Dynamic Bandwidth Allocation for VBR Video Transmission

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To guarantee quality of service (QoS), the requirements for video transmission, such as delay and cell loss rate (CLR), are very stringent. These constraints are difficult to meet if high network utilization is desired. In this paper, dynamic bandwidth allocation algorithms are proposed to improve the bandwidth utilization. The first approach based on scene change identification, in which the bandwidth is allocated based on the maximum and mean bandwidth of the scene, is applicable to delivering pre-recorded videos. The second approach, in which the bandwidth is adjusted based on the current frame size, can be used to deliver real-time videos on-line. When the bandwidth deviation is large enough, the bandwidth renegotiation process is triggered. Compared with the CBR service, network utilization can be improved significantly for the same CLR. In general, to achieve a very low CLR and high bandwidth utilization, the renegotiation frequency may become high. Algorithms, which are proven to be effective in reducing the renegotiation frequency while keeping the bandwidth utilization at a reasonable level, are also proposed.

Keywords: QoS, VBR, bandwidth allocation, MPEG, video transmission.

1. Introduction

The main design objective of emerging broadband networks is to provide high speed transmission of a wide range of quality of services. Video is becoming the major component of broadband network traffics and, therefore, an efficient video traffic transmission mechanism is important to network operators. The IP-based Internet was not designed to support QoS guarantees; it offers “best effort” services, in which the network allocates bandwidths among all of the instantaneous users as best as it can, and attempts to service all of them without any explicit commitment on the rate and other service qualities. Real time applications especially for MPEG videos with bursty characteristics often do not work well across the best effort service because of variable queuing delays and congestion losses. In addition, it may not be possible to retransmit information for a real time service, and so any loss in the network results in lost information at the decoder, rather than just increased delays in the case of file transfer. Much work has been focused on provisioning QoS support to the Internet service model such as Integrated Service and Differentiated Service. Many mechanisms, architecture, and algorithms are proposed to transport video over IP networks based on these two models [1][2][3].

While asynchronous transfer mode (ATM) networks are more suited to real time and guaranteed QoS communications, the bursty nature of VBR video, combined with the diversity of its QoS requirements, make it difficult to transport video traffic in a cost effective manner. For example, the ratio between the peak and average bit rate may be as large as 12 for the *Star Wars* video sequence. If the bandwidth is allocated according to the peak rate of the *Star Wars* video, no packet loss occurs, but a substantial amount of bandwidth is wasted during most of transmission; on the other hand, if the bandwidth is allocated based on the mean cell rate, the video service will suffer from unacceptable losses and delays, especially those with hard real time constraints. It is very difficult to meet the QoS parameters (such as delay and cell loss ratio) for such kind of traffic while keeping high network utilization.

Dynamic bandwidth allocation approach (or Renegotiated CBR) is an alternative for improving network utilization that allows users to dynamically reserve or adjust network resources. When there is not enough reserved resource for the user to transmit its traffic, a renegotiation is initiated to ask for more. If the reserved resource is more than enough, some bandwidth can be released. In such a way, network utilization can be improved significantly. Our work focuses on dynamic bandwidth allocation for transporting MPEG video traffic over ATM networks.

The rest of the paper is organized as follows. In Section 2, related works are reviewed. Section 3 describes the dynamic bandwidth allocation based on scene changes for pre-recorded videos. A simple procedure for scene change identification is adopted, and ideas for improving the bandwidth utilization are also introduced. Section 4 covers the on-line dynamic bandwidth allocation for real time video delivery. Algorithms to reduce renegotiation frequency and improve bandwidth utilization are also presented. Conclusions are drawn in Section 5, and simulation results are presented in respective sections.

2. Related works

Emergence of multimedia communications has inspired a number of dynamic bandwidth allocation schemes.

The papers ([4], [5], [6]) address the problem of transporting pre-recorded videos for video on demand (VoD). These papers consider transmission of stored videos from a server to the client across a network, and explore how the client buffer space can be used most efficiently toward reducing the variability of the transmitted traffic. A number of cells should be built up in the viewer's buffer before the commencement of playback; the build up, cell transmission rate, and set-top memory size must be chosen so that there is no starvation or overflow. In our scheme for pre-recorded videos, we do not smooth the transmitted traffic, and the client does not need a large buffer at the receiver which is expensive. The renegotiation for bandwidth is triggered by video sources.

For real-time video transmission, one major class of dynamic resource management algorithms is based on parameter measurements. Several measurement based dynamic bandwidth allocation algorithms, which initiate their renegotiation processes based on the actual measurement of CLR or user parameters (UPs), have been proposed [7], [8], [9]. In [7], the CLR is calculated up to the current period, and the service rate for the next period is adjusted based on the current CLR. Owing to the difficulty in assessing the CLR on line and the indirect relationship of the current CLR and UPs with future bandwidth requirements, these approaches are not effective enough to enhance QoS and improve network utilization. In [8], the UPs, such as the peak rate and sustained rate, are adjusted for every GOP (group of picture). UPs could be inherently inaccurate because they are calculated from previous GOPs. To reduce the buffer size, the source quantization step is adjusted on line. The major drawback of this algorithm is that the user parameters (peak rate, sustained rate, and burst length) need to be renegotiated for each GOP, which is a big burden to network management.

Another major class of algorithms is based on prediction. User parameters or bit rates are predicted on-line based on the available information [10], [11], and resources are allocated based on the predicted results. In [10], a traffic model called the Deterministic Bounding Interval (D--BIND) is used. The allocation algorithm stores the currently reserved D-BIND parameters and calculates the D-BIND parameters for the last M frames. A renegotiation takes place when a difference exists between the reserved and measured D-BIND parameters. The calculation of the D-BIND parameters may be problematic since it is done for each frame. So the estimation of the bounding rate over the interval is computationally expensive. Chong *et al.* [12] approached the problem in the frequency domain. They proposed a method to dynamically allocate the bandwidth based on the predicted low frequency band of the video traffic. The low frequency band represents the slow variation of the VBR rate. It is important to predict these parameters accurately so that network resources can be used efficiently.

An adaptive linear prediction scheme was proposed by Adas [11]. This scheme does not require any prior knowledge of the video statistics nor does it assume stationary, and thus very suitable for on line real time prediction. One problem associated with this algorithm is its slow convergence. For MPEG Video characterized by frequent scene changes, this algorithm may result in an extended period of intractability, and thus excessive cell loss during scene changes. In [13], a fast convergent algorithm was proposed. This algorithm not only incurs small prediction errors but, more importantly, achieves fast convergence.

All these bandwidth allocation algorithms measure or predict parameters on line. The source information, or *a priori* information, is not exploited. For videos, the source information is available to the network, and can be exploited to ease network management. Based on the belief that the source information should be used to manage network resources, a new approach, in which a renegotiation process is initiated only when a scene change occurs, is proposed here. It is applicable to pre-recorded videos. It is well known that the bit rate changes dramatically only when a scene change occurs, and thus, the renegotiation is necessary only at that time. Intuitively, the renegotiation frequency should be lower as compared to those proposed in [11], [8]. The CLR is guaranteed to be zero if the maximum bandwidth for every scene can be satisfied.

The scene change-based approach requires a holding time of (variable) scene lengths, and is thus only applicable to pre-recoded videos. For real time video delivery, one has to make decisions within two video frames holding time. An on-line dynamic bandwidth allocation approach, which allocates bandwidth based on the value of the bandwidth deviation from the currently allocated bandwidth, is therefore proposed to enable real-time video delivery.

3. Dynamic Bandwidth Allocation Based on Scene Changes

A representative portion of an empirical video trace is plotted in Fig. 1. The vertical axis represents the number of bits per frame, and the horizontal axis represents the corresponding frames. It is clear that the data record appears to be composed of stationary segments. The average bit rate of each segment changes abruptly from one segment to another. Visually, these abrupt transitions coincide with scene changes [14].

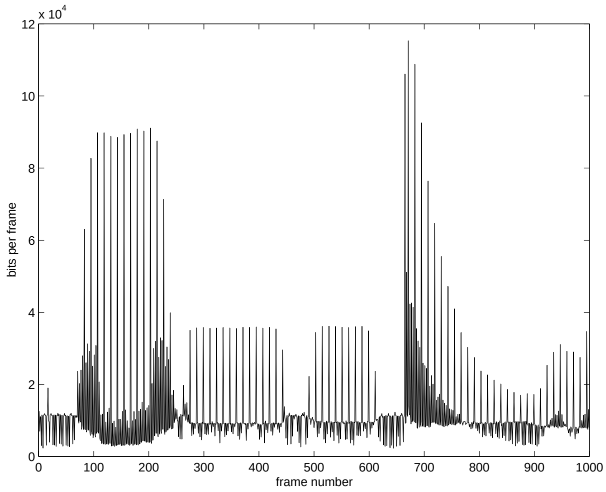

Fig. 1. Video traffic of *Star Wars*.

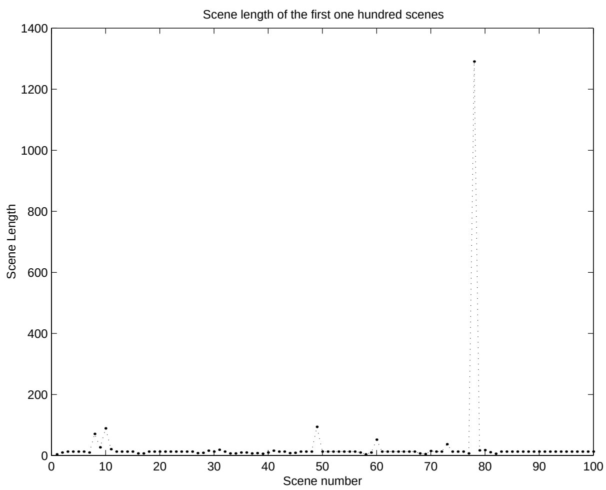

Fig. 2. Scene length.

To detect scene changes in the empirical trace, the algorithm introduced in [14] is adopted. A scene change is declared if the change of the number of bits between successive frames exceeds a certain threshold in a sustained manner. Denote X_n as the number of bits in the *nth* I frame, and J_{min} the threshold. Define J_n as:

$$J_n = \begin{cases} 1 & |X_n - X_{n-1}| > J_{min}, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The indicator function for the *nth* I frame is then given by

$$S_n = \begin{cases} 1 & \text{if } J_n = 1, J_{n-1} \neq 1, \\ & J_{n-2} \neq 1, \cdots, J_{n-L_{min}} \neq 1, \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

where L_{min} is the minimum scene length in frames. The frame whose indicator function is one corresponds to a scene change. It was empirically determined [14] that for the *Star Wars* video, $J_{min} = 5000$, and $L_{min} = 2$. Fig. 2 shows the scene length of the first 100 scenes.

For MPEG coded video movies, the ratio of the peak to average rate may vary significantly from segment to segment. If CBR service is used to transmit MPEG video traffic, it is difficult to guarantee QoS while keeping bandwidth utilization high. For instance, network utilization will be low if the bandwidth is allocated to a value equal to the peak rate, while the delay or the CLR will be high if the average bit rate is allocated.

It is intuitive that the bit rate does not vary much during a scene, as shown in Fig. 1, and hence, low CLR, small delay, and high network utilization can be expected. Based on this premise, the following dynamic bandwidth allocation algorithm is proposed[1]:

1. Identify the scene change.
2. If a scene change occurs, determine the maximum bandwidth needed (which can be found in advance for stored videos).
3. Initiate a negotiation process for the maximum bandwidth for this scene.
4. Go to Step 1.

The maximum bandwidth for every scene should be determined and stored beforehand. During the retrieval process, if a scene change is detected, the maximum bandwidth for the new scene can be read and the bandwidth can be allocated for this scene.

Let C be the maximum number of bits that can be transmitted by the channel, and M be the total number of bits transmitted. The bandwidth utilization factor is defined as:

$$\rho = \frac{M}{C}. \tag{3}$$

For the *Star Wars* video, if the peak bit rate is used for the CBR service, the utilization factor is 0.0842. Using the proposed method, the utilization factor becomes 0.1962 (an improvement by a factor of 2.3). Compared with the methods proposed by Reininger *et al.* [8] and Adas [11], our method can achieve a reduction of the renegotiation frequency by a factor of 7 with zero CLR and no delay[2].

3.1. Improving Bandwidth Utilization

The algorithm introduced above achieves zero CLR at the expense of bandwidth utilization. The bandwidth utilization can be improved with buffering. To improve network utilization, the following procedure is proposed.

1. Identify the scene change.
2. If a scene change occurs, determine the mean bandwidth **B** of this scene.
3. Initiate a negotiation process to acquire bandwidth $\beta\mathbf{B}$ for this scene, where $\beta > 1$ is a constant.
4. Go to Step 1.

The average bandwidth for each scene should be determined off-time. For stored video traffics, it is very easy to find the average bit rate of each scene.

Suppose that the movie has N scenes. B_i is the mean frame size of the *ith* scene, and L_i is the number of frames in the *ith* scene. Then,

$$M = \sum_{i=1}^{N} L_i B_i \tag{4}$$

$$C = \sum_{i=1}^{N} \beta L_i B_i \tag{5}$$

and

$$\rho = \frac{M}{C} = \frac{\sum_{i=1}^{N} L_i B_i}{\sum_{i=1}^{N} \beta L_i B_i} = \frac{1}{\beta}, \tag{6}$$

where M is the total number of bits of the movie, and C is the maximum number of bits that the source can transmit. It is clear that the bandwidth utilization is the reciprocal of β.

Video trace *Star Wars*[3] was used in our simulations. The data file for the trace consists of

[1] The idea was first presented at ITCC2000 [15].
[2] Since [8] and [11] are based on prediction, zero CLR can hardly be achieved unless a very large buffer is used.
[3] The MPEG-I coded data were the courtesy of M.W. Garrett of Telecordia and M. Vetterli of UC Berkeley.

174,136 integers, whose values are frame sizes (bits per frame). The largest frame has 185267 bits, and the smallest one has 476 bits. This is a good representative movie sequence for benchmark comparison, with scenes ranging from low complexity/motion to high and very high actions.

In Fig. 3, the relationship between CLR and buffer size is illustrated for different values of β. The value of β varies from 2 to 9, from top to bottom, with a step size of 0.5. When β is larger than 9, the CLR becomes zero for any buffer size. The curve at the top corresponds to $\beta = 2$. Compared with the CBR service, CLR can be reduced by an order of 2-3 using our proposed techniques with a fixed buffer size and bandwidth utilization. Likewise, with the fixed CLR and bandwidth utilization, the buffer size can be reduced by a factor of 2-4.

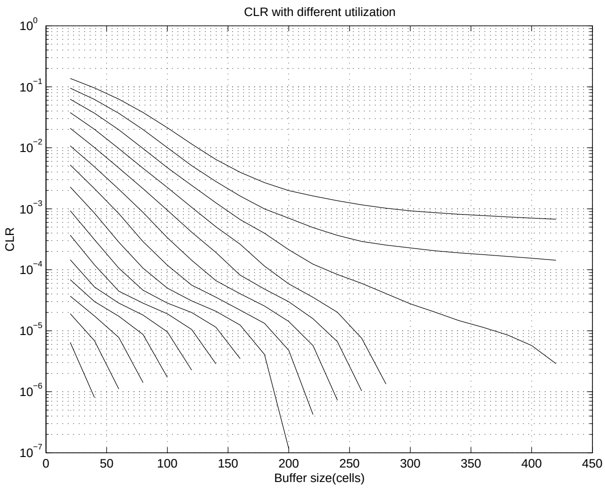

Fig. 3. CLR versus buffer size under different network utilization factors; β varies from 2 to 9 from top to bottom with a step size of 0.5.

4. Dynamic Bandwidth Allocation for Real Time MPEG Video Transmission

Note that, if the renegotiation is initiated by the video source (or codec), it is easier to realize a more effective bandwidth allocation algorithm because the immediate frame size (frame size means bits used to represent the frame) is known before transmission.

Suppose the current transmission rate is R bits per second, the size of the frame that will be transmitted is S bits, and the frame refresh rate is N frames per second. The bandwidth allocation can be done in the following way[4]:

- if $|R - N \times S| < \delta$, transmission rate R is kept unchanged,
- $R = S \times N$, otherwise,

where δ is the threshold.

The value of δ affects the bandwidth utilization, the size of the buffer needed, renegotiation frequency, and cell loss ratio. In order to increase bandwidth utilization and decrease CLR, the value of δ should be small. On the other hand, the value of δ should be large enough to achieve a small number of renegotiations. To evaluate the effect of δ, an ATM switch with a limited buffer size is simulated for different values of δ, as shown in Figure 4.

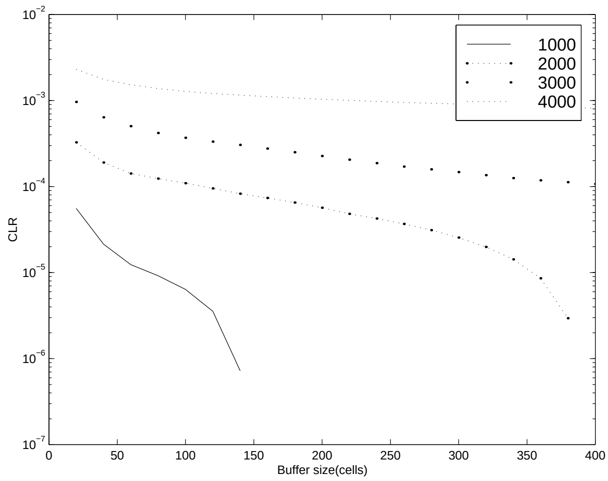

Fig. 4. CLR versus buffer size for different values of δ using dynamic bandwidth allocation.

From the figure, in order to achieve satisfactory CLR, the value of δ should be small, implying that a large number of renegotiations is needed. When the buffer size is large enough, CLR decreases rapidly, implying that buffering is effective in reducing CLR, which is difficult to achieve by CBR service. The actual bandwidth allocation for $\delta = 1000$ is shown in Fig. 5. The renegotiation frequency and bandwidth utilization for different thresholds are illustrated in Table 1.

[4] This idea was first presented at ITCC2001 [16].

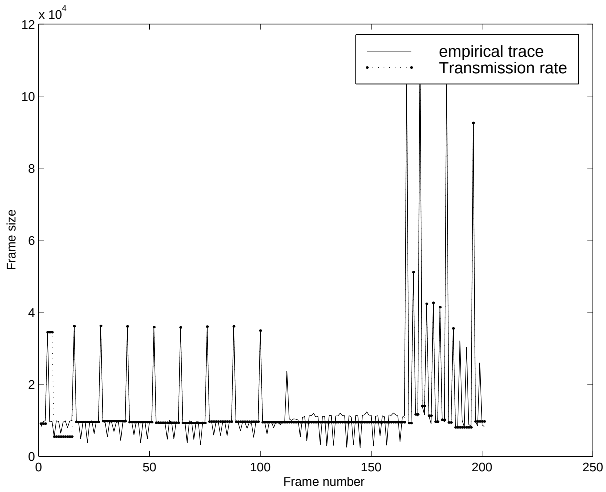

Fig. 5. Actually allocated bandwidth.

δ	1000	2000	3000	4000
FREQ.	71007	67229	63557	60197
Util.	0.9992	0.9988	0.9986	0.9982

Table 1. The number of renegotiations and bandwidth utilization for decisions based on each frame.

4.1. Reducing the Number of Renegotiations

Although the bandwidth utilization has been improved by dynamic bandwidth allocation, the renegotiation is still a big burden to network management. To reduce the renegotiation frequency while keeping the bandwidth utilization reasonably high, an algorithm based on I frames is introduced in this section.

Through the analysis of the MPEG video trace we find that I frames often have large frame sizes, and B frames have small frame sizes. Most of the time, when the I frame size changes significantly, P and B frame sizes also change significantly, implying that the increase or decrease of the I frame size often indicates the increase or decrease of P and B frame sizes, and therefore, we can base on I frames to allocate bandwidth to improve QoS and network utilization.

To allocate bandwidth, the algorithm is required to hold I frames to determine the size of I frames. When the I frame size changes significantly, a renegotiation can be triggered to ask for reallocation of bandwidth.

Suppose the I frame of the *kth* GOP is just ready to be transmitted. Let I_k be the size of the I frame of the *kth* GOP and R be the transmission rate for the previous GOP, δ be a threshold, then the dynamic bandwidth allocation algorithm can be stated as follows:

- if $|I_k - R/N| < \delta$, then the transmission rate remains unchanged.
- if $|I_k - R/N| \geq \delta$, then $R = I_k \times N$,

where N is the number of frames needs to be transmitted per second.

The negotiation frequency can be reduced significantly because only I frames need to be checked. Since the size of I frame is the largest in a GOP most of the time, the bandwidth allocated is very close to the largest one needed for the transmission of frames in the GOP, and therefore the CLR can be kept small. The negotiation frequency and bandwidth utilization are tabulated in Table 2 while the CLR for different values of δ are shown in Fig. 6. The results demonstrate that the renegotiation frequency can be reduced significantly.

δ	1000	10000	150000	20000
FREQ.	9208	2479	1694	1211
Util.	0.2584	0.2583	0.2588	0.2589

Table 2. The number of renegotiations and bandwidth utilization for decisions based on I frames.

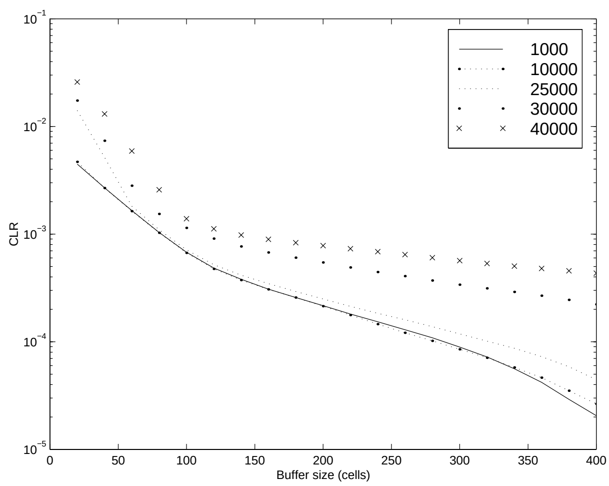

Fig. 6. CLR versus buffer size for different values of δ.

The actual bandwidth allocated when $\delta = 3000$ is shown in Fig. 7. From the table and figures, the CLR almost remains unchanged even when δ changes significantly, implying that the number of renegotiations can be reduced significantly without deteriorating the CLR performance.

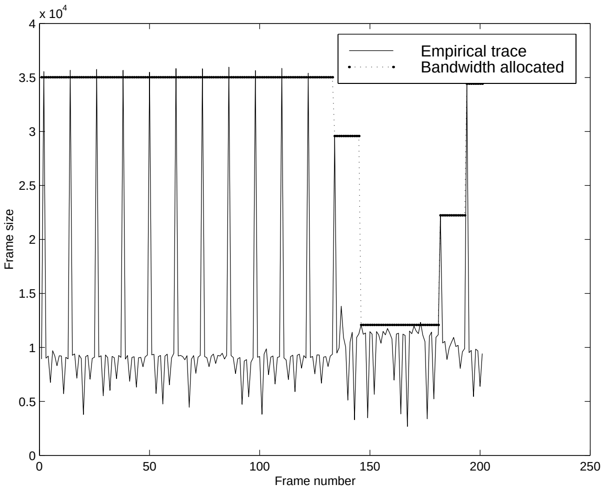

Fig. 7. Actually allocated bandwidth when δ=3000.

4.2. Increasing Bandwidth Utilization

As mentioned earlier, most of the time, I frames have the largest frame size in the respective GOPs, i.e, most of the time the bandwidth is not used efficiently. From the analysis of the empirical trace we can see that the difference between B frames for each GOP is not large. We can use this characteristic to increase the bandwidth utilization.

Again suppose that I_k is the size of the I frame of the kth GOP, B_k is the size of the B frame immediately following the I frame in the kth GOP, and R is the transmission rate for the previous GOP, and δ is the threshold. Assuming these two frames are ready for transmission, the dynamic bandwidth allocation algorithm can be altered as follows:

- if $|B_k + \alpha(I_k - B_k) - R/N| < \delta$, the transmission rate remains unchanged.
- otherwise, $R = [B_k + \alpha(I_k - B_k)] \times N$,

where δ is still the threshold, and α is a parameter which can be used to adjust the trade off between CLR and bandwidth utilization.

In general, the value of α should be less than one in order to have high bandwidth utilization. The value of α, however, can be larger than one if very good CLR performance is needed. The CLR performance for different α and δ are shown in Figs. 8 and 9. The renegotiation frequency and bandwidth utilization for $\alpha = 0.7$

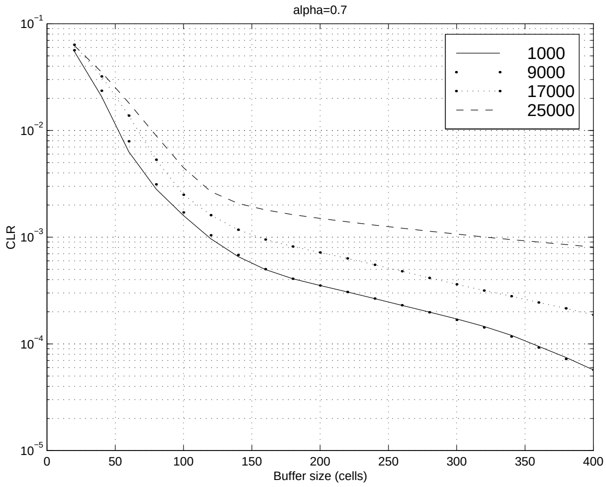

Fig. 8. CLR performance versus buffer size and δ, $\alpha = 0.7$.

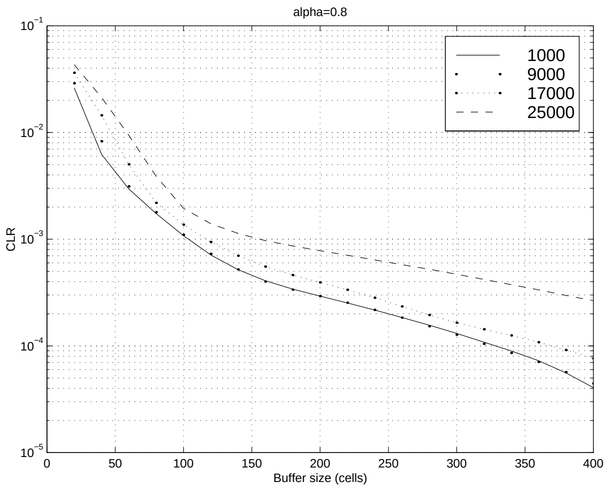

Fig. 9. CLR performance versus buffer size and δ, $\alpha = 0.8$.

δ	1000	7000	11000	19000
FREQ.	8113	2482	1611	763
Util.	0.3511	0.3508	0.3503	0.3515

Table 3. The number of renegotiations and bandwidth utilization for decisions based on I and B frames for $\alpha = 0.7$.

are shown in Table 3. The actual bandwidth allocated for the case $\delta = 9000$ and $\alpha = 0.8$ is shown in Fig. 10.

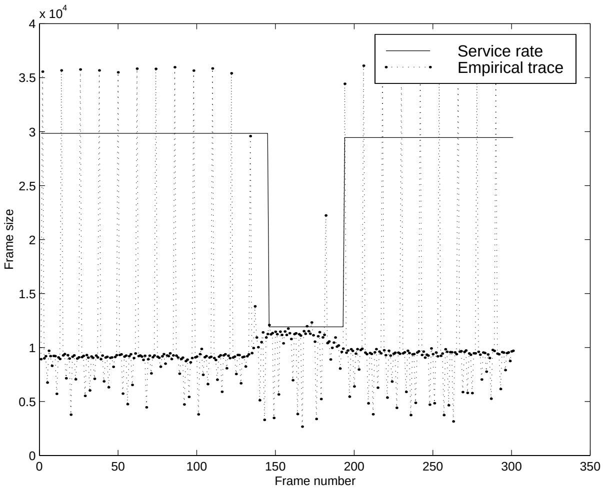

Fig. 10. Actually allocated bandwidth when δ=9000 and α=0.8.

We have experimented with other video traces, and similar results have been obtained using our proposed algorithms.

5. Conclusions

Several dynamic bandwidth allocation algorithms have been proposed for pre-recorded videos. Simulations demonstrate that the bandwidth utilization can be improved by a factor of 2 to 5, the buffer size can be reduced by a factor of 2 to 4, and the CLR can be reduced by an order of 2 to 3. Zero CLR with no delay can be achieved while the network utilization can be improved by a factor of 2.3. Three algorithms for real-time video delivery have also been proposed to renegotiate bandwidth on line to increase the bandwidth utilization and reduce CLR. It has been shown by simulations that the bandwidth utilization can be improved significantly, and the renegotiation frequency can be reduced to only several hundreds.

Acknowledgment

This work has been supported in part by the NJ Commission on Higher Education via the NJI-TOWER project, and New Jersey Commission on Science and Technology via the NJ Center for Wireless Telecommunications.

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Received: April, 2003
Accepted: October, 2003

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