Video on Demand over ATM: System Design and Networking Requirements

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Abstract

In recent years there has been a strong interest in transmitting compressed Video over ATM. Previous work has dealt with transmitting MPEG over CBR and VBR services of ATM. The ABR service of ATM is expected to be much more cost effective than CBR or VBR. There has been a limited amount of work done in transmitting video over ABR. However, there hasn't been much work done on running client/server applications (for example, video on demand) over ABR.

In this paper, we propose models for the design of video on demand systems transmitting MPEG-2 video over an ATM network using the ABR service category. By using the Real Time Dynamic Equilation (RTDE) analysis, we proposed models to determine buffering requirements at the client and the server of the system. We have also developed an analytical method to determine the ABR field parameters (such as PCR and ACR) required to run interactive client/server multimedia applications over an ATM network using the ABR service.

Keywords: Video-on demand, video over ABR, client/server design, performance evaluation, network design.

1 Introduction

ATM is a multiservice network which is capable of carrying voice, video and data over the same network. Consequently, interest in multimedia applications, such as video on demand and video conferencing, over ATM networks has been rapidly growing. Their further development will probably offer the greatest promise applications in communication and entertainment.

Currently, the ATM Forum has standardized four types of ATM bearer services: Constant Bit Rate (CBR), Variable Bit Rate (VBR), Available Bit Rate (ABR) and Unspecified Bit Rate (UBR). Of them, the ABR service has the highest utilization of network resource and offers an acceptable quality of service at low cost.

In the past few years, a limited amount of work has been carried out in transporting video over ATM using the CBR and VBR service categories. In [1, 2, 3, 4, 5, 6], the authors have discussed traffic shaping, congestion control, bandwidth allocation and rate control for VBR video over ATM, while in [7, 8], the authors investigated the bandwidth requirement for VBR video, The buffering requirements for stored video on demand was discussed in [9]. Quality control for VBR video over ATM for ABR service was presented in [10]. Simulation studies of bursty internet TCP traffic over ABR were presented in [11, 12], while the feedback control mechanism and service architecture for MPEG video were studied in [13, 14]. In [15], the authors proposed a scheme for transporting VBR compressed video over ATM using the Explicit-Rate congestion control mechanism of ABR.

Since MPEG-2 has a number of improvements over MPEG-1, such as random access, trick modes, multicast to many terminal types, multiple audio/video and compatible stereoscopic 3-dimension picture, it is expected that MPEG-2 will be widely used in the near future. Since ABR provides much more cost effective service for video than offered by CBR or VBR, it is crucial to study the performance, design and networking requirements of MPEG-2 video over ATM using the ABR service category. Previous efforts on transporting video over ATM mainly focussed on either source behavior or user performance, and most of them were concerned with the CBR and VBR service categories without studying the interactive nature of the client and its impact on the server.

A client/server video application running over a network (see Figure 1) typically uses a buffer at the client to smooth out network jitter (delay variations) [16, 17], and another buffer at the server to prevent cell losses when the network is congested. To make such a system commercially viable, it is essential to reduce the cost of the client and the server by optimizing the size of these buffers. Moreover, studying such a system requires the development of new client and server models which will reflect the interactive nature of the client and the uncertainty in bandwidth available to the server from the network. The *objective* of this paper is to develop methods which will enable us to design cost effective client/server applications and to determine networking requirements to run such applications over the ABR service in ATM networks.

In this paper, we have:

- proposed *new models of the client and the server* which take into account the interactive nature of the client and the uncertainties in the bandwidth available from the network due to the ABR ser-

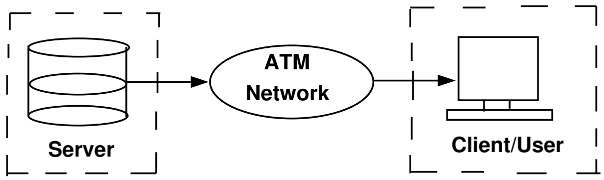

Figure 1: A networked client/server video application.

vice;

- developed analytical models to determine the *minimum fill level* at the client buffer to allow continuous playing of the video;
- developed models to determine the *optimal buffer size* at the client and the server;
- proposed techniques to evaluate the values of the *RM cell parameters* for transmitting interactive video over an ABR service;
- evaluated the effect of varying the *Group of Picture (GoP) size* of MPEG-2 video on buffering requirements;
- defined and evaluated *frame jump probability* at the client as a result of the server discarding frames due to a lack of bandwidth required to transmit frames during the fastforward/fastbackward operation of the client;

Since analytical techniques offer greater insight into the functionality of a system, and also allows a quick method of fine tuning the system parameters, we carry out our study using Markov chains and Real Time Dynamic Equilation techniques.

The rest of the paper is organized as follows. In Section 2, we propose a new client model and its interaction with the ABR service, analyze its operation, determine the minimum fill level of the buffer to avoid underflow and obtain the required minimum buffer size. In Section 3, we propose a novel server model which is compatible with the ABR service category, obtain the minimum buffer size required at the server, and obtain the RM cell parameters required to transmit video over the ABR service. Numerical results are presented in Section 4, followed by conclusions in Section 5.

2 Client Model and Operating Principle

The client is modeled as consisting of a buffer and a video decoder/display as shown in Figure 2. The buffer is required to smooth out fluctuations in the rate at which the client receives data from the network. We characterize the client behavior and operating modes as follows.

- The video stream coming to the buffer from the ATM network, at time t, has a frame rate $f(t)$ and each frame is of size $s(t)$. The bit rate $\mu(t)$ from the network is:

$$\mu(t) = f(t)s(t) \tag{1}$$

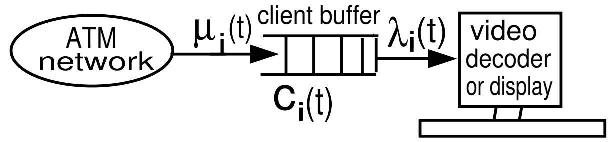

Figure 2: The client model.

- The client buffer, having a maximum size of C_u, has a fill level $C(t)$ at time t. We assume that the buffer is initially empty.

The client has four operating states and we model the client operation by a Markov chain as follows (see Figure 3):

1. *State C0:* The *stop* state where the client is not receiving video.
2. *State C1:* The *playback* state where the client receives data at the normal playback speed. In this states, the client consumes frames at a rate $q(t)$ at time t. The bit rate, $\lambda_1(t)$, at which the buffer is emptied is given by:

$$\lambda_1(t) = q(t)s(t) \tag{2}$$

3. *State C2:* This is the *fastforward* state (FFW) where the client sends a fastforward request to the server and consumes the current content of the client buffer at a speed which is k times faster than the rate at which it consumes data during the normal playback. Therefore, the data consumption rate, $\lambda_2(t)$, is:

$$\lambda_2(t) = kq(t)s(t) \tag{3}$$

4. *State C3:* This is the *fastbackward* state (FBW) where the client sends a fastbackward request to the server and consumes the current content of the client buffer at a speed which is k times faster than the rate at which it consumes data during the normal speed display. The consumption rate is therefore expressed by Eq. (3).

The state transition diagram of the client behavior is shown in Figure 3, where $\tau^c_{i,j}$ represent the state transition probability from state i to state j of the client. The client operates as follows:

- The client always start from state C0 and can only go to state C1;
- The client can perform a FFW or FBW directly from state C1; after the completion of the FFW or FBW, it must return back to state C1.

According to the properties of Markov chain [18], for our above client model, a stationary state exists for a long-run behavior. For the client states, we assume a steady state probability vector $V^c = (V^c_0, V^c_1, V^c_2, V^c_3)$ which satisfies:

$$V^c = V^c P^c \tag{4}$$

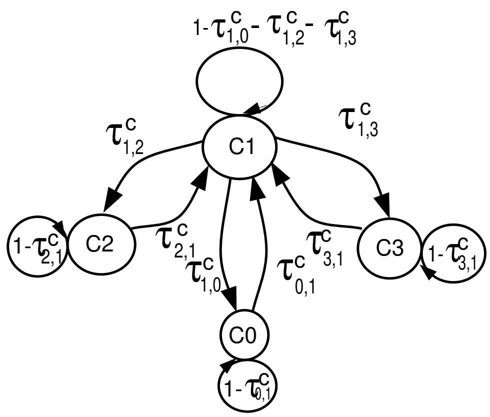

Figure 3: The state diagram of client.

The transition matrix P^c is given by:

$$P^c = \begin{bmatrix} 1-\tau^c_{0,1} & \tau^c_{0,1} & 0 & 0 \\ \tau^c_{1,0} & 1-\tau^c_{1,2}-\tau^c_{1,3}-\tau^c_{1,0} & \tau^c_{1,2} & \tau^c_{1,3} \\ 0 & \tau^c_{2,1} & 1-\tau^c_{2,1} & 0 \\ 0 & \tau^c_{3,1} & 0 & 1-\tau^c_{3,1} \end{bmatrix}$$

We can solve the above equations to obtain the steady state probability vector of the client states as follows:

$$\begin{aligned} V^c_0 &= \frac{1}{1+\tau^c_{0,1}/\tau^c_{1,0}(1+\tau^c_{1,2}/\tau^c_{2,1}+\tau^c_{1,3}/\tau^c_{3,1})} \\ V^c_1 &= \frac{\tau^c_{0,1}}{\tau^c_{1,0}(1+\tau^c_{0,1}/\tau^c_{1,0}(1+\tau^c_{1,2}/\tau^c_{2,1}+\tau^c_{1,3}/\tau^c_{3,1}))} \\ V^c_2 &= \frac{\tau^c_{0,1}\tau^c_{1,2}}{\tau^c_{1,0}\tau^c_{2,1}(1+\tau^c_{0,1}/\tau^c_{1,0}(1+\tau^c_{1,2}/\tau^c_{2,1}+\tau^c_{1,3}/\tau^c_{3,1}))} \\ V^c_3 &= \frac{\tau^c_{0,1}\tau^c_{1,3}}{\tau^c_{1,0}\tau^c_{3,1}(1+\tau^c_{0,1}/\tau^c_{1,0}(1+\tau^c_{1,2}/\tau^c_{2,1}+\tau^c_{1,3}/\tau^c_{3,1}))} \end{aligned}$$

Therefore, at any given time t, the expected data consumption rate by the client can be found by:

$$E[\lambda(t)] = \sum_{i=1}^{3} V^c_i \lambda_i(t) \tag{5}$$

Since the frame rate of MPEG-2 video is constant [16], we can write

$$E[\lambda(t)] = [V^c_1 + k(V^c_2 + V^c_3)]\lambda_1(t) \tag{6}$$

We now use the Real Time Dynamic Equilation (RTDE) method in our following analysis. Assuming that the client buffer is empty at time $t = 0$, if the buffer does not overflow or underflow during the time period $[0, t]$, the following equation must be satisfied.

$$0 \le C(t) \le C_u, \text{for all } t \ge 0 \tag{7}$$

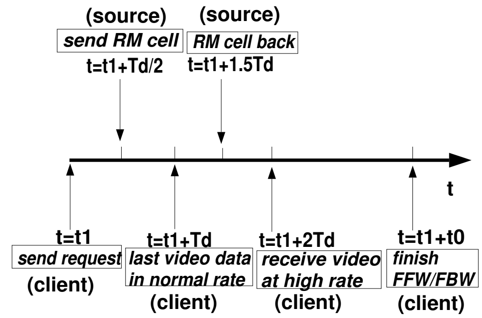

Figure 4: The illustration for calculate C_{min}.

The buffer fill level $C(t)$ at time t is then obtained from

$$C(t) = \int_0^t (\mu(t) - \lambda(t))dt \tag{8}$$

Assume that at time t_1, the client switches from playback to fastforward (or fastbackward) which has a duration of time t_0. The server will react to this operation after a single trip delay time $T_d/2$, where T_d is the round trip delay in the ATM network. Therefore, from time t_1 to $t_1 + T_d$, the input bit rate to the client buffer will still be $\mu_i(t)$. During this duration, the client will consume from the buffer an amount of data Q_d and get a input amount of data Q_{in1} given by:

$$Q_d = \int_{t_1}^{t_1+t_0} k\lambda_1(t)d(t) Q_{in1} = \int_{t_1}^{t_1+T_d} \mu_1(t)d(t) \tag{9}$$

From the Figure 4, the client will receive the video sent at speed k'$\mu_1(t)$ after $2T_d$ delay, the amount of data is Q_{in2} as:

$$Q_{in2} = \int_{t_1+2T_d}^{t1+t_0} k'\mu_1(t)d(t) \tag{10}$$

Therefore, during the entire FFW/FBW there exist the following requirement for no starvation:

$$C(t_1) + Q_{in1} + Q_{in2} - Q_d \ge 0 \tag{11}$$

substituting into the expressions for Q_d, Q_{in1}, Q_{in2}, we get:

$$\begin{aligned} C(t_1) + \textstyle\int_{t_1}^{t_1+T_d} \mu_1(t)d(t) + \int_{t_1+2T_d}^{t1+t_0} k'\mu_1(t)d(t) \\ - \textstyle\int_{t_1}^{t_1+t_0} k\lambda_1(t)d(t) \ge 0 \end{aligned} \tag{12}$$

where k' is the speed increase factor for server.

$$\begin{aligned} C(t) \quad \ge \quad & (2k-1)T_d \max(E[\lambda_1(t)], E[\mu(t)]) + (t_0 - \\ & 2T_d)(k-k')max(E[\lambda_1(t), E['\mu(t)]) \end{aligned} \tag{13}$$

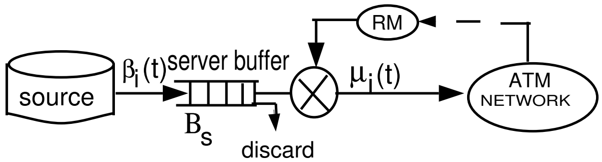

Figure 5: The server model.

Normally, $t_0 >> T_d$, at the optimal condition that the input data rate match with the consum data rate at client, we get the minimum buffer fill level required at the client to prevent underflow (which also sets a limit on the minimum buffer size) is given by:

$$C(t)_{\min} \geq (2k-1)T_d E[\lambda(t)] \tag{14}$$

3 Server Model and Operation

The server uses the ABR service to send video through the network. The server consists of the source (see Figure 5) which sends MPEG-2 video to a server buffer to smooth the video traffic before injecting it into the ATM network. The backward RM cell from the ATM network determines the bit rate from the server to the network. The MPEG-2 video normally has an MmNn group of picture (GoP). Since the server states depend on the state of the client, we can describe the server state as follows (see Figure 6).

- *State S0:* represents the stop state;
- *State S1:* represents the state where the server is sending data for normal playback at the client;
- *State S2:* represents the state where the server is sending data at a high speed, corresponding to the FFW or FBW state of the client.

The state transition probability from state i to j is represented by $\tau^s_{i,j}$. The server operates as follows:

- server always starts from state S0, and can only move to state S1 from state S0;
- at the beginning, the server sets its ICR equal to PCR, the ACR equal to the mean bit rate of the MPEG-2 corresponding to the current GoP, and the MCR equal to the bit rate of the B frame;
- at the end of each GoP, it asks for a PCR bandwidth; after sending the I frame, it slow down to the ACR rate;
- when the server receives a FFW or FBW request from the client, it first stops sending data and sends an RM cell requesting a higher bandwidth. After receiving the backward RM cell, the server starts sending video data at the authorized higher rate;
- at the end of the FFW or FBW operation, the server returns to state S1;
- if the available bandwidth is less than the requested value, the B frames are discarded first, followed by P frames if needed. Since P frames are more important than B frames in the reassembly of frames at the client, we drop the B frames first.

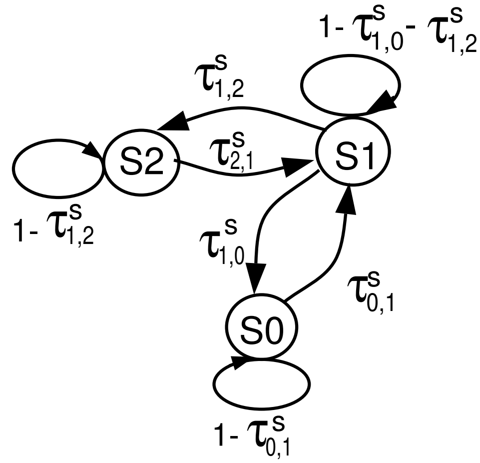

Figure 6: State transition diagram of the server.

The state transition matrix P^s for the server is given by:

$$P^s = \begin{bmatrix} 1-\tau^s_{0,1} & \tau^s_{0,1} & 0 \\ \tau^s_{1,0} & 1-\tau^s_{1,2}-\tau^s_{1,0} & \tau^s_{1,2} \\ 0 & \tau^s_{2,1} & 1-\tau^s_{2,1} \end{bmatrix} \tag{15}$$

The steady state probability vector $V^s = (V^s_0, V^s_1, V^s_2)$ corresponding to the states of the buffer is given by:

$$\begin{aligned} V^s_0 &= \frac{1}{1+\tau^s_{0,1}/\tau^s_{1,0}(1+\tau^s_{1,2}/\tau^s_{2,1})} \\ V^s_1 &= \frac{\tau^s_{0,1}}{\tau^s_{1,0}(1+\tau^s_{0,1}/\tau^s_{1,0}(1+\tau^s_{1,2}/\tau^s_{2,1}))} \\ V^s_2 &= \frac{\tau^s_{0,1}\tau^s_{1,2}}{\tau^s_{2,1}\tau^s_{1,0}(1+\tau^s_{0,1}/\tau^s_{1,0}(1+\tau^s_{1,2}/\tau^s_{2,1}))} \end{aligned} \tag{16}$$

We now want to determine the values of the RM cell parameters shown in Table 1. Let

$T_f =$ duration of a frame

Table 1: RM Cell Field Parameters.

PCR	decided by Eq. (18)
MCR	$E[\beta_B]$ mean bit rate for B-frame of MPEG-2
ICR	PCR
ACR	$E[\beta]$ average bit rate for MmNn GoP of MPEG-2
TBE	$C(t)_{\min}$
RIF	1 or 2
RDF	1 or 2

$\beta_I=$ mean bit rate of I frame

$\beta_P=$ mean bit rate of P frame

$\beta_B=$ mean bit rate of B frame

$E[\beta]=$ average bit rate of MmNn GoP

$\beta_a=$ bit rate requested by the server in the FFW or FBW state

$B_s=$ minimum buffer size for server

$C(t)_{\min}=$ minimum fill level of client buffer.

To determine the optimal buffer size at the server, the dynamic variation of the buffer accumulation at the server should be zero for each GoP:

$$\delta(\text{buffer accumulation}) = 0 \tag{17}$$

Also, the PCR and ACR must satisfy the following relationship:

$$\begin{aligned}(\beta_I - PCR) \quad &\leq \quad ACR(N-1) - \beta_P(N/M-1) - \\ &\quad\quad \beta_B N/M(M-1)\end{aligned} \tag{18}$$

If PCR is equal to the ACR, we obtain the requirement for ACR as:

$$ACR \geq E[\beta] \tag{19}$$

Therefore, the minimum size of server buffer B_s is given by:

$$B_s = (E[\beta_I] - PCR)T_f \tag{20}$$

Typically, for an MPEG-2 M3N9 GoP, $\beta_I = 8.25$ Mb/s, $\beta_P = 2.25$ Mb/s, $\beta_B = 0.6$ Mb/s, $E[\beta] = 1.817$ Mb/s and $T_f = 0.033$ sec [19]. This gives a minimum buffer size for the server to be about 200 Kb at PCR=2 Mb/s and ACR=1.817 Mb/s.

The combined client and server model is shown in Figure 7. In this simple model, the network acts as a transmission channel with a fixed round trip time (FRTT) equal to T_d, and also allocates bandwidth to the server through the backward RM cells.

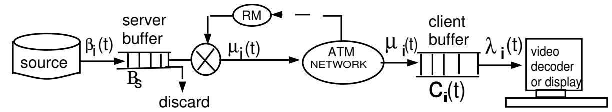

Figure 7: The client/server model.

We want to determine the effect of the network rejecting the bandwidth requested by the server. We assume that the network rejects any request for a higher bandwidth by an exponential distribution as follows:

$$P(\beta_a) = 1 - e^{-\alpha\frac{\beta_a - \beta_m}{\beta_p - \beta_m}} \tag{21}$$

where α is a constant, and β_p, β_m, and β_a are the PCR, MCR and ACR respectively. When the server can not obtain the requested bandwidth from network, it will discard B and/or P fames resulting in frame jumps at the client. The frame jump probability P_j resulting from the FFW/or FBW operation can be expressed as:

$$P_j = V_2^s P(\beta_a) \tag{22}$$

4 Numerical Results

The relationship between the client buffer size versus the FRTT is shown in Figures 8 and 9 corresponding to the two client states for GoP of M3N9 and M3N15. It is seen that the the minimum receiver buffer size increases linearly with an increase in the the FRTT as expected from Equation (14). For a fixed value of FRTT, if the probability of the client being in the FFW/FBW state increases, the required buffer size increases.

Figures 10 and 11 show the minimum client buffer size as a function of the FFW/FBW probability for T_d = 50 ms and 20 ms and for GoP of M3N9 and M3N15.

For small values of FRTT, the required minimum client buffer size does not vary much as a function of the FFW/FBW probability. On the other hand, for large values of FRTT, the required client buffer size varies significantly with the FFW/FBW probability.

For both the small and large values of FRTT, M3N15 GoP need smaller client buffer size than that required for M3N9 GoP. This is because M3N15 GoP has a relatively smaller burst compared to that of M3N9 GoP.

Figures 12 and 13 show the frame jump probability of client while the client is in the FFW or FBW state.

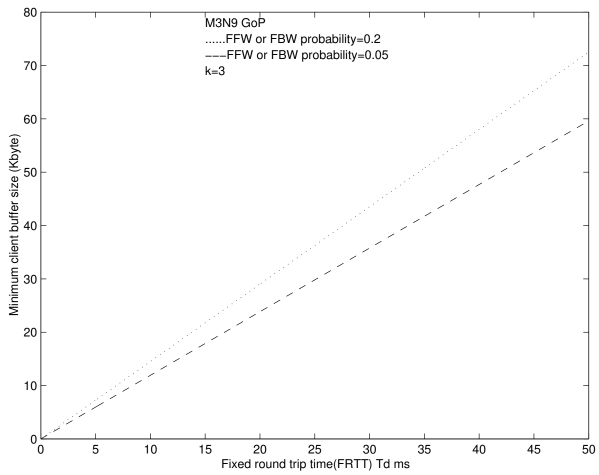

Figure 8: Minimum client buffer size versus FRTT for M3N9 GoP.

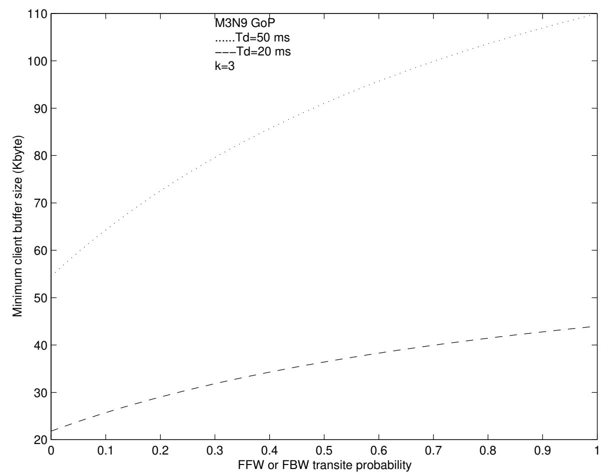

Figure 10: Minimum client buffer size versus FFW/FBW probability for M3N9 GoP.

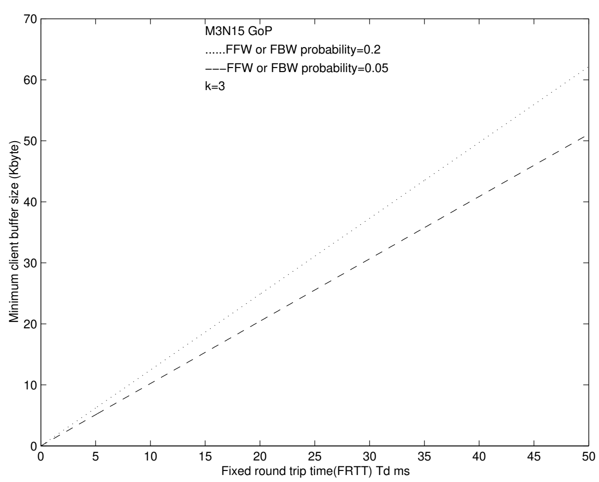

Figure 9: Minimum client buffer size versus FRTT for M3N15 GoP.

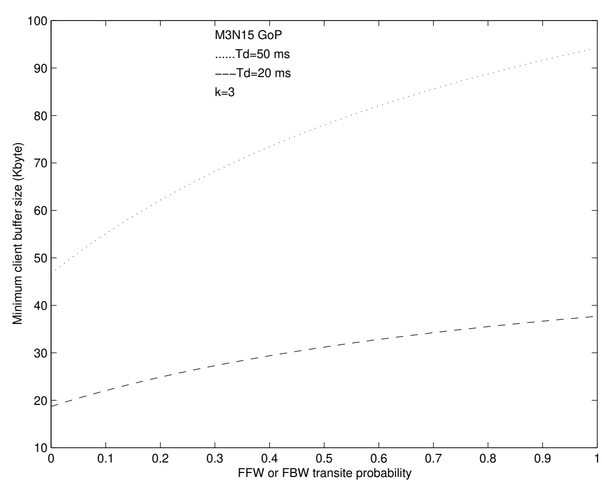

Figure 11: Minimum client buffer size versus FFW/FBW probability for M3N15 GoP.

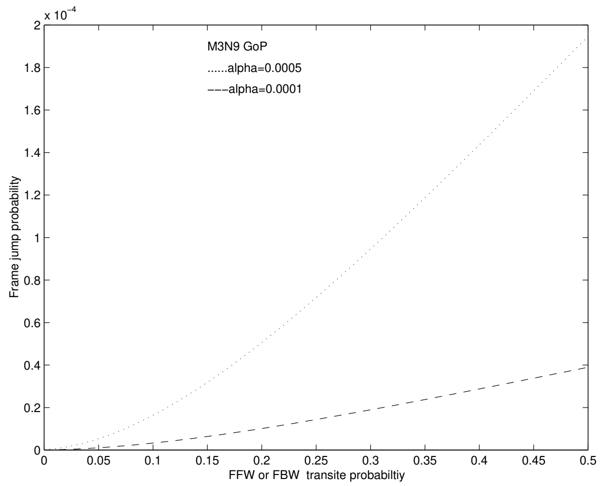

Figure 12: Frame jump probability versus FFW/FBW probability for M3N9 GoP for two network states.

It is seen that the frame jump probability increase exponentially with an increase in the FFW/FBW probability. We also observe that the M3N9 GoP results in a smaller frame jump probability than that due to M3N15 GoP. This is because M3N9 GoP has fewer B and/or P frames per GoP as compared to M3N15 GoP.

The dynamic fill level of the server buffer for different GoP is shown in Figures 14 and 15. It is seen that the server buffer fill level increases initially due to the high data burst coming from the I frame. This is followed by B frames which have data rates lower than the rate at which the buffer sends data to the network. This results in a reduction of the buffer fill level. Since P frames contain a large amount of data, the buffer fill level goes up momentarily whenever the P frames are transmitted. At the end of the period required to transmit a GoP, the buffer level fills to zero as is required by Equation (17). This further proves that the RM cell parameters set by Equations (18) and (19) are correct.

5 Conclusion

We have established the design criteria and networking requirements for a video on demand system carrying MPEG-2 video over an ATM network using the Available Bit Rate service. First, we have proposed the the client and server models for the above system. Secondly, by using the Real Time Dynamic Equilation analysis, we have determined the values of the required RM cell parameters of the ABR service. Thirdly, we have formulated analytical expressions to

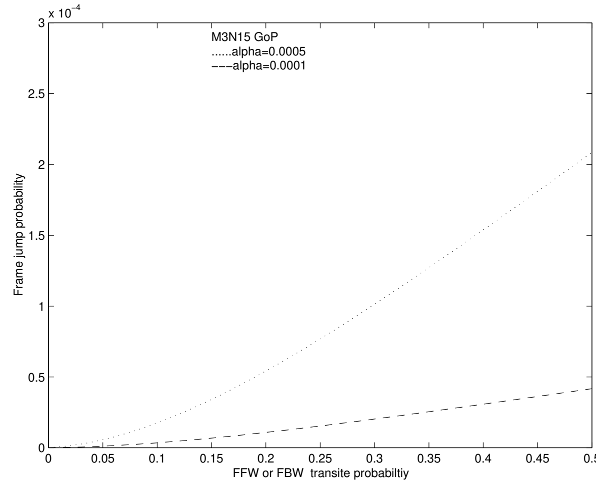

Figure 13: Frame jump probability versus FFW/FBW probability for M3N15 GoP for two network states.

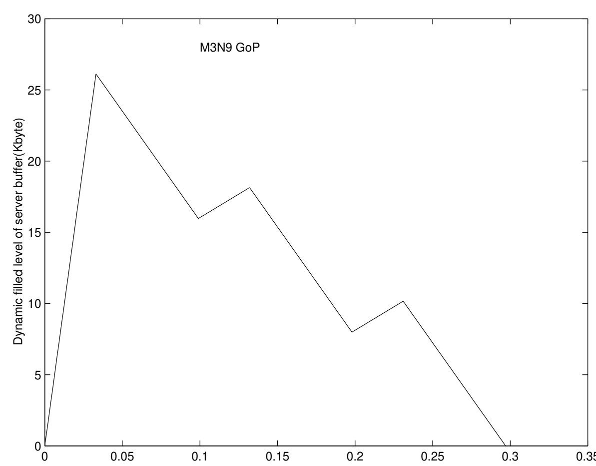

Figure 14: The dynamic fill level of server buffer for a M3N9 GoP.

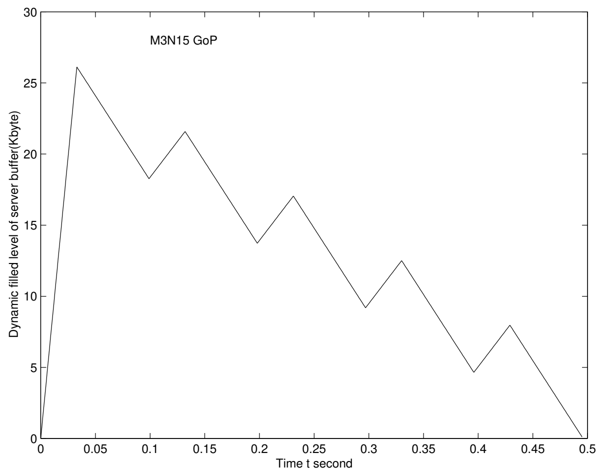

Figure 15: The dynamic fill level of server buffer for a M3N15 GoP.

determine the minimum buffer size at the server and at the client to prevent underflow at the client. We have also looked at the interactions between the client and the server with the various trick modes of the client operation.

We conclude that the client buffer size depends directly on the FFW/FBW probability; the higher the probability, the larger is the required size of the buffer. Our second conclusion is that the larger the GoP of an MPEG-2 stream, the lower is the required size of the client buffer. This is because the larger the value of the GoP, the less bursty is the video stream which in turn requires less buffering at the client.

Our third conclusion is that the frame jump probability has an exponential relationship with the FFW/FBW probability. A higher value of GoP implies a larger number of B and P frames before an I frame is repeated. Therefore, the higher the size of the GoP, the higher is the frame jump probability and smaller is the required buffer size. However, it should be noted that the higher the value of GoP the lower is the quality of the video received at the client in the case of frame jumps. We also showed that the frame jump probability was directly governed by the available network bandwidth.

We also found that there is a trade-off between the required buffer size, the desired QoS, and the value of the GoP of an MPEG-2 video. If the aim is to reduce the burstiness of the data and to decrease the required client buffer size, a high value of GoP should be employed. On the other hand, to improve the QoS of the video for a given network specification, a small value of GoP should be used.

6 Acknowledgment

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