_k$. Also, define the set

$$M^D = \{k \in \{1, \dots M\} | S_k^D \ne \varnothing\}.$$

Then, the singular value λ_2, which is necessarily the closest to λ from above is given in terms of λ by

$$\lambda_2 = \min\left\{ \frac{R_k(b_k) - R_k({b_k}^o(\lambda))}{{b_k}^o(\lambda) - b_k} \middle| k \in M^D, b_k \in S_k^D \right\}.$$

The last two lemmas say that by knowing a singular value, the next from below or from above can be found, and thus, all singular values and all solutions $\vec{B}^o(\lambda)$ can be located.

We can now present the optimal resource reservation algorithm used in section 9:

1) Obtain an initial value of λ.

2) Solve the unconstrained problem. If λ is not singular, there is only one such solution and one constraint $C_B^o(\lambda)$. If λ is singular, then there are at least two different solutions. Find the two solutions from $\{\vec{B}^o(\lambda)\}$ with greatest and smallest constraints denoted by ${C_B}^l(\lambda)$ and ${C_B}^h(\lambda)$, respectively.

3) If the desired constraint C_B is such that ${C_B}^l(\lambda) \le C_B \le {C_B}^h(\lambda)$, then obtain all solutions in $\{\vec{B}^o(\lambda)\}$ and find the one for which the constraint, denoted by ${C_B}^a(\lambda)$, is the closest to C_B from below. If $C_B = {C_B}^a(\lambda)$, an exact optimal solution has been found. If not, an approximate solution has been found. Go to step 6.

4) If $C_B \le {C_B}^o(\lambda)$ [or $C_B \le {C_B}^l(\lambda)$], find the next singular λ using the current solution which corresponds to ${C_B}^o(\lambda)$ [or ${C_B}^l(\lambda)$]. Then, go to step 2.

$C_B^o(\lambda)$ that equals C_B. The key question then becomes the problem of finding the corresponding λ efficiently. This forms the main portion of the optimal resource reservation algorithm.

The crucial point in solving the unconstrained problem is that the solution is obtained by minimizing each term of the sum separately.

If $\vec{B}^o(\lambda)$ is the solution to the optimization problem, we denote by $b_k{}^o(\lambda)$ the kth component of $\vec{B}^o(\lambda)$, and define $S_k = \{p_k, p_k + 1, \ldots q_k\}$. Then $b_k{}^o(\lambda)$ solves

$$\min \{R_k(b_k) + \lambda \cdot b_k | b_k \in S_k\}.$$

Given λ, one can solve for all $b_k{}^o(\lambda)$, sum them all up to get $C_B^o(\lambda)$, and then compare this value to the desired constraint C_B. If $C_B^o(\lambda) = C_B$, the desired solution has been found. Note that $b_k{}^o(\lambda)$ may not be unique. Therefore, the solution $\vec{B}^o(\lambda)$ is also not necessarily unique.

The following points show that it is not necessary to sweep over all λ (all values on the non-negative real line) in order to find the solutions to the unconstrained problem. The proof of these points are given in [13]

1) $b_k{}^o(\lambda)$ either decreases or remains unchanged as λ increases.

2) Any given λ can either have a *singular* or *non-singular* solution $b_k{}^o(\lambda)$ to the unconstrained problem. Singular points are values of λ for which more than one solution exists. Non-singular points only have one solution.

3) Two adjacent singular values have one and only one solution in common.

4) All non-singular values of λ between two adjacent singular values have the same (single) solution.

A typical dependency of the solution rate $C_B^o(\lambda)$ on the lagrange multiplier λ can be shown to have the form of figure 12. It shows a decreasing staircase curve where the discontinuities correspond to singular values of λ.

The main conclusion from the above points is that to find a constraint which satisfies $C_B^o(\lambda) = C_B$, it is not necessary to search over all singular λ. It is sufficient to check only the singular points. Locating the desired solution requires the knowledge of the singular λ. The following lemma are used to locate all the singular λ.

Lemma 1: Let λ_1 be singular, $\lambda > \lambda_1$, and $\vec{B}^o(\lambda)$ be a common solution associated with λ and λ_1. Define the set

$$S_k^I = \{b_k{}^o + 1, \ldots q_k\}.$$

plexity heuristic algorithm which approximates the theoretical optimal solution within 10%. The retrieval schedule and resource reservation algorithms are flexible enough to be implemented on general purpose computers. Performance evaluations based on simulations using MPEG2 trace data were presented. We found that the retrieval schedule and resource reservation algorithm dramatically improves the performance and flexibility of video servers compared to previous approaches.

To support heterogeneous clients, we also applied scalable video coding to our retrieval schedule and resource reservation algorithm. We proposed a new retrieval method for scalable video- progressive display, and showed a significant increase in system utilization and efficiency.

Appendix A Optimal resource reservation algorithm for MR retrieval

For the notation defined in table 4, the optimal resource reservation problem was shown in section 9 to be equivalent to the following two step algorithm:

1) Find the reservation vector $\vec{B}^o$ which is the solution to the following non-linear constrained minimization problem:

$$\min M_T = \sum_{k=1}^{M} R_k(b_k)$$

Subject to

$$B_T = \sum_{k=1}^{M} b_k \le C_B, \ \vec{B} \in S$$

2) If $M_T \le C_M$ (system memory constraint), the set of all streams can be supported by the system, otherwise the set of streams cannot be supported.

The solution to the constrained minimization problem is based on the following theorem:

Theorem: For any $\lambda \ge 0$, the solution $\vec{B}^o(\lambda)$ to the *unconstrained* minimization problem

$$\min \left\{ \sum_{k=1}^{M} R_k(b_k) + \lambda \sum_{k=1}^{M} b_k \right\}, \text{ subject to } \vec{B} \in S$$

is also the solution to the *constrained* minimization problem with the constraint $C_B^o(\lambda) = \sum_{k=1}^{M} b_k{}^o(\lambda)$.

The proof of this theorem is presented in [13]. This theorem does not guarantee a solution to the constrained minimization problem. It just says that for every λ, there is a corresponding constrained problem for which the solution is the same as that of the unconstrained problem. The main point is that if $C_B^o(\lambda)$ happens to equal C_B, then $\vec{B}^o(\lambda)$ is the desired solution to the original constrained problem.

In solving the constrained problem, we can sweep over λ from 0 to ∞ and try to find a corresponding

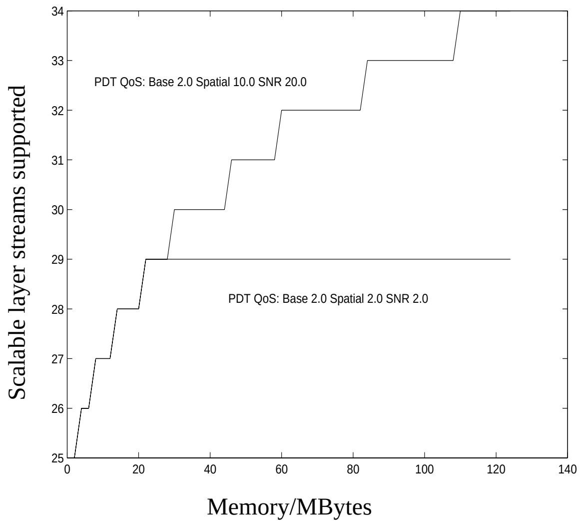


Fig. 17. Performance evaluation for progressive display of scalable video (disk system 1)
(a) Progressive display (Base layer PDT QoS: 2.0, spatial layer PDT QoS: 10.0, SNR layer PDT QoS: 20.0)

12 Implementation status

In Columbia's VoD testbed, audio-video content has been both hardware and software encoded and stored as MPEG-2 audio-video elementary streams. Audio-video data are transmitted as MPEG-2 transport streams. The video transmission has been tested over the campus ATM network and the wide area NYNET ATM network. A real time video pump and a distributed application control protocol (MPEG-2's DSM-CC) have been incorporated. Both hardware and software decoders and set-tops have been incorporated to test wide-area *video interoperability* [6].

A prototype video server using MR retrieval and the resource reservation algorithm is being developed on a general purpose multiprocessing system. Our system has eight 2GB disks, 2GB RAM system memory, and six 150MHz MIPS R4400 processors. The system has a 1.2GB/s system bus and the I/O bus has an attached *Asynchronous Transfer Mode* (ATM) network interface card for network communications.

13 Conclusions

In this research we have presented a new retrieval schedule for the retrieval of bursty VBR video data from the disk system to the memory of a video server. MR retrieval allows a range of bandwidths to be reserved for retrieval and guarantees a minimal buffer requirement for each bandwidth reservation. We presented a resource reservation algorithm for video server resources based on the MR retrieval schedule. We provided theoretic proofs for the optimality of the resource allocation algorithm. We also presented a fast, low com-

Table 5: Simulation parameters

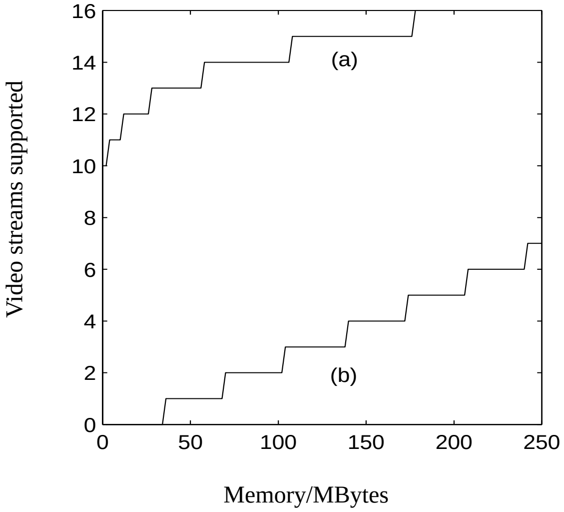
No. of videos	5
Mean of Avg. bit rates of all videos/Mbps	2.52
Mean of peak rate of all videos/Mbps	8.86
Mean PDT QoS/sec	5.0

Performance comparison of progressive and non-progressive display of scalable video

In figure 17, we compare the progressive display for the interactive viewing of scalable video with non-progressive display of scalable video. All streams are retrieving the same MPEG-2 scalable video. The video sequence is from the movie ‘Ben Hur’ and the related information is shown in table 6. The request pattern for the scalable layers of the video is uniform. For progressive display, progressively higher PDT QoS values are specified for the progressively higher scalable layers (table 6). In non-progressive display, the same PDT QoS is specified for the full resolution of video to achieve the same degree of interactivity. Figure 17 shows that using progressive display for the interactive viewing of scalable video increases the number of streams supported by a video server. For disk system 1, if a video server has a memory resource of 120 MB, progrssive display supports 17% more scalable layer streams than non-progressive display.

Table 6: Simulation parameters

Scalable layer	Base	Spatial	SNR
Avg. rate/Mbps	0.7	0.44	2.5
Peak rate/Mbps	1.8	1.0	4.7
Non-progressive display PDT QoS/Sec	2.0	2.0	2.0
Progressive display PDT QoS/Sec	2.0	10.0	20.0



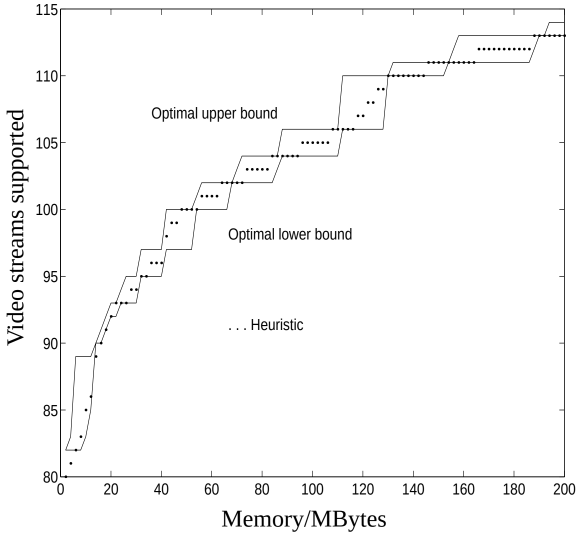


Fig. 15. Performance comparison of MR and CD retrieval (disk system 1)

(a) MR retrieval (PDT QoS 135.0 sec)

(a) CD retrieval (PDT QoS 135.0 sec)

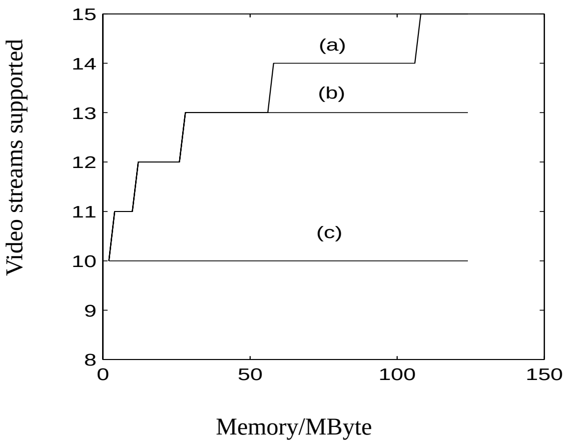
Fig. 16. Performance comparison of optimal and heuristic resource reservation algorithms

Performance comparison of optimal and heuristic resource reservation algorithm

Figure 16 compares the maximum number of streams that can be supported concurrently by a video server for the optimal resource reservation algorithm and the heuristic resource reservation algorithm. The simulation parameters are given in table 5. The request pattern for videos is uniform. The videos are sequences from the movie ‘Forrest Gump‘ and ‘Ben Hur’. For each request for a video, the mean PDT QoS is shown in table 5. For this simulation, we used the performance characteristics of disk system 2, however, we considered a large scale disk system with 16 disks.

For the optimal algorithm the exact optimal solution is not computed due to high computation requirements. Instead, an upper and lower bound on the number of admissible streams is found. The derivation of these bounds are discussed in appendix A.

Figure 16 shows that as the memory resource is increased, the number of streams also increases. It was found that the difference in the number of streams that can be admitted between the heuristic and optimal algorithm is less than 10% for this simulation. Therefore, the performance of the heuristic algorithm is very close to that of the optimal algorithm.



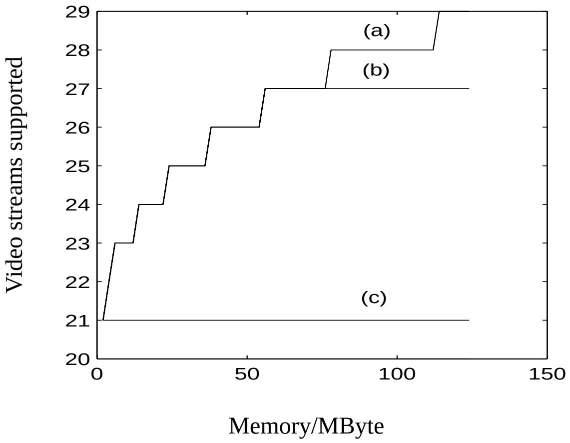


Fig. 13. Performance comparison of MR and CT retrieval (disk system 1)

(a) MR retrieval PDT QoS 10.0 (b) MR retrieval PDT QoS 2.0 (c) CT retrieval (PDT QoS 0.0)

Fig. 14. Performance comparison of MR and CT retrieval (disk system 2)

(a) MR retrieval PDT QoS 10.0 (b) MR retrieval PDT QoS 2.0 (c) CT retrieval (PDT QoS 0.0)

Performance comparison of MR and CD retrieval

Figure 15 compares the performance of MR and CD retrieval scheduling. Each line corresponds to a single simulation run. In each simulation all streams are accessing the same MPEG-2 VBR video which has the trace data shown in figure 1. Also, in each simulation, each stream specifies the same PDT QoS value. For disk system 1, if a video server has 150 MB, MR retrieval supports 275% more video streams than CD retrieval. CD retrieval is memory bound.

In the case of MR retrieval scheduling, we used the fast heuristic resource reservation algorithm to maximize the number of streams that can be supported concurrently by a video server. In the case of CD retrieval, the resource reservation algorithm is based on two facts. Firstly, each stream requires a bandwidth reservation equal to the average data rate of the requested video. Secondly, there is a fixed memory requirement for the retrieval of the video. Figure 15 shows the total number of admissible streams at the video server system as the on-board memory resource is increased, while keeping the disk bandwidth the same.

We can see that the number of streams supported by CD retrieval is generally much lower than MR retrieval. This scheme is essentially *memory bound*. The bandwidth is not fully utilized since the memory requirements are the limiting factor in the resource reservation.

Figure 13 and 14 compares the performance of MR and CT retrieval scheduling. Each line corresponds to a single simulation. In each simulation, all streams are accessing the same MPEG-2 VBR video which has the trace data shown in figure 1. Also, in each simulation, each stream specifies the same PDT QoS value. For disk system 1, if a video server has 120 MB, MR retrieval supports 50% more streams than CT retrieval, if users can tolerate a pre-fetch delay of 10.0 sec.

In the case of MR retrieval scheduling, we used the heuristic resource reservation algorithm to maximize the number of streams that can be supported concurrently by a video server. In the case of CT retrieval, the resource reservation algorithm is based on the fact that each stream requires a bandwidth reservation equal to the peak data rate of the requested video. Figures 13 and 14 show the total number of admissible video streams at the video server system as the total memory resource is increased, while keeping the disk system the same.

For MR retrieval, we can see that the number of streams that can be supported increases as the video server memory resources are increased. For continous, lossless retrieval in interactive viewing, the resource reservation algorithm based on MR retrieval guarantees that no other retrieval schedule can support more video streams for a given set of video server resources.

It can be seen that CT retrieval cannot take advantage of any increase in the memory resource of a video server. The advantage of the CT retrieval schedule is that the PDT QoS is always zero. This does not mean that the total delay that the client experiences before receiving its requested video is zero. However, the pre-fetch delay is zero. It can be seen that the performance of this scheme is the same as MR retrieval in which clients specify a PDT QoS of zero.

Table 4: Disk performance parameters

Parameter	Disk system 1	Disk system 2
Disk cycle time/second	0.5	0.5
Max. rotation latency/ms	14.2	7.1
Max. seek latency/ms	18.0	9.0
Min. seek latency/ms	1.5	0.75
Max. disk transfer rate/Mbps	60.0	120.0
No. of disks in array	4	4

In the progressive display of scalable video for interactive viewing, a progressively increasing PDT QoS is specified for the progressively higher scalable layers of a video. Each scalable layer is considered as an independent video. This is in constrast to non-progressive display of scalable video in which a single PDT QoS is specified.

In progressive display, the pre-fetch data for progressively higher layers are retrieved simultaneously since each layer is considered to be an independent video. At any given time, a video is transmitted only with all the scalable layers for which the pre-fetch data have been fully retrieved. For example, suppose that transmission is to be resumed at some point of a video after an interactive function. If enough time has elapsed only for the pre-fetch data of the lowest scalable layer to have been retrieved, only the lowest scalable layer is transmitted. If enough time has elapsed for the pre-fetch data of the first two layers to have been retrieved, the first two scalable layers are transmitted.

Progressive display improves the performance of the video server supporting scalable video. For scalable video, let the lowest layer of video have a PDT QoS of l sec. The higher layers will have PDT QoS values larger than l sec. In non-progressive display of scalable video, to achieve the same degree of interactivity, all the scalable layers have the same PDT QoS value of l sec. We will demonstrate the performance improvement in the next section.

11 Performance evaluation

For performance evaluation, we used the disk performance characteristics of three disk systems as shown in table 4. Disk system 1 has the disk performance characteristics of a current magnetic disk. In disk system 2, the performance parameters were improved by a factor of two to project the performance characteristics of the next generation of magnetic disk systems. For performance evaluation, trace data for MPEG2 scalable and non-scalable video was obtained using Columbia’s full-profile, standard-conforming MPEG2 software encoder/decoder [15].

In the following simulations, the video server receives requests for videos from clients. Each new request specifies a certain video which is stored on the video server, for which there exists a resource relation. Each request also has an associated PDT QoS. For each new request, the video server determines if it can accept the request or not. If the video server can accept the new request, a stream is established for the new request. For each simulation the total number of video streams that can be supported by the video server is found for a given set of available video server resources. The simulations find the total number of admissible streams to the video server system as the on-board memory resource is increased, while maintaining a fixed disk bandwidth resource.

Performance comparison of MR and CT retrieval

$$g_k = R_k(b_k - 1) - R_k(b_k) \ , \ G = \{k; p_k < b_k\}$$

G defines the set of all streams for which the bandwidth reservation can be incrementally decreased. We find the video stream k_{min} for which the above is minimized i.e.

$$g_{k_{min}} = \min \{g_k\} , \ k \in G$$

If the set G is null, then the set of video streams cannot be accommodated by the video server. Stop the algorithm.

If a minimum is found, step 2 is repeated with the following resource reservation:

$$\vec{B} = (b_1, \ldots b_{k_{min}} - 1, \ldots b_M)$$

10 Scalable video

In this section we integrate scalable video with MR retrieval and the resource reservation algorithm to present a scheme for the *progressive display* of scalable video. Progressive display improves the performance of a video server supporting interactive viewing of video.

Compared to simulcast coding, scalable coding schemes can provide multiple levels of video with a minimal cost of extra bandwidth or storage capacity. In scalable video coding, subsets of the full resolution bitstream are used to obtain subsets of the full resolution video [4, 9, 11]. Scalable video will be used in advanced computer networks to support heterogeneous clients. Mobile wireless clients may only have computing resources to receive the lowest layer of video, while high performance workstations will request all the scalable layers of video.

The MPEG2 standard allows a combination of *spatial, SNR (signal-to-noise ratio) and temporal scalability* for up to three layer coding of video sequences. In one possible hybrid, three layer scalable coding scheme, the base layer provides the initial resolution of video. The spatial enhancement layer enables the upsampling and hence increase in frame size of the base layer. Finally, the SNR enhancement layer increases the visual quality of the (base+spatial enhancement) layers of video [9]. In another scheme for MPEG-2 video, three layer temporally scalable video is achieved as follows. The lowest scalable layer is comprised of the I frames of a video (I layer). The P frames (P layer) enable an increase in the temporal resolution of the I frame layer. Finally, the B frames (B frames) increase the temporal resolution of the I+P layers. We refer to this as IPB scalable video. In this scheme, scalabilty is inherently provided by the MPEG-2 encoding structure. We have developed and tested a simple but robust system to extract the I, P, B layers from an MPEG-2 sequence and also to combine the multiple layers (I, I+P, I+P+B) for decoding.

There are various ways for scalable video data to be placed on disks [4, 11]. In this research, we assumed that each scalable layer is stored separately as an independent ‘video’ and that each layer is interleaved over all disks.

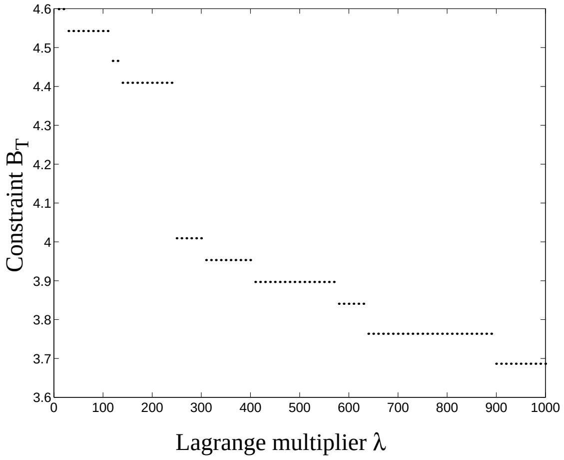


Fig. 12. Variation in constraint function with λ

Heuristic resource reservation algorithm

In [12] we presented a low complexity heuristic resource reservation algorithm. The algorithm is presented here, and in section 12, we compare the performance of this algorithm with the optimal resource reservation algorithm presented above. We found by simulation that the performance of this algorithm typically performs within 10% of the optimal resource reservation algorithm.

1) For all video streams, the retrieval bandwidths $\vec{B}$ are initially set to the peak data rate of the videos.

2) Compute total memory and bandwidth requirement:

$$M_T = \sum_{k=1}^{M} R_k(b_k),\ B_T = \sum_{k=1}^{M} b_k$$

3) If $M_T > C_M$: the video server *cannot* support all the video streams specified (memory limited). Stop the algorithm.

4) If $M_T < C_M$:

If $B_T \le C_B$: The video server *can* support all the video streams specified. Stop the algorithm.

If $B_T > C_B$: Reduce total bandwidth by increasing buffer requirements (step 5).

5) Reduce total bandwidth.

First find the video stream for which there is a minimal increase in buffer with an incremental decrease in bandwidth. Define g_k as the incremental increase in buffer of each video stream *k* with an incremental decrease in bandwidth of the bandwidth reservation for the video stream.

present the development of the optimal algorithm for completeness.

As part of the two step resource reservation algorithm we have to solve the following *constrained* minimization problem:

$$MIN\ M_T = \sum_{k=1}^{M} R_k(b_k)\ ,\ subject\ to\ B_T = \sum_{k=1}^{M} b_k \le C_B\ ,\ \vec{B} \in S$$

The solution to this constrained minimization problem is based on the following theorem:

Theorem: For any $\lambda \ge 0$, the solution $\vec{B}^o(\lambda)$ to the *unconstrained* minimization problem

$$MIN \left\{ \sum_{k=1}^{M} R_k(b_k) + \lambda \sum_{k=1}^{M} b_k \right\},\ subject\ to\ \vec{B} \in S$$

is also the solution to the *constrained* minimization problem with the constraint

$$C_B^o(\lambda) = \sum_{k=1}^{M} b_k{}^o(\lambda)\ .$$

The proof of this theorem is presented in [13]. This theorem does not guarantee a solution to the constrained minimization problem. It just says that for every λ, there is a corresponding constrained problem for which the solution is the same as that of the unconstrained problem. The main point is that if $C_B^o(\lambda)$ happens to equal C_B, then $\vec{B}^o(\lambda)$ is the desired solution to the original constrained problem.

In solving the constrained problem, we can sweep over λ from 0 to ∞ and try to find a corresponding $C_B^o(\lambda)$ that equals C_B. A typical dependency of the solution rate $C_B^o(\lambda)$ on the lagrange multiplier λ can be shown to have the form of figure 12. It shows a decreasing staircase curve where the discontinuities correspond to singular values of λ.

The key question then becomes the problem of finding the corresponding λ efficiently. This forms the main portion of the optimal resource reservation algorithm. The development of the algorithm and the optimal resource reservation algorithm is presented in appendix A.

$$M_T = \sum_{k=1}^{M} R_k(b_k) \le C_M \text{ (memory constraint),}$$

$$B_T = \sum_{k=1}^{M} b_k \le C_B \text{ (bandwidth constraint),}$$

$$\vec{B} \in S \text{ (PDT QoS constraint).}$$

If the reservation vector exists, the set of streams can be supported by a video server, otherwise the set of streams cannot be supported. Note that in an actual system, the computation of the total bandwidth reservation is not as simple as above, since the SCAN disk head schedule is assumed. The actual computation based on simplifying assumptions is given in [2, 11]. The resource reservation problem above can be shown to be equivalent to the following two step algorithm:

1) Find the reservation vector $\vec{B}^o$ which is the solution to the following constrained minimization problem:

$$MIN\ M_T = \sum_{k=1}^{M} R_k(b_k) \text{ subject to } B_T = \sum_{k=1}^{M} b_k \le C_B,\ \vec{B} \in S$$

2) If $M_T \le C_M$ (system memory constraint), the set of all streams can be supported by the system, otherwise the set of streams cannot be supported.

Let A be the set of *all reservation vectors* that meet both the PDT QoS constraints $\{d_k, k = 1, \ldots M\}$ and the system bandwidth constraint C_B specified above. The non-linear minimization problem gives us $\vec{B}^o$, which is the reservation vector in A that minimizes the total system memory requirement M_T. If M_T is greater than the system memory constraint, then there can be no reservation vector in A that will also meet the memory resource constraint C_M. This is because the reservation vector $\vec{B}^o$ is the vector in A that *minimizes* the memory requirement. This means that there can be no reservation vector that meets all system resource constraints C_M, C_B, and the PDT QoS constraint. Therefore the two step algorithm is equivalent to the optimal resource reservation algorithm.

Optimal resource reservation algorithm

In this section we outline the main approach we used in finding an optimal resource reservation algorithm. The algorithmic solution to the optimal resource reservation problem is based on a version of the Lagrange multiplier method as applied to bit allocation problems in video coding [13]. The approach places no restriction on the form of the stream resource relations e.g. the resource relations need not be strictly convex. In this section, we only present the main theorem associated with this method. In appendix A, we

Table 3: Notation for resource reservation

M	Total number of streams
$k \in \{1, \ldots M\}$	Stream index
B_I	Bandwidth increment
$b_k \cdot B_I$, $b_k \in \{1, 2, \ldots\}$	Stream bandwidth reservation
$b_k^o \cdot B_I$, $b_k^o \in \{1, 2, \ldots\}$	Optimal stream bandwidth reservation
p_k	Lower bound for stream bandwidth reservation
q_k	Peak bandwidth of video accessed by stream k)
$R_k(b_k)$	Stream buffer-bandwidth resource relation
d_k	Stream PDT QoS
C_M	System memory resource constraint
C_B	System disk bandwidth resource constraint
$\vec{B} = (b_1, \ldots b_M)$	Reservation vector for all streams
$\vec{B}^o = (b_1^o, \ldots b_M^o)$	Optimal reservation vector for all streams
S	Reservation vectors with $p_k \le b_k, k = 1, \ldots M$

The lower bound on the stream bandwidth reservation is determined as follows:

$$p_k = MIN\{b_k\}, \text{ subject to } \frac{R_k(b_k)}{b_k} \le d_k ,$$

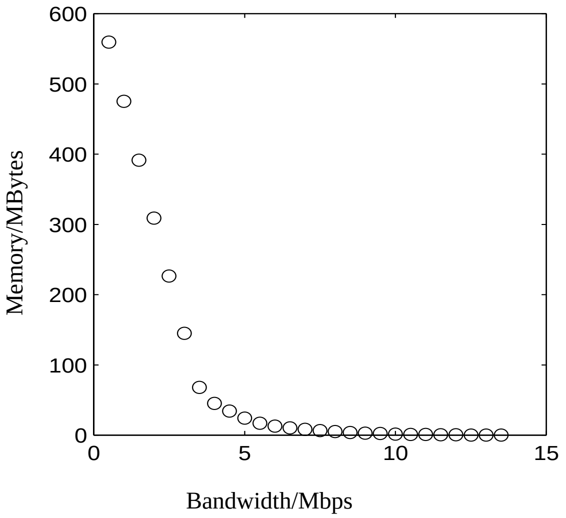
where $\frac{R_k(b_k)}{b_k}$ is the pre-fetch delay.

Problem formulation

Our objective in a video server is to maximize the number of streams that can be supported. Therefore, we formulate the resource reservation problem as follows:

For a given set of streams, determine if there exists a reservation vector $\vec{B}$ for all streams that satisfies the following constraints:

retrieval, by increasing the bandwidth reserved for each stream, the memory requirement for each stream can be substantially reduced. In this way, the bandwidth resources can be utilized to alleviate the memory bottleneck of a video server. By reducing the total memory reserved for all the streams, the video server can potentially support more streams.



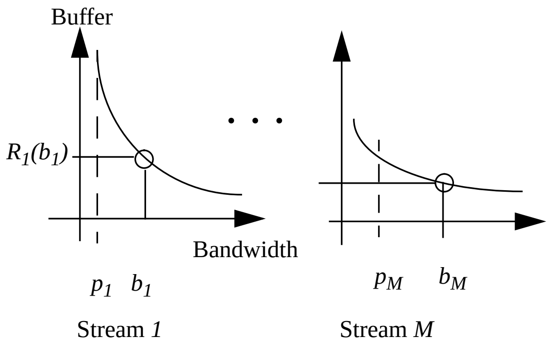


Fig. 10. Resource relation of MPEG-2 VBR video

Fig. 11. Resource reservation problem

9 Resource reservation for MR retrieval

In the previous section we developed and presented the MR retrieval schedule. It was found that the worst case memory buffer requirement for the retrieval of a VBR video decreases as the bandwidth reservation increases. It was seen that MR leads to a buffer-bandwidth resource relation. In this section, we develop the resource reservation algorithm based on MR retrieval for multiple streams in a video server.

In a video server, data for *multiple, concurrent* streams is retrieved from the disk system to memory and then transmitted into the network. The video server has resources of disk bandwidth and memory that have to be shared amongst all streams. If MR is used for the retrieval of each stream, the important question remains as to what buffer and bandwidth reservations should be made for each stream i.e. the operating point on the resource relation of the video retrieved by each stream must be determined. For each incoming stream, the reservations should be made to maximize the number of streams that can be supported by a video server while guaranteeing the continous, lossless retrieval and PDT QoS of each stream. Before describing the reservation problem, we present some definitions in table 3.

For a given bandwidth reservation, MR retrieval minimizes the worst case buffer that is necessary for continous, lossless retrieval. It can also be shown that increasing the reserved disk bandwidth will reduce the minimized worst case buffer requirement. Therefore, MR retrieval leads to a buffer-bandwidth resource relation for the retrieval of a video. Figure 10 shows the buffer-bandwidth resource relation for the MPEG2 encoded video trace data shown in figure 1. From this relation, the corresponding worst case pre-fetch delay can be found. If the worst case buffer requirement for the retrieval of a given video is m, then the worst case pre-fetch delay is m/b, where b is the corresponding reserved bandwidth.

For the interactive viewing of videos, we introduce the concept of a *Pre-fetch Delay Tolerance Quality of Service* (PDT QoS). A PDT QoS is specified for each stream that a video server supports, and it specifies the worst case pre-fetch delay that can be tolerated during interactive viewing. It is shown that a PDT QoS specified for a stream s that retrieves video $v(s)$ is equivalent to placing a lower bound on the bandwidth that can be reserved for stream s. The lower bound for the bandwidth can be determined from the buffer-bandwidth resource relation of video $v(s)$.

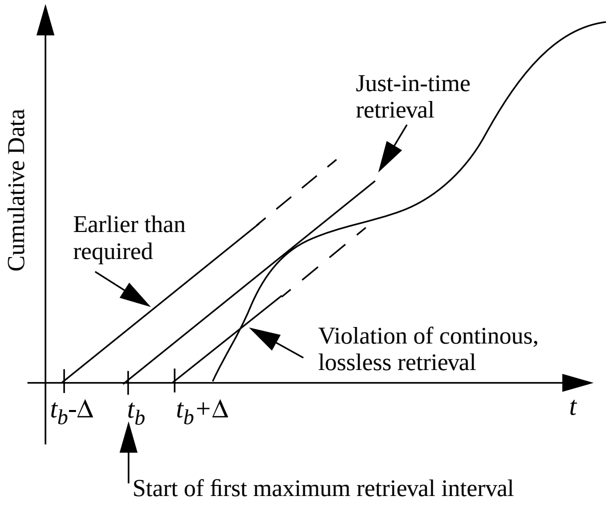
The primary strength of MR retrieval is the flexibility to optimally trade bandwidth and buffer. This is captured in the buffer-bandwidth resource relation. While CD and CT retrieval are each represented by a single point on the resource relation for the stored video, MR retrieval can operate at multiple operating points on the resource relation. MR retrieval can set any bandwidth reservation. As the bandwidth reservation is reduced, it is necessary to increase the reserved buffer. Consider a video server that uses MR retrieval. We present two cases to demonstrate the advantage of using MR retrieval over CD or CT retrieval.

Case 1. Assume that initially, each stream has a bandwidth reservation equal to the peak data rate of the video being retrieved. Assume that the total bandwidth reserved for all streams is equal to the total bandwidth of the video server. Assume that a large buffer memory exists in the video server. Using CT retrieval, no more streams can be supported by the video server because of the bandwidth limitation. In MR retrieval, if all viewers can tolerate a pre-fetch delay, the bandwidth reserved for all the streams can be substantially reduced from the peak bandwidth. Reducing the reserved bandwidth for each stream requires an increase in pre-fetch buffer requirements for each stream, if continous, lossless retrieval is to be guaranteed. In this way, memory resources can be utilized to alleviate the I/O bandwidth bottleneck. By reducing the total bandwidth reserved for all the streams, the video server can potentially increase the number of streams that are supported.

Case 2. Assume that initially each stream has a bandwidth reservation equal to the average data rate of the video being retrieved. Each stream has a pre-fetch buffer requirement. Assume that the total buffer memory reserved for all streams is equal to the total memory resource of the video server. However, assume that total bandwidth reserved for all streams is less than the total disk bandwidth of the video server. Using CD retrieval, no more streams can be supported by the video server because of the memory limitation. In MR

Proof of MR retrieval optimality

MR retrieval can be shown to minimize the worst case pre-fetch buffer requirement for a given bandwidth reservation for the continous, lossless retrieval of a video. We can prove this by showing that MR retrieval is based on *just-in-time* retrieval. Consider the first maximum retrieval interval [t_b, t_e]. In MR retrieval, the retrieval rate during a maximum retrieval interval is *b*. We define a small time interval Δ. Consider the start of retrieval to be delayed to $t_b + \Delta$. In this case, it can be seen that even if the retrieval is at the maximum retrieval rate of *b*, the continous retrieval constraint will be violated (figure 8). Therefore, t_b is the latest time at which pre-fetch of data can start if continous retrieval is to be guaranteed up to t_e. Consider the start of retrieval to start earlier at $t_b - \Delta$. It can be seen that the buffer requirement will increase for any possible retrieval schedule as data is retrieved earlier than required. This analysis can be done iteratively for all the maximum retrieval intervals. Therefore, since MR retrieval is based on *just-in-time* retrieval, it minimizes the buffer requirement while satisfying the constraints for continous, lossless retrieval.



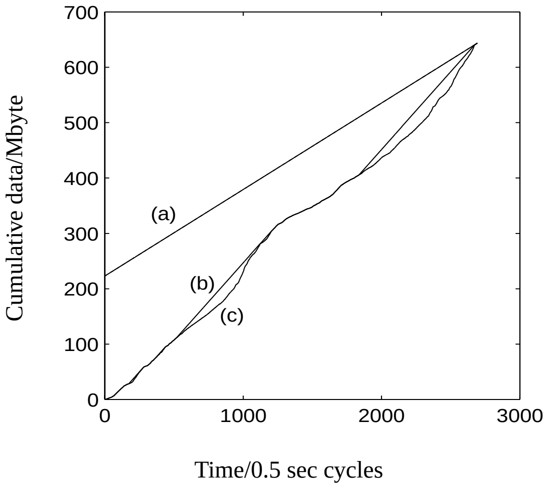


Fig. 8. MR retrieval optimality

Fig. 9. MR retrieval of MPEG-2 VBR video

(a) *i(t)* for MR retrieval with reserved bandwidth of 2.5 Mbps

(b) *i(t)* for MR retrieval with reserved bandwidth of 4.5 Mbps

(c) *o(t)*

Buffer-bandwidth resource relation of MR retrieval

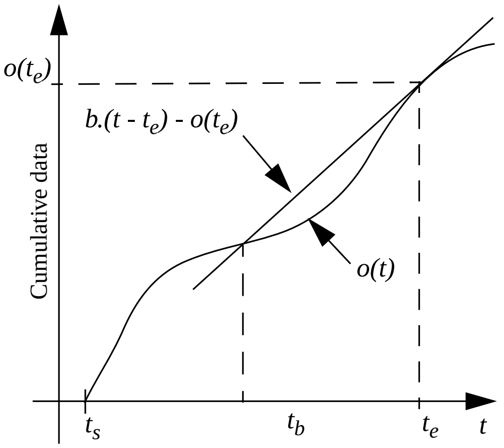
Table 2: MR retrieval

1. Set $t_e = t_s + T$
2. Decrease t_e until $\left.\frac{do(t)}{dt}\right|_{t_e} \ge b$
3. Find the intersection of $a(t_e, o(t_e))$ with $o(t)$
4. Let $t_b < t_e$ equal the intersection point
5. Mark the interval $[t_b, t_e]$ as a *maximum retrieval* interval
6. If $t_b \le t_s$ then stop
7. Set $t_e = t_b$ and return to step 2

MR retrieval is defined by the maximum retrieval intervals. Figure 7 shows $i(t)$ for MR retrieval. If the time t falls inside any of the maximum retrieval intervals, the retrieval rate is at the maximum bandwidth *b*. Otherwise, the retrieval amount is equal to the data rate. The buffer status at time t is $m(t) = i(t) - o(t)$. The worst case pre-fetch delay is:

$$d = \frac{MAX\{m(t)\}}{b},\ t_s \le t \le t_s + T\ .$$

Figure 9 shows MR retrieval of the MPEG-2 VBR video shown in figure 1.



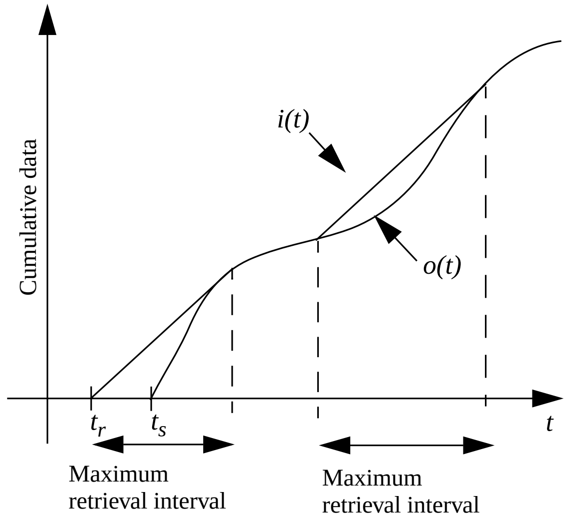


Fig. 6. Determination of MR retrieval

Fig. 7. Cumulative data for MR retrieval

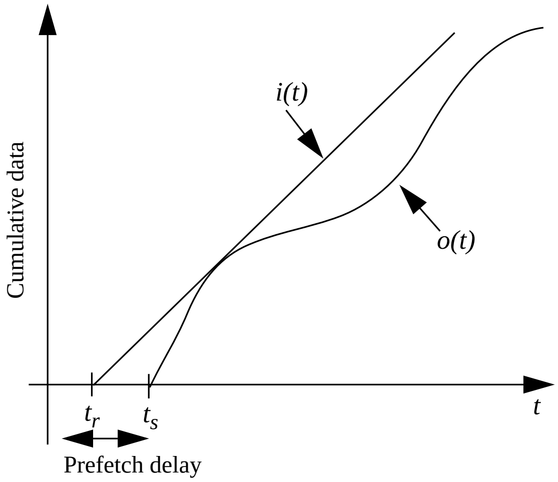


Fig. 5. Cumulative data for CD retrieval

8 Minimal resource retrieval

In this section, we present a new Minimal Resource (MR) retrieval schedule for continous, lossless retrieval of VBR video. MR retrieval is similar to CD and CT retrieval in that the retrieval alternates between intervals of constant time retrieval and constant data retrieval. However, it differs in that a *range* of bandwidths can be reserved for the retrieval. CD retrieval requires that a bandwidth equal to the average data rate is reserved, while CT retrieval requires a bandwidth reservation equal to the peak data rate.

If the bandwidth reserved for retrieval of VBR video is less than the peak data rate, then data has to be prefetched to ensure continous, lossless retrieval. Therefore, a buffer for pre-fetch data is required. In order to minimize the buffer requirement, data should be pre-fetched *just-in-time*. For the retrieval of VBR video, MR retrieval minimizes the worst case buffer requirement that is required for a given disk bandwidth reservation. It will be shown that this property of MR retrieval fully utilizes the resources of a video server.

We first describe the MR retrieval schedule and then discuss its properties. As before, let t_s be the start of transmission of a stream. The accumulated data output from the memory to network is $o(t)$. $o(t) = 0$, $t \le t_s$. The bandwidth reserved for the retrieval is b. We define a function $a(\alpha, \beta) = b \cdot (t - \alpha) + \beta$ that we will use in describing MR retrieval. We also use two new variables t_b, t_e to mark the beginning and end of each *maximum retrieval* interval. MR retrieval of stored video is described in table 2 and is shown graphically in figure 6.

Fig. 3. Buffers for CT retrieval

Fig. 4. Buffers for CD retrieval

7 Constant data retrieval

In constant data (CD) retrieval, a bandwidth of b Mbps equal to the average data rate of a video is reserved. The reserved bandwidth is typically much smaller than in CT retrieval, in which the peak bandwidth is reserved.

CD retrieval retrieves a fixed amount of data $b \cdot t_c$ during each cycle until all the data has been transmitted (figure 4, 5). This differs from CT retrieval, in which a variable amount of data is retrieved in each cycle. In this scheme, data has to be pre-fetched to ensure that continous, lossless retrieval of the video is guaranteed. The continous, lossless retrieval constraint is violated if buffer starvation occurs. This can occur because the amount of data transmitted during each cycle is variable, while the amount of data retrieved from the disk system is constant during each time cycle. Since a pre-fetch data has to be retrieved, there is a pre-fetch delay associated with CD retrieval. The worst case pre-fetch delay $t_s - t_r$ can be determined for stored video because the entire trace is known a-priori:

$$t_s - t_r = \frac{p}{b},$$

$$p = MAX\{-(b \cdot \Delta - o(t_s + \Delta))\} \quad 0 \le \Delta \le T$$

The major disadvantage of CD retrieval is that it cannot fully utilize video server resources to maximize the number of streams.

Consider a video server that uses CD retrieval. Each stream has a bandwidth reservation equal to the average data rate of the video being retrieved. Each stream has a pre-fetch buffer requirement. Assume that the total buffer memory reserved for all streams is equal to the total memory resource of the video server. However, assume that total bandwidth reserved for all streams is less than the total disk bandwidth of the video server. Using CD retrieval, no more streams can be supported by the video server because of the memory limitation. It will be shown that by increasing the bandwidth reserved for each stream, the memory requirement for each stream can be substantially reduced. In this way, the bandwidth resources can be utilized to alleviate the memory bottleneck of a video server. By reducing the total memory reserved for all the streams, the video server can potentially support more streams.

CD retrieval continues to retrieve a constant amount of data until all data has been retrieved. Data is sometimes retrieved earlier than is required, leading to potentially unnecessarily large buffer requirements. For the MPEG-2 VBR video shown in figure 1, CD retrieval reserves a bandwidth of 3.8 Mbps for the entire duration of retrieval. The buffer requirement for a video server operating at 0.5sec cycle time is found to be 50 MB.

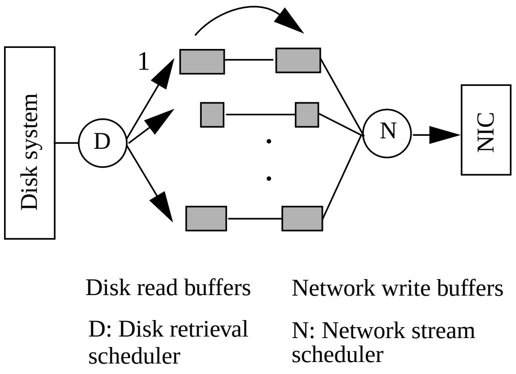
work write buffer. Therefore, network transmission can only begin after a delay of one cycle. This delay is different from the pre-fetch delay mentioned in the following sections and is common to all the retrieval schedules. We shall ignore this delay in the following sections. The pre-fetch delay for CT retrieval is zero. For each stream, a disk bandwidth of b equal to the peak data rate of the video being retrieved must be reserved for the entire duration of an interactive viewing session:

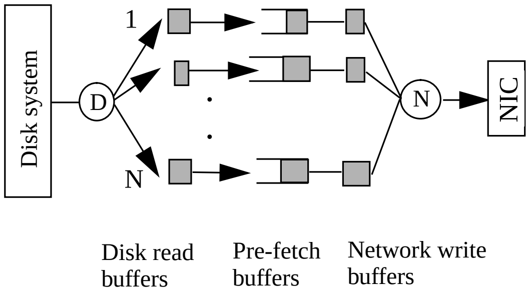
$$b = \max\ \{r(t), 0 \le t \le T\}\ .$$

In the following sections, we ignore the disk read buffers and network write buffers and only consider the pre-fetch buffers. For CT retrieval, for each stream, the memory requirement for pre-fetch buffers is zero. The major disadvantage of CT retrieval is that it cannot take advantage of memory resources to maximize the number of streams supported by a video server.

Consider a video server that uses CT retrieval. Each stream has a bandwidth reservation equal to the peak data rate of the video being retrieved. Assume that the total bandwidth reserved for all streams is equal to the total bandwidth of the video server. Assume that a large buffer memory exists in the video server. Using CT retrieval, no more streams can be supported by the video server due to the bandwidth limitation. It will be shown that if all viewers can tolerate a pre-fetch delay, the bandwidth reserved for all the streams can be substantially reduced from the peak bandwidth. Reducing the reserved bandwidth for each stream will be shown to require an increase in pre-fetch buffer requirements for each stream, if continous, lossless retrieval is to be guaranteed. In this way, memory resources can be utilized to alleviate the I/O bandwidth bottleneck. By reducing the total bandwidth reserved for all the streams, the video server can potentially increase the number of streams that are supported. CT retrieval does not take advantage of viewers that can tolerate a pre-fetch delay and always assigns a pre-fetch delay of zero to all streams.

For the MPEG-2 VBR video shown in figure 1, CT retrieval has to reserve a bandwidth of 14 Mbps for the entire duration of retrieval. The buffer requirement for a video server operating at 0.5sec cycle time is 1.75 MB.





the following sections.

Table 1: Notation

$r(t)$	Data rate of stored video
t_s	Start of network transmission
t_r	Start of disk retrieval
T	Duration of video
$o(t)$	Accumulated data transmitted out of memory into network (output).
$i(t)$	Accumulated data retrieved from disk into memory (input)
m	Buffer memory reserved for retrieval
b	Disk bandwidth reserved for retrieval

Let us assume that $o(t)$ is the integral of $r(t-t_n)$. The retrieval constraints for the retrieval of a video are as follows:

1) $i(t) \geq o(t)$ (Continous retrieval constraint)

2) $i(t) - o(t) \leq m$ (Buffer constraint)

3) $\frac{di(t)}{dt} \leq b$ (Disk bandwidth constraint)

6 Constant time retrieval

Constant time (CT) retrieval retrieves data from disk to memory *according* to the video data rate. This scheme is described by the equation $i(t) = o(t)$. The accumulated input data and accumulated output data are equivalent. In an actual system, the network stream scheduler waits one cycle time t_c after disk retrieval begins before it can start transmission into the network.

The delay of one cycle exists because we assume that the video server uses a double buffer scheme for retrieval and transmission (figure 3). During each cycle, data is read from the disk into the disk read buffers for each stream. Each disk executes one SCAN cycle. Concurrently, data is written from the network write buffers into the network interface card (NIC) for each stream. At the end of each cycle, the contents of the disk read buffers are written onto the network write buffers, and the process repeats. No pre-fetch buffer is required for CT retrieval. In the first cycle, the disk read buffer is being filled, while the network write buffer is empty. At the end of the first cycle, the contents of the disk read buffer are copied onto the net-

The network can accommodate the peak bandwidth of all video streams and introduces zero delay and zero jitter. The limitations of the network are not considered. In future research we will consider the limitations of the network, and we will also consider the interaction between the disk retrieval scheduler and network stream schedulers. In particular, we will consider the interaction of our disk retrieval scheduler with network stream scheduling algorithms to smooth VBR video data for transmission in networks.

The video server supports completely interactive viewing and continous, lossless retrieval. Video servers supporting completely interactive viewing allow viewers to pause and resume playback at any time during a viewing session. Playback can also resume at any point of a video. Video servers supporting continous, lossless retrieval provision resources so that once playback of a portion of a video has started, no delay is introduced and no data is lost. Note that this does not mean that there can be no delay *before* playback begins e.g. after a pause.

The video server has a fixed bandwidth and fixed buffer reserved for the entire duration of interactive retrieval. There are no renegotiations of resources for each video stream during a viewing session. This is a key simplifying assumption in our research. There is no renegotiation of resources for the retrieval during a viewing session. This will be investigated in future research.

4 CBR and VBR compressed digital video

In our research we used MPEG2 compressed digital video. However the retrieval schedule and the resource reservation algorithm are directly applicable to any video codec that results in VBR video. The variable bit rate of MPEG2 video is dependent on the encoding structure of the MPEG2 coding algorithm. In the MPEG2 digital video technology, compression is achieved by the combination of techniques such as the discrete cosine transformation (DCT), variable length codes, quantization of DCT coefficients, motion estimation and motion compensated inter-frame prediction. MPEG2 has a buffer control mechanism in which the quantization parameter can be varied adaptively in order to achieve a constant average bit rate of the compressed video. The disadvantage of this mechanism is that the subjective visual quality will be variable, since the quantization parameter is continually varied. An alternative is to maintain a constant quantization parameter during the encoding of video. This results in variable bit rate video, in which the amount of data to represent different time scales of video (macroblock, slice, frame, group of pictures etc.) are variable. The research presented in this paper maximizes the number of VBR streams that can be supported by a video server.

5 Retrieval constraints

In the following sections, although the operation of a video server is based on discrete time cycles, we will use continous time notation to clearly convey the central ideas. Table 1 defines the notation we will use in

In [5], CD retrieval is the basis for both a deterministic and statistical admission control scheme. The retrieval scheme is referred to as Constant Data Length (CDL) retrieval. In [1], two retrieval schemes called traditional CDL and generalized CDL (GCDL) are presented. The traditional CDL scheme described in [1] is actually very different from the CDL scheme of [5]. In the traditional CDL scheme of [1], a constant amount of data is retrieved from the disk for a video stream in the first disk cycle. In the second cycle, the same constant amount of data is retrieved only if it is required to prevent buffer underflow. Otherwise, no data is retrieved. This process repeats throughout the retrieval. Therefore, each retrieval cycle is either an idle or active round. Although a constant data amount is retrieved during an active round, the overall retrieval can be considered to be variable bit rate. This is different from [5] in which the overall retrieval is constant bit rate i.e. there are no idle rounds. In [1], the GCDL scheme is an extension of the traditional CDL scheme in which the retrieval round can be different for different video streams and which are a multiple of the disk cycle. This is shown to reduce the buffer requirements compared to traditional CDL.

3 System Model

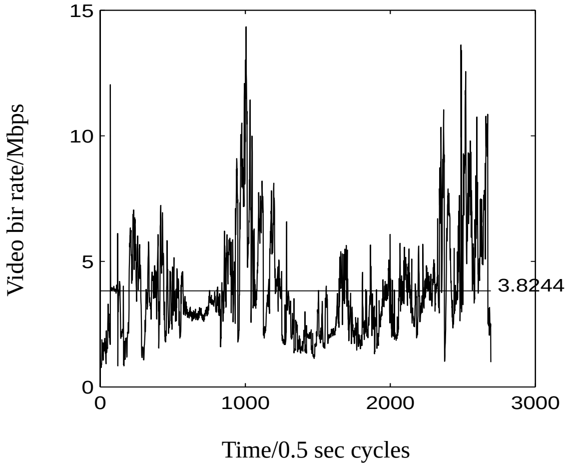
In this section we describe the video server system model relevant to our research. The system model is shown in figure 2. The video server has a fault tolerant disk array for the storage of video data, a memory resource, and a network interface for transmission into the computer network.

The disk retrieval scheduler has a cyclic operation [4, 10, 11, 12]. Each cycle, the disk retrieval scheduler retrieves data for multiple video streams from the disk system to the memory. The network stream scheduler also has a cyclic operation, although the cycle time of the network stream scheduler will typically be much smaller than the cycle time of the disk retrieval scheduler. The network stream scheduler transmits data for multiple video streams into the network during each cycle.

The video data is interleaved over all the disks of the array. During each cycle, the disk heads of each disk in the array complete one cycle of a SCAN disk head schedule. The disk head scans the disk starting from the inner most track to the outer most track [2, 7]. While scanning the disk, data blocks belonging to different streams are read from the disk. Upon reaching the outer most track, the head is returned back to its initial position. The performance analysis is given in [2]. Although multiple blocks for each video stream are being retrieved from the disks each cycle, the overhead of disk head seeks is greatly reduced by using the SCAN disk head scheduling algorithm.

There is no special data layout of the videos on the disks. Implementing such schemes is difficult [3]. It is often not possible to find out the real drive geometry. Track and sector sparing, automatic sector reassignment etc. all combine to make the drive’s physical characteristics irrelevant. Also, the actual disk layout is hidden from the user.

video. We discuss the limitations of each approach. Section 8 presents our new minimal buffer retrieval schedule for VBR video data. We discuss how this retrieval schedule overcomes the limitations of the previously proposed approaches. Section 9 presents a resource reservation algorithm based on MR retrieval that is necessary to maximize the number of video streams that a server can support. Section 10 briefly overviews scalable video and then presents a scheme for the progressive display of scalable video. Progressive display improves the performance of video server supporting scalable video. Section 11 presents extensive performance evaluations of the MR retrieval schedule in comparison to other proposed approaches. Finally, in section 11, we discuss our VoD testbed and components that have already been implemented.



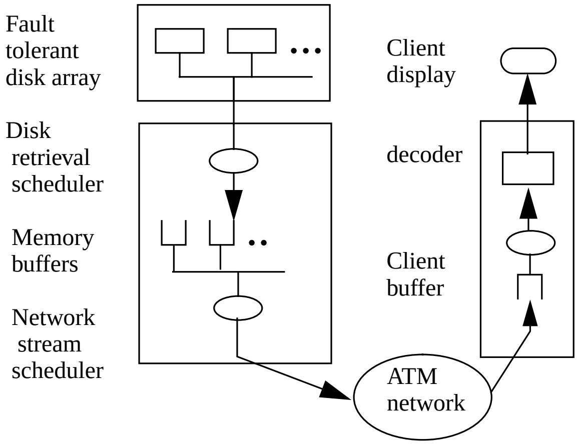


Fig. 1. MPEG-2 VBR video trace data

Fig. 2. Video server/ VoD architecture

2 Related work

In [14], CT retrieval is the basis for the admission control scheme in multimedia servers. The primary contribution of the work in [14] is that *statistical service guarantees* are provided to all streams. In other words, for each stream, a continous retrieval is guaranteed to a fixed percentage of the video data. It is proposed that a certain percentage of video data can have the continuity requirement violated without significantly affecting the quality of the video. This leads to an improvement in the utilization of the server. New clients are admitted for service as long as the statistical estimate of the aggregate data rate requirement (rather than the peak data rate requirement) can be met. The approach of ensuring statistical guarantees, rather than deterministic guarantees is certainly effective in increasing the performance of a multimedia server. However, the approach proposed in [14] is based on CT retrieval and has the drawback that memory resources cannot be fully utilized maximizing the number of supported streams.

video server supports, and it specifies the worst case pre-fetch delay that can be tolerated during interactive retrieval. It is shown that a PDT QoS specified for a stream s that retrieves video $v(s)$ is equivalent to placing a lower bound on the bandwidth that can be reserved for stream s. The lower bound for the bandwidth can be determined from the buffer-bandwidth resource relation of video $v(s)$.

For MR retrieval, we developed an optimal resource reservation algorithm for multiple streams. The resource reservation algorithm determines what buffer and bandwidth should be reserved for each stream. The objective of the resource reservation algorithm is to maximize the number of video streams for a given set of video server resources, while ensuring the PDT QoS and retrieval constraints of each stream. It can be shown that the resource reservation algorithm based on MR retrieval fully utilizes the bandwidth resources and maximizes the number of supported video streams.

We present performance evaluations based on simulations using MPEG2 trace data. It is found that the optimal resource reservation algorithm based on MR retrieval dramatically improves the performance of video servers compared to resource reservation algorithms based on CT or CD retrieval. For a video server configuration with 4 disks and a memory resource of 120 MBytes, our approach supports 50% and 275% more video streams than approaches based on CT and CD retrieval, respectively. We also show that as the PDT QoS is increased, the number of streams supported by a video server is increased.

Compared to simulcast coding, scalable coding schemes can provide multiple levels of video with a minimal cost of extra bandwidth or storage capacity. In scalable video coding, subsets of the full resolution bitstream are used to obtain subsets of the full resolution video. In the paper we present a scheme for the *progressive display* of scalable video for interactive viewing. In this scheme, a progressively increasing PDT QoS is specified for the progressively higher scalable layers of a video. Each scalable layer is considered as an independent video. This is in constrast to non-progressive display of scalable video in which a single PDT QoS is specified for all the scalable layers. For a video server with 4 disks and a memory resource of 120 MBytes, progressive display supports 17% more scalable layer streams than non-progressive display.

Finally, we describe the development of our video server and VoD testbed. The MR retrieval schedule and resource reservations algorithms are flexible enough to be implemented on general purpose computers. Our approach does not depend on any special video data layout strategies on disks, and is directly applicable to video servers that are based on general fault tolerant storage architectures (e.g. RAID [8]).

This paper is organized as follows. Section 2 we first discuss the state-of-the-art research in retrieval scheduling and resource reservation. Section 3 presents our basic assumptions and the video server system model that our research is based on. Section 4 discusses the main differences between CBR and VBR video. Section 5 outlines the retrieval constraints that are necessary for continous, lossless retrieval of VBR video in video servers. Section 6 and 7 examines in depth two approaches for retrieval scheduling of VBR video provides several advantages over constant bit rate (CBR) video, including consistent video quality and lower encoder complexity. However, the bursty nature of compressed video raises research challenges in the storage, retrieval and transmission of video servers. In general, bursty VBR video complicates the design of real time systems such as video servers, in contrast to the simpler case of CBR video.

Video servers operate in cycles, and during each cycle time, data is retrieved by a disk retrieval scheduler from the disk system to memory for each stream that is supported. For CBR data, the disk retrieval is simple. During each cycle, a constant amount of data is retrieved for each stream. However, for VBR video, it is not clear how data should be retrieved for each stream.

In Constant Time (CT) retrieval of VBR data [5, 14], data corresponding to a constant time is retrieved for each stream during each cycle of operation of a video server. Let $v(s)$ be the video that a stream s is retrieving. For continous, lossless retrieval, it is necessary to reserve a disk bandwidth equal to the peak data rate of video $v(s)$ for stream s. We will show that video servers based on CT retrieval cannot fully utilize the memory resources of a video server in maximizing the number of supported streams.

In Constant Data (CD) retrieval of VBR data [1, 5], a constant amount of data is retrieved for each stream during each cycle of operation of a video server. A disk bandwidth equal to the average data rate of video $v(s)$ is reserved for stream s. In general, this scheme requires data to be pre-fetched into a buffer before transmission to ensure that buffer starvation does not occur. Buffer starvation can occur because the amount of data transmitted during each cycle is variable for VBR video, while the amount of data retrieved from the disk system is constant during each cycle. We will show that video servers based on CD retrieval cannot fully utilize the bandwidth resources of a video server in maximizing the number of supported video streams.

To overcome the limitations of CD and CT retrieval, we developed a *Minimal Resource* (MR) retrieval schedule and an associated optimal resource reservation algorithm that can fully utilize any given set of video server resources to maximize the number of supported video streams.

In MR retrieval, a range of disk bandwidths can be reserved for the retrieval of VBR data. This is in contrast to CD and CT retrieval, in which a disk bandwidth equal to either the average data rate or peak data rate of a VBR video is reserved, respectively. In MR retrieval, as the reserved bandwidth is reduced, the worst case buffer requirement increases. A buffer is required for data that has to be pre-fetched to ensure continous, lossless retrieval. For a given bandwidth reservation, MR retrieval *minimizes* the worst case buffer memory requirement for continous, lossless retrieval.

MR retrieval leads to a *buffer-bandwidth resource relation* for each VBR video. The resource relation shows the worst case buffer requirement for a given bandwidth reservation. We can show that increasing the reserved bandwidth reduces the worst case pre-fetch delay. Based on this, we introduce the concept of a *Pre-fetch Delay Tolerance Quality of Service* (PDT QoS). A PDT QoS is specified for each stream that a

Columbia University Technical Report CU/CTR/TR 470-97-04

Video server retrieval scheduling and resource reservation for variable bit rate scalable video

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Abstract. In advanced computer networks, computers will be able to connect to remote video servers and receive digital video streams. State of the art digital video compression produces bursty, variable bit rate video. The bursty nature of compressed video raises research challenges in the storage, retrieval and transmission in video servers. In this paper, we first present an efficient schedule for the retrieval of bursty video data from the disk system to the memory of a video server. Video data has to be retrieved from the disk system to memory before transmission into the network. For a single video stream, the schedule minimizes the buffer requirement for continous retrieval, given that a fixed disk bandwidth is reserved for the entire duration of retrieval. Secondly, we present an optimal resource reservation algorithm for multiple video streams based on the proposed retrieval schedule. The resource reservation algorithm maximizes the number of bursty video streams that can be supported by a video server. Thirdly, we present a progressive display scheme for scalable video that is based on the retrieval schedule and resource reservation algorithm. Performance evaluations based on simulations using MPEG-2 trace data are presented. For a video server with 4 disks and a memory resource of 120 MBytes, our approach supports 50% to 275% more video streams than previously proposed approaches. For the same configuration, progressive display supports 17% more scalable layer streams than non-progressive display. The retrieval schedule and resource reservation algorithms are flexible enough to be implemented on general purpose computers.

1 Introduction

In advanced computer networks, computers will be able to connect to remote, geographically distributed video servers and receive continous digital video streams. Video servers are computers that store multiple videos (and other associated media such as audio) and transmit multiple concurrent video streams to computers over a network. Video servers enable applications such as Video-on-Demand (VoD) and digital libraries and will provide an unprecedented amount of digital video information in networks. In this paper, we present our research results in maximizing the number of variable bit rate, scalable video streams that can be supported by a video server.

State of the art digital video compression produces bursty, variable bit rate (VBR) video. Figure 1 shows trace data for MPEG-2 VBR video data. The video sequence is from the movie ‘Forrest Gump’. VBR

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