Analysis of Priority Based Scheduling of Real-Time Video over 3G Wireless Network

Ji-An Zhao*, Bo Li*, Chi-Wah Kok**, and Ahmad Ishfaq*

* Department of Computer Science
The Hong Kong University of Science & Technology
Clear Water Bay, Kowloon, Hong Kong, China
Correspondence: Bo Li, Tel: +852 23586976
Email: zhaojian@cs.ust.hk, bli@cs.ust.hk, iahmad@cs.ust.hk
** Department of Electrical & Electronic Engineering
The Hong Kong University of Science & Technology
Clear Water Bay, Kowloon, Hong Kong, China
Email: eekok@ust.hk

Abstract

In this paper we proposed a performance model for real-time video transmission over the uplink of the third generation wireless network. The video traffic arrival is modeled as a marked discrete time batch Markovian arrival process with priorities. The wireless channel is assumed to have correlated errors that follow a hidden Markov model. We propose a priority based scheduling with automatic repeat request and overdue control for layered video transmission. The transmission time for an arbitrary radio link control data burst is shown to follow a discrete phase type distribution. A *DBMAP / PH / 1* priority queueing model is formulated for the video transmission buffer and the queueing behavior is simulated. Simulation results showed that better quality of service could be achieved for the high priority queue.

1 Introduction

In recent years, wireless video communication has received much attention. The deployment of third generation (3G) wireless networks will inevitably accelerate the application of wireless video. Various radio transmission technologies (RTT) are adopted in 3G wireless networks. The UMTS Terrestrial Radio Access (UTRA) and CDMA2000 are based on CDMA while UWC-136 is based on TDMA. The basic transmission unit for 3G wireless networks is defined by time slot. During each time slot, a specific size of data block, depending on channel coding methods, can be transmitted. This unit of data block is referred as radio link control (RLC) burst. Real-time variable bit rate (VBR) compressed video is an important application in wireless networks. Real-time video service is bandwidth starving and delay-constrained. VBR video source traffic may have high peak-to-mean ratios and high autocorrelations. A survey of VBR video source model can be found in [9]. We are interested in the discrete time batch Markovian arrival process (DBMAP), which had been introduced to model VBR video traffic [2]. The paper is organized as follows. In Section 2 we introduce the marked DBMAP process as real-time video traffic source model. In Section 3, based on a hidden Markov modeled (HMM) wireless channel, we show that the transmission time of an arbitrary RLC date burst follows a discrete PH-type distribution, and we propose a priority based scheduling algorithm with ARQ control for video data transmission. In Section 4, a *DBMAP / PH / 1* priority queueing model is formulated for the video transmission buffer. Finally we introduce the simulation model for the *DBMAP / PH / 1* priority queue and provide simulation results in Section 5.

2 Video Source Model: Marked DBMAP with Priorities

Consider the transmission procedure of a video packet over time-slotted 3G network, generally, the video packet is first cut into data link layer segments. At the medium access control (MAC) layer, these link layer segments are further segmented into fixed size RLC bursts. These RLC bursts are then fed into the wireless transmission buffer. The video packet can have variable size, as a result, each video packet corresponds to a random-sized batch of RLC bursts. Further, arrival patterns of video sources are often correlated, which can be captured by a Markov chain. These features naturally lead to a discrete time batch Markovian arrival process (DBMAP) modeled video source [1,2]. The DBMAP process, however, can only describe single class or priority of arrivals. To extend the DBMAP process to more than one class or priority of arrivals, we take the approach as the Markovian arrival process with marked transition [5].

Consider an n-state DBMAP arrival process with *2* types of arrivals, one type belongs to the high priority and the other belongs to low priority. In most applications, the maximum allowable arrival batch size is often bounded. For example, a video packet only contains finite bytes of data. Let the maximum batch size for high priority arrival and low priority arrival be b_1 and b_2,

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respectively. The parameter matrices for the marked DBMAP are $\{D_{00}, D_{01}, \Lambda\ , D_{b_1b_2}\}$, all are $n \times n$ matrices. Suppose that at time $t, t \geq 0$, the underlying Markov chain of the DBMAP process is in state $j, 1 \leq j \leq n$; then at time epoch $t + 1$, with conditional probability $D_{i_1i_2}(j, j'), i_1 \geq 0, i_2 \geq 0$, there is a transition to state $j', 1 \leq j' \leq n$, with a batch of i_1 high priority arrivals and a batch of i_2 low priority arrivals, simultaneously. Here i_1, i_2 could be *0*. The transition probability matrix of the underlying Markov chain is $D = \sum_{i_1=0}^{\infty} \sum_{i_2=0}^{\infty} D_{i_1i_2}$, and the initial vector is α, with $\alpha = \alpha D$. The arrival rates for the high and low priority queue are given by

$$\lambda_h = \pi(\sum_{i_1=1}^{\infty} \sum_{i_2=1}^{\infty} i_1 D_{i_1i_2})e, \lambda_l = \pi(\sum_{i_1=1}^{\infty} \sum_{i_2=1}^{\infty} i_2 D_{i_1i_2})e.$$

We shall refer the above priority arrival model as a marked DBMAP process with *2* priority levels.

3 Wireless Channel and Service Model

Due to the presence of multi-path fading effects, movement of mobile terminals and interference caused by high-bandwidth transmissions, wireless data communication channel exhibits correlated errors. To capture the error correlation characteristic of the wireless channel, a hidden Markov based channel model (HMM) had been proposed in [11]. Consider a binary wireless channel that is time slotted and one date burst can be transmitted in each time slot. Assume the error process be modeled by a stationary HMM process which is defined by $2\, m \times m$ transition probability matrices $P_E, E = 0,1$. Suppose at time *t*, the channel is in state $i, 1 \leq i \leq m$; then at time $t + 1$, the channel evolves from state *i* to state *j*, with a correct transmission probabilities of $P_0(i, j)$ and error transmission probabilities of $P_1(i, j)$. P_0 and P_1 are called transition probability matrices for a correct reception and error reception, respectively. The wireless channel evolves following a Markov chain with transition probability matrix $P_0 + P_1$. Assume the channel process is stationary, the steady state probability vector is θ such that $\theta(P_0 + P_1) = \theta, \theta e = 1$.

We adopt ARQ based protocol for error recovery during wireless video transmission. We ignore the feedback delay for the acknowledgement such that retransmission can be invoked immediately in the next time slot when error occurs. Since real-time video is considered, when the wireless channel quality becomes bad, the serving RLC data burst should not occupy the channel for prolonged period of time and thus block the buffering of video data. Therefore, we set an overdue time for each RLC burst such that once the overdue time is exceeded, further (re)transmission attempt for the serving RLC bursts of a video packet will stop, and the overdue RLC burst will be dropped. To better serve the video through an unreliable network, like wireless network, various video standards had proposed to transmit the video data in layered format [10], such that the lower layer data when received by the client will allows a faithful reconstruction of the video. If the client further receives the enhancement layer data, higher quality video can be reconstructed. Considering this, we proposed to prioritize the incoming video packets into *2* levels - say, a MPEG-4 *I*-frame packet has higher transmission priority than a *P*-frame packet. Higher priority packets are always transmitted ahead of the buffered lower priority packets. Suppose that sufficient bandwidth is allocated to a real-time video session. When the wireless channel quality if good, almost all the queueing RLC data bursts can be served in time and the highest video quality can be achieved. When the quality of wireless channel decreases, the ARQ protocol will request for more RLC burst retransmission. This results in a decrease of the buffer depletion rate. Since higher priority RLC bursts gets served first, the burst overdue probability will be less than of the lower priority bursts. This simple service differentiation can ensure that higher priority packets have better chance of successful delivery. Thus faithful video quality can be maintained in the receiver side even when the quality of the wireless channel becomes bad.

Assume the maximum tolerable transmission time for a RLC burst is $d, d > 1$, the service time or the channel occupation time till correct receipt or drop due to overdue can be derived as following. Define the service state $\{(l, j), 1 < l < d, 1 < j < m\}$, which corresponds to the situation that the serving burst is in *l*-th (re)transmission and the channel phase is in *j*. The channel itself evolves according to stochastic matrix $P = P_0 + P_1$ as defined above. When the channel evolves according to sub-stochastic matrix P_0, the transmission is successful and the service process will terminate, with transition probability vector of $P_0 e$. When the channel evolves according to sub-stochastic matrix P_1, the transmission is failing, *l* will change to *l+1* and *j* will change accordingly. Thus the transition probability matrix of the service process is given by S as below, where P_0, P_1 are $m \times m$ size sub-stochastic matrices and S is $(dm + 1) \times (dm + 1)$ size stochastic matrix. Let $\beta = [1,0,0,\Lambda\ ]$, let S' be the left-upper sub-matrix of S with the last row and last column deleted, resulting in a $dm \times dm$ size sub-stochastic matrix. It is obvious the service time for an arbitrary RLC burst follows a discrete PH-type distribution [3] with representation (β, S').

$$S=\begin{bmatrix} 0 & P_1 & 0 & \cdots & 0 & P_0e \\ 0 & 0 & P_1 & \cdots & 0 & P_0e \\ \vdots & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \ddots & P_1 & P_0e \\ 0 & 0 & 0 & \ddots & 0 & e \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix}.$$

4 $DBMAP/PH/1$ priority queueing model

Let the arrival process parameters are given by $\{D_{00}, D_{01}, \cdots, D_{b_1b_2}, \alpha, D\}$, and the service processes for the high and low priority data bursts are given by $\{(\beta_1, S_1), (\beta_2, S_2)\}$. The dimension for D, S_1, S_2 are $n\times n$, $m_1\times m_1$, $m_2\times m_2$, respectively. Assume the service discipline is preemptive priority, a $DBMAP/PH/1$ priority queueing model can be formulated with the following state space:

$$\Delta_1 = \{(0,0,j), j=1,2,...n\}$$
$$\Delta_2 = \{(0,i_2,j,k_2), i_2\ge 1; j=1,2,...n; k_2=1,2,...m_2\}$$
$$\Delta_3 = \{(i_1,i_2,j,k_1), i_1\ge 1; i_2\ge 0; j=1,2,...n; k_1=1,2,...m_1\}.$$

In Δ_1, $(0,0,j)$ represents the case when the server is idle with the arrival process in phase *j*. In Δ_2, $(0,i_2,j,k_2)$ represents the case there are only i_2 ($i_2\ge 1$) low priority bursts in the system, with the arrival process in phase *j* and service process in phase k_2. In Δ_3, (i_1,i_2,j,k_1) represents the case when there are at lease i_1 ($i_1\ge 1$) high priority bursts in the system and there are i_2 ($i_2\ge 0$) low priority bursts in the system, the arrival process is in phase *j*, and the service process is in phase k_1. The queueing system can be described by a $M/G/1$ type [4] Markov chain with state space $\Delta=\Delta_1\cup\Delta_2\cup\Delta_3$. The transition probability matrix *P* of the Markov chain is

$$P=\begin{bmatrix} B_{00} & B_{01} & B_{02} & \cdots & B_{0b_1} & & & & \\ B_{10} & A_0 & A_1 & \cdots & A_{b_1-1} & A_{b_1} & & & \\ & A_{-1} & A_0 & \cdots & A_{b_1-2} & A_{b_1-1} & A_{b_1} & & \\ & & A_{-1} & \cdots & A_{b_1-3} & A_{b_1-2} & A_{b_1-1} & A_{b_1} & \\ & & & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \end{bmatrix},$$

with the following sub-matrices:

$$B_{00}=\begin{bmatrix} B_{00}^{00} & B_{00}^{01} & B_{00}^{02} & \cdots & B_{00}^{0b_2} & & & & \\ B_{00}^{10} & B_{00}^{0} & B_{00}^{1} & \cdots & B_{00}^{b_2-1} & B_{00}^{b_2} & & & \\ & B_{00}^{-1} & B_{00}^{0} & \cdots & B_{00}^{b_2-2} & B_{00}^{b_2-1} & B_{00}^{b_2} & & \\ & & B_{00}^{-1} & \cdots & B_{00}^{b_2-3} & B_{00}^{b_2-2} & B_{00}^{b_2-1} & B_{00}^{b_2} & \\ & & & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \end{bmatrix},$$

$$B_{00}^{00}=D_{00}$$
$$B_{00}^{0i_2}=D_{0i_2}\otimes\beta_2, i_2=0,1,...,b_2$$
$$B_{00}^{10}=D_{00}\otimes S_2^0$$
$$B_{00}^{i_2}=D_{0i_2}\otimes S_2+D_{0(i_2+1)}\otimes S_2^0\beta_2,$$
$$i_2=0,1,...,b_2-1$$
$$B_{00}^{b_2}=D_{0b_2}\otimes S_2, B_{00}^{-1}=D_{00}\otimes S_2^0\beta_2,$$

$$B_{0i_1}=\begin{bmatrix} B_{0i_1}^{00} & B_{0i_1}^{01} & B_{0i_1}^{02} & \cdots & B_{0i_1}^{0b_2} & & & \\ B_{0i_1}^{-1} & B_{0i_1}^{0} & B_{0i_1}^{1} & \cdots & B_{0i_1}^{b_2-1} & B_{0i_1}^{b_2} & & \\ & B_{0i_1}^{-1} & B_{0i_1}^{0} & \cdots & B_{0i_1}^{b_2-2} & B_{0i_1}^{b_2-1} & B_{0i_1}^{b_2} & \\ & & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \end{bmatrix}$$
$$i_1=0,1,...,b_1,$$

$$B_{0i_1}^{0i_2}=D_{i_1i_2}\otimes\beta_1, i_2=0,1,...,b_2$$
$$B_{0i_1}^{-1}=D_{i_10}\otimes S_2^0\beta_1$$
$$B_{0i_1}^{i_2}=D_{i_1(i_2+1)}\otimes S_2^0\beta_1+D_{i_1i_2}\otimes S_2e\beta_1, i_2=0,1,...,b_2-1$$
$$B_{0i_1}^{b_2}=D_{i_1b_2}\otimes S_2e\beta_1,$$

$$A_{-1}=\begin{bmatrix} A_{-1}^{0} & A_{-1}^{1} & A_{-1}^{2} & \cdots & A_{-1}^{b_2} & & \\ & A_{-1}^{0} & A_{-1}^{1} & \cdots & A_{-1}^{b_2-1} & A_{-1}^{b_2} & \\ & & \ddots & \ddots & \ddots & \ddots & \ddots \end{bmatrix},$$

$$A_{-1}^{i_2}=D_{0i_2}\otimes S_1^0\beta_1, i_2=0,1,...,b_2.$$

$$B_{10}=\begin{bmatrix} B_{10}^{00} & B_{10}^{01} & B_{10}^{02} & \Lambda & B_{10}^{0b_2} & & & \\ & B_{10}^{0} & B_{10}^{1} & \Lambda & B_{10}^{b_2-1} & B_{10}^{b_2} & & \\ & & B_{10}^{0} & \Lambda & B_{10}^{b_2-2} & B_{10}^{b_2-1} & B_{10}^{b_2} & \\ & & & O & O & O & O & O \end{bmatrix},\quad \begin{aligned} &B_{10}^{00}=D_{00}\otimes S_1^0\\ &B_{10}^{0i_2}=D_{0i_2}\otimes S_1^0\beta_2',i_2=0,1,...,b_2\\ &B_{10}^{i_2}=D_{0i_2}\otimes S_1^0\beta_2,i_2=0,1,...,b_2\\ &\beta_2' \text{ satisfies } \beta_2'=\beta_2'(S_2+S_2^0\beta_2) \text{ and } \beta'e=1, \end{aligned}$$

$$A_{i_1}=\begin{bmatrix} A_{i_1}^{0} & A_{i_1}^{1} & A_{i_1}^{2} & \Lambda & A_{i_1}^{b_2} & & \\ & A_{i_1}^{0} & A_{i_1}^{1} & \Lambda & A_{i_1}^{b_2-1} & A_{i_1}^{b_2} & \\ & & O & O & O & O & O \end{bmatrix},\quad \begin{aligned} &A_{i_1}^{i_2}=D_{(i_1+1)i_2}\otimes S_1^0\beta_1+D_{i_1i_2}\otimes S_1,\\ &\qquad i_1=0,1,...,b_1-1,i_2=0,1,...,b_2\\ &A_{i_1}^{i_2}=D_{b_2i_2}\otimes S_1,i_2=0,1,...,b_2, \end{aligned}$$

Note that the above $DBMAP/PH/1$ priority queue is a natural extension of the $DMAP/PH/1$ priority queue in [12]. It is clear that the underlying Markov chain of the $DBMAP/PH/1$ priority queue is of $M/G/1$ type [4]. Thus it is possible to compute some performance measures for the queueing model with matrix analytic methods. A numerical solution to the problem is presented in a subsequent paper [6].

5 Simulation Model and Results

We make extension on the simulation model for single class DBMAP process in [7], and develop a simulation model for the marked DBMAP process with priorities. Let the parameters of the DBMAP process are $\{D_{00},D_{01},\Lambda\ ,D_{b_1b_2},\alpha,D\}$, let $J(t)$ be the state of the Markov chain immediately after time t, let $Y_1(t)$ and $Y_2(t)$ are the numbers of arrivals for high priority queue and low priority queue at the t-th transition, we simulate the random variable sequence $\{J(t),Y_1(t),Y_2(t)\}$ for t up to T with the following numerical method:

Arrival process initialization
Generate the initial state $J(0)$ according to a multinomial trail with density α, set $t=0$, $Y_1(t)=0$, $Y_2(t)=0$.

Arrival process state machine evolution
while $(t<T)$
{
Choose the state $J(t+1)$ as a multinomial variate with density

$$(D_{J(t),1}D_{J(t),2},\Lambda\ D_{J(t),n}).$$

Set $Y_1(t+1)=\left\lfloor \frac{i}{b_2+1}\right\rfloor$, $Y_2(t+1)=i \bmod (b_2+1)$, where the index i is generated according to a multinomial trail with the following density

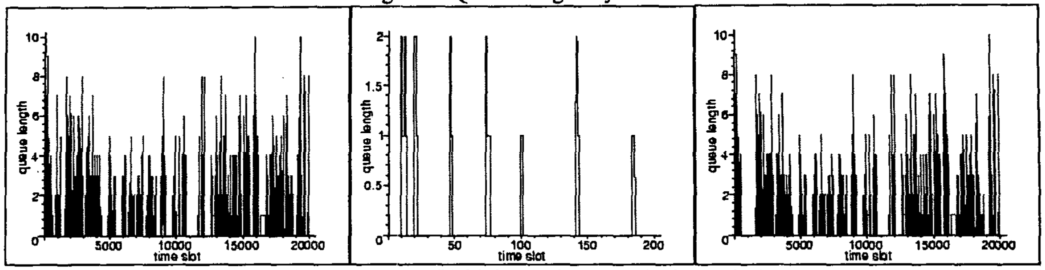
$$\left(\frac{[D_{00}]_{J(t),J(t+1)}}{D_{J(t),J(t+1)}},\frac{[D_{01}]_{J(t),J(t+1)}}{D_{J(t),J(t+1)}},\Lambda\ ,\frac{[D_{b_1b_2}]_{J(t),J(t+1)}}{D_{J(t),J(t+1)}}\right).$$

Enqueue a batch of $Y_1(t+1)$ high priority bursts and a batch of $Y_2(t+1)$ low priority bursts. Note that $Y_1(t+1)$ and $Y_2(t+1)$ might be *0*.

Set $t=t+1$.
}
As a result, the state machine for the arrival process is totally driven by $\{D_{00},D_{01},\Lambda\ ,D_{b_1b_2},\alpha,D\}$. The queueing behavior is thus simulated with the following arrival and service settings:

$$S_1=S_2=\begin{bmatrix} 0.0 & 0.2 & 0.0\\ 0.0 & 0.0 & 0.2\\ 0.0 & 0.0 & 0.0 \end{bmatrix},\begin{matrix}\beta_1=\beta_2=[1.0,0.0,0.0]^T\\ S_1^0=S_2^0=[0.8,0.8,1.0]^T\end{matrix},$$

Figure 1: Queue Length Dynamics



(a) non-priority queueing(b) high priority queue(c) low priority queue

$$D_0 = \begin{bmatrix} 0.7 & 0.1 \\ 0.1 & 0.6 \end{bmatrix}, D_1 = \begin{bmatrix} 0.0 & 0.05 \\ 0.05 & 0.1 \end{bmatrix}, D_2 = \begin{bmatrix} 0.05 & 0.05 \\ 0.05 & 0.05 \end{bmatrix}, D_3 = \begin{bmatrix} 0.01 & 0.04 \\ 0.02 & 0.03 \end{bmatrix},$$

$$D_{00} = D_0, D_{10} = 0.2 \times D_1, D_{20} = 0.2 \times D_2, D_{30} = 0.2 \times D, D_{01} = 0.8 \times D_1, D_{02} = 0.8 \times D_2, D_{03} = 0.8 \times D_3.$$

The above arrival setting is similar with that in [18], except that *20%* of the arrivals are distributed to the high priority queue and the rest *80%* to the low priority queue. The service setting corresponds to the case when each RLC block has at most *3* transmission attempts including ARQ, and successful transmission probability is *0.8*.

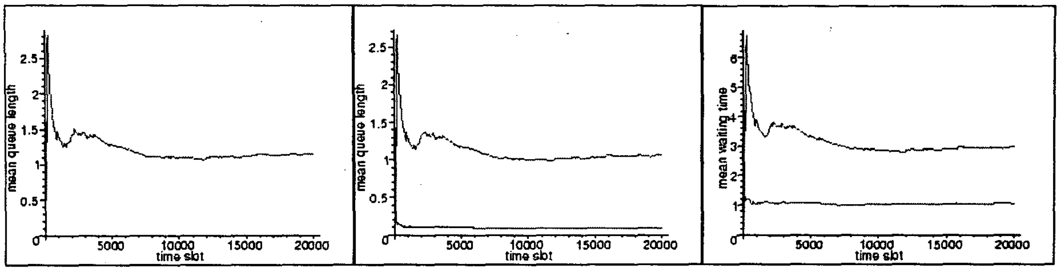
First, a non-priority $DBMAP / PH / 1$ queue is simulated to exam the burstiness of the queue. Figure 1(a) shows the queue length dynamics against time. It can be seen the queue length is highly fluctuating. In this case, as no service differentiation is allowed, more important packets such as MPEG-4 *I*-frames can suffer from the same fluctuation of wait time and drop probability as that of the less important packets such as MPEG-4 *P*-frames. This can result in poor video quality when the wireless channel error rate is high. Next, we examine the priority queueing case. Showing in Figure 1(b) and Figure 1(c) are the queue length dynamics of the high and low priority queue, respectively. Observe from the figure, the queue fluctuation for the high priority queue is much less than that of the low priority queue, and is also lower than that of the non-priority case as shown in Figure 1(a). The low queue length fluctuation of the high priority queue suggests that a better service quality is achieved for the high priority data bursts, which demonstrates that the proposed priority queueing with ARQ control protocol is effective to maintain a basic level of QoS for video delivery in HMM wireless channel. Showing in Figure 2(b) is the mean queue lengths for the *2* priority queues. Observe from the figure, the mean queue length of the low and high priority queue are asymptotic to *1.1* and *0.1*, respectively. The sum of the mean queue length is lower than that of the non-priority queueing case, which is near *1.38* as shown in Figure 2(a). This implies that the suggested priority queueing method can successfully overcome the network congestion problem. This is because of the effective overdue estimation in the suggested priority queueing ARQ methods. Note that the quality of the real-time video application is delay sensitive, as a result, a low end-to-end delay should be maintained. Figure 2(c) and Figure 2(d) are the mean waiting time and mean service time of the priority queueing ARQ method. Observed from the figure, the mean waiting time of the two queues are approaching *3* and *1* for the low and high priority queue, respectively. The mean waiting time for the high priority queue is much lower than that of the low priority queue. This further confirms higher service quality is achieved for the high priority video data. As a result, when the network error rate is high, faithful quality video is expected when compared to the non-priority queueing case. As shown in Figure 2(d), the mean service time for the high and low priority queue are about *1.24* and *1.28*, respectively. As observed, the mean service times for the two queues are very close. Hence, we can conclude that prioritizing the arrival bursts will not introduce noticeable extra delay in serving the data bursts after classification. Figure 2(e) and Figure 2(f) are the plots of the sample arrivals in the high and low priority queues, respectively. The arrival bursts in the two graphs are clustered into smaller clusters. As a result, we can conclude that the DBMAP process can grasp the bursty and correlation nature of the video traffic.

From the simulation results we can find that high priority RLC bursts can always get better service under an erroneous service environment. The proposed scheduling and control protocol is work-conserving, thus when the wireless network is in good condition, it can achieve at least the same video quality as that of the non-priority queueing case. The protocol is simply, should be easy to implement in resource (CPU, memory, power) limited wireless and mobile computing terminals. As a result, it is applicable for next generation wireless/mobile video transmission system.

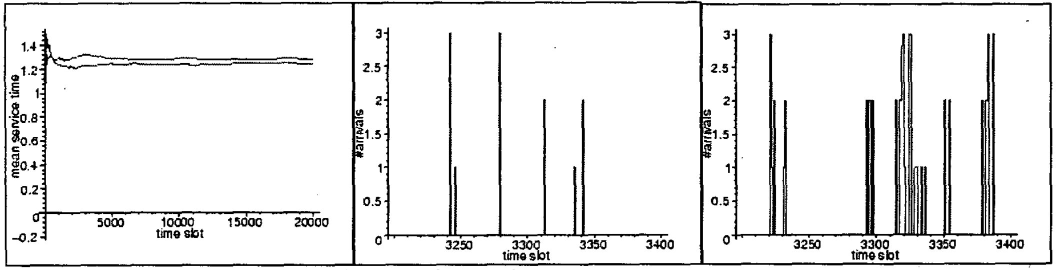
6. Conclusion and future work

In this paper we proposed a performance model for real-time wireless video. We modeled the video traffic as a DBMAP process with *2* priority levels. We proposed a priority based scheduling and ARQ overdue control protocol for video data transmission over the uplink of the third generation (3G) wireless network. The transmission time for a RLC data burst in a HMM wireless channel is proved to follow a discrete PH-type distribution. A $DBMAP / PH / 1$ priority queueing model is formulated. Simulation results are presented to demonstrate the performance gain of the proposed

Figure 2: Mean Queue Length, Mean Waiting Time, Mean Service Time, and Sample Arrivals



(a) mean queue length(b) mean queue length(c) mean waiting time
non-priority caseupper curve: low priority queueupper curve: low priority queue



(d) mean service time(e) sample arrivals(f) sample arrivals
upper curve: low priority queuehigh priority queuelow priority queue

protocol, such that the high priority queue is shown to achieve a higher QoS even under severe network condition. As a result, if layered video is applied to the proposed protocol and models, faithful video playback could be obtained when network quality is bad. The same video playback quality can be obtained when compared to non-priority queueing method with good network condition. It should be noted that the proposed $DBMAP/PH/1$ priority queue can be applied to other layered network service in order to achieve higher QoS, when the network quality is varying. In a subsequent paper numerical solution to the $DBMAP/PH/1$ priority queueing model will be reported [6]. We'll also investigate the parameter identification problem as suggested in [8] for the marked DBMAP model with real-time video traces.

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