Performance Analysis of an ATM Multiplexer with Multiple QoS VBR Traffic

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ABSTRACT

In this paper, we propose a new queuing model, $MMDP/MMDP/1/K$, for an asynchronous transfer mode (ATM) multiplexer with multiple quality of service (QoS) variable bit rate (VBR) traffic in broadband-integrated services digital network (B-ISDN). We use the Markov Modulated Deterministic Process (MMDP) to approximate the actual arrival process and another MMDP for service process. Using queuing analysis, we derive a formula for the cell loss probability of the ATM multiplexer in terms of the limiting probabilities of a Markov chain. The cell loss probability can be used for connection admission control in ATM multiplexer and the calculation of equivalent bandwidth for arrival traffic. The major advantages of this approach are simplicity in analysis, accuracy of analysis by comparison of simulation, and numerical stability.

I. INTRODUCTION

The B-ISDN network based on ATM technology is intended to support all kinds of telecommunication services with a variety of traffic characteristics and QoS requirements. In the network, a generic network element determining network performance is ATM multiplexer. An ATM multiplexer allows several streams of cells to share a transmission capacity with buffers allowing cells to be stored temporarily while awaiting transmission. An accurate estimation of the cell loss probability in the ATM multiplexer is important to estimate the QoS provided by the ATM network. It also provides an important parameter for connection admission control (CAC) for guaranteed QoS.

The ATM multiplexer with several different traffic classes which request different QoSs may implement different queue disciplines or scheduling policies. Generally, there are two control schemes in dealing with heterogeneous traffic in ATM multiplexers. The first one is to provide a single buffer on which all traffic requesting different QoS are multiplexed statistically [1]-[3], and the other one is to provide a segregated and individually managed buffer for each QoS class [4]-[7]. Each scheme has pros and cons in view of trade-off between control complexity and resource management.

The former has a relatively simple architecture and control scheme. The first-in-first-out service discipline is generally assumed. However, in that case, the bandwidth should be allocated according to the most stringent QoS traffic for guaranteed QoS, which results in wastes of bandwidth. If one intends to design the multiplexer dealing with multiple QoS in a single buffer architecture, control schemes such as the multiple thresholds or the push-out scheme must be employed to manage priority of traffic [8]-[9]. This may result in another type of complexity for buffer management. On the other hand, the latter is more efficient in utilizing the link bandwidth, but it raises a scheduling problem of each queue for the corresponding traffic class. For optimal scheduling of each queue for guaranteed QoS, the equivalent bandwidth of each traffic class should be based on the performance of statistical multiplexing of the traffic in the class.

In this paper, we propose a new queuing model, $MMDP/MMDP/1/K$, for ATM multiplexers with VBR traffic. We consider an ATM multiplexer serving a superposition of a real-time VBR (rt-VBR) traffic which is loss and delay sensitive and a non-real-time VBR (nrt-VBR) traffic which is less loss and delay sensitive.

Since the characteristics of VBR traffic play a significant role in the ATM network performance, there have been efforts to describe the bursty traffic characteristics. Several stochastic models for the VBR traffic were defined. For an on-off and a shaped traffic, an Interrupted Poisson Process (IPP) and an Markov Modulated Poisson Process (MMPP) model are used, respectively [12]-[14]. For bursty sources whose cell arrivals are more random and less correlated, a Markov Modulated Bernoulli Process (MMBP) model is used [15]-[16]. Yang *et al.* studied an estimation method for the cell loss probability of an ATM multiplexer loaded with homgeneous on-off bursty sources. In their study, MMDP model is used to approximate the actual arrival process, and they show that the MMDP approach has an important advantage over the MMPP approach in that the actual cell arrival rate is more realistically modelled [17]-[18].

We consider highly correlated bursty on-off VBR traffic in this paper. The VBR traffic source can be in one of two states: on or off. When the source is on, it generates a stream of cells that are equally spaced at a rate of peak cell rate (PCR) [10]. When it is off, it generates no cells at all. Both the distribution of on and off periods are independent exponential random variables with parameters μ^{-1} and λ^{-1}, respectively. We deal with the mixture of M and N independent and identical on-off sources for nrt-VBR and rt-VBR traffic, respectively. We approximate each class of arrival process of the multiplexed VBR traffic by a MMDP in which cells arrive according to a deterministic renewal process whose rate is controlled by a Markov process. We are mainly concerned in the cell loss probability of the nrt-VBR connections in the multiplexer under the condition of coexistence with rt-VBR traffic which has higher service priority.

The remainder of this paper is organized as follows. In Section 2, we present Markovian models of arrival and service processes for the nrt-VBR traffic. In Section 3, we present an analysis of the MMDP/MMDP/1/K queuing system and derive a fomula for the cell loss probability in terms of limiting probabilities of the relevant Markov chain. We also discuss an application of the $(M+1)$-state/$(N+1)$-state MMDP approximation to the ATM multiplexer with rt-VBR and nrt-VBR traffic, and compute the cell loss probability for the nrt-VBR traffic. In Section 4, we present numerical results for the method and compare them to those from simulations. Finally, we conclude with discussions related future research in Section 5.

II. SYSTEM MODEL

We consider an ATM multiplexer with two separate queues: the one is for rt-VBR traffic with queue size k and the other is for nrt-VBR traffic with queue size K as shown in Fig. 1, where the output link capacity is C cells/s. Due to the loss sensitivity and delay sensitivity of rt-VBR traffic, a sufficient bandwidth for the traffic is assigned, and the buffer size k is very small. The buffer for the rt-VBR traffic is for preventing the cell loss due to simultaneous cell arrivals from independent streams. For nrt-VBR traffic, available link capacity, as well as the reserved bandwidth for the nrt-VBR is used after serving the rt-VBR traffic. As the nrt-VBR traffic is loss sensitive, a large buffer is used to accommodate the instantaneous arrival rate of the superposition which is greater than the multiplexer capacity.

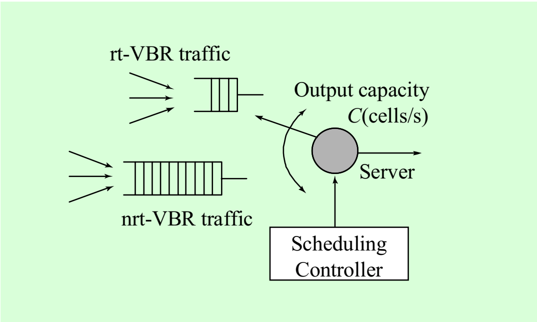

Fig. 1. Multiplexer model with real-time and non-real-time VBR traffic.

An on-off nrt-VBR traffic can be modeled approximately by a 2-state MMDP. An on-off traffic source generates cells at the PCR Λ_p cells/s during the active state whose duration is exponentially distributed with mean μ_{nrt}^{-1}, and is followed by the idle state distributed exponentially with mean λ_{nrt}^{-1}. Therefore, the 2-state MMDP of the on-off traffic is characterized by Λ_p, μ_{nrt}^{-1}, and λ_{nrt}^{-1}.

For the multiplexed nrt-VBR traffic, we assume that M independent and homogeneous on-off bursty sources are multiplexed. We define $A(t)$ as the number of active sources that are in the *on* state at time t. Then, this multiplexed traffic can be approximated by an $(M+1)$-state MMDP model since cell arrivals are governed by an irreducible Markov process $A(t)$ [15]. When the process $A(t)$ is in state i, $i=0, 1, 2, \cdots, M$, the multiplexed cells arrive with a deterministic rate Λ_i, which is equal to $i\cdot\Lambda_p$. From the arrival renewal assumption [15]-[16], [19], we assume that the cell arrival process is always renewed immediately after a transition epoch of $A(t)$. Let $\mathbf{P}^a$ be the transition probability matrix for $A(t)$ and γ_i^{-1} be the mean sojourn time of $A(t)=i$. Then, the $(M+1)$-state MMDP arrival process is determined by the vectors $\mathbf{\Lambda} =(\Lambda_0, \Lambda_1, \Lambda_2, \cdots, \Lambda_M)$, $\mathbf{\Gamma} =(\gamma_0^{-1}, \gamma_1^{-1}, \gamma_2^{-1}, \cdots, \gamma_M^{-1})$, and the transition probability matrix $\mathbf{P}^a$.

For the service process of the nrt-VBR traffic in the multiplexer, we first consider the rt-VBR traffic. We assume that maximally N independent and identical rt-VBR traffic connections can be accepted by CAC in the multiplexer. Let $T(t)$ be the number active rt-VBR connections at time t. An on-off traffic source for rt-VBR generates cells at the PCR B_p cells/s during the active state which is exponentially distributed with mean μ_{rt}^{-1}, and is followed by the idle state distributed exponentially with mean λ_{rt}^{-1}. Therefore, the 2-state MMDP of the on-off traffic is characterized by B_p, μ_{rt}^{-1}, and λ_{rt}^{-1}. Then, the multiplexed rt-VBR arrival process is approximated as an $(N+1)$-state MMDP, since cell arrivals are governed by an irreducible Markov process $T(t)$.

Since the rt-VBR traffic is served with

higher priority than nrt-VBR traffic, the service process for rt-VBR traffic should be the corresponding MMDP for guaranteed QoS. As a result, the service process for the nrt-VBR traffic can be considered as another MMDP. Let $S(t) = N - T(t)$. Then, the service process for the multiplexed nrt-VBR traffic can be approximated by an $(N+1)$-state MMDP model, since services are governed by an irreducible Markov process $S(t)$. When the process $S(t)$ is in state i, $i = 0, 1, 2, \cdots, N$, the cells are served with a deterministic rate B_i, which is equal to $i \cdot B_p + \beta$, where β is the reserved bandwidth for nrt-VBR traffic. From the service renewal assumption [15]-[17], we assume that the cell service process is always renewed immediately after a transition epoch of $S(t)$. Let $\mathbf{P}^s$ be the transition probability matrix for $S(t)$ and υ_j^{-1} be the mean sojourn time of $S(t) = j$. Then, the $(N+1)$-state MMDP service process is determined by the vectors $\mathbf{B} = (B_0, B_1, B_2, \cdots, B_N)$, $\boldsymbol{\Upsilon} = (\upsilon_0^{-1}, \upsilon_1^{-1}, \upsilon_2^{-1}, \cdots, \upsilon_N^{-1})$, and the transition probability matrix $\mathbf{P}^s$. Therefore, in the view of the nrt-VBR traffic, the multiplexer can be considered as an MMDP/MMDP/1/K queuing system.

III. ANALYSIS OF MMDP/MMDP/1/K QUEUING SYSTEM

We consider a single-server queuing system with a buffer of K cells. Cells arrive according to the $(M+1)$-state MMDP with parameters $(\boldsymbol{\Lambda}, \boldsymbol{\Gamma}, \mathbf{P}^a)$ and are served according to the $(N+1)$-state MMDP with parameters $(\mathbf{B}, \boldsymbol{\Upsilon}, \mathbf{P}^s)$. Let $A(t)$, $S(t)$, and $Y(t)$ be the states of the modulating Markov process of the arrival, the service, and the number of cells in the buffer including the one being served, respectively, at time t.

Consider a continuous-time stochastic process $\{(A(t), S(t), Y(t)), t \geq 0\}$ which characterizes the dynamics of the system. We define transition epochs of $A(t)$ or $S(t)$ as embedded points. Let τ_n and τ_n^+ be the n-th embedded point and just after the transition, respectively. With assumptions of the service renewal and the arrival renewal [15]-[17], and definitions of $A_n \equiv A(\tau_n^+)$, $Y_n \equiv Y(\tau_n^+)$, and $S_n \equiv S(\tau_n^+)$, the embedded process $\{(A_n, S_n, Y_n), n \geq 0\}$ becomes an embedded Markov chain.

The transition can be occurred either from state (i, j, l) to state (i', j, l') which represents an arrival renewal, or from state (i, j, l) to state (i, j', l') which represents a service renewal in the embedded Markov chain. Let $q_{(i,j,l)(i',j,l')}$ and $q_{(i,j,l)(i,j',l')}$ be the transition probabilities from state (i, j, l) to state (i', j, l') and from state (i, j, l) to state (i, j', l'), respectively. Then,

$$q_{(i,j,l)(i',j,l')} = P[Y_{n+1} = l' \mid A_n = i, S_n = j, Y_n = l] \cdot p^a_{i,i'} \cdot \delta^s_{ij} \quad (1)$$

$$= p^a_{i,i'} \cdot \delta^s_{ij} \cdot H^{ij}_{l,l'} \quad (2)$$

$$q_{(i,j,l)(i,j',l')} = P[Y_{n+1} = l' \mid A_n = i, S_n = j,$$

$$Y_n = l] \cdot \delta^a_{ij} \cdot p^s_{j,j'} \quad (3)$$
$$= \delta^a_{ij} \cdot p^s_{j,j'} \cdot H^{ij}_{l,l'} \quad (4)$$

where $H^{ij}_{l,l'} = P[Y_{n+1} = l' \mid A_n = i, S_n = j, Y_n = l]$, and $p^a_{i,i'}$ is an element of the transition matrix $\mathbf{P}^a$, and $p^s_{j,j'}$ is an element of the transition matrix $\mathbf{P}^s$. The δ^s_{ij} is the probability that when the embedded Markov chain $\{(A_n, S_n, Y_n), n \geq 0\}$ is in state (i, j, l), the first renewal is an arrival, so the service MMDP remains in the j state. Similarly, the δ^a_{ij} is the probability that when the embedded Markov chain $\{(A_n, S_n, Y_n), n \geq 0\}$ is in state (i, j, l), the first renewal is a service, so the arrival MMDP remains in the i state.

The probability transition matrix, $\mathbf{Q}$, of MMDP/MMDP/1/K system can be partitioned into $\mathbf{Q}'_{ii}s$ and $\mathbf{Q}'_{ii'}s$ $(i \neq i')$ as follows.

$$\mathbf{Q} = \begin{bmatrix} \mathbf{Q}_{00} & \mathbf{Q}_{01} & \cdots & \mathbf{Q}_{0M} \\ \mathbf{Q}_{10} & \mathbf{Q}_{11} & \cdots & \mathbf{Q}_{1M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Q}_{M0} & \mathbf{Q}_{M1} & \cdots & \mathbf{Q}_{MM} \end{bmatrix}, \quad (5)$$

where the $\mathbf{Q}_{ii}$ $(i = 0, \cdots, M)$ are the transition matrices representing the case of service transitions, and $\mathbf{Q}_{ii'}$ are the transition matrices representing the case of arrival transitions, respectively. We can partition $\mathbf{Q}_{ii}$ and $\mathbf{Q}_{ii'}$ into blocks, each of which is a $(K+1) \times (K+1)$ matrix as follows.

$$\mathbf{Q}_{i,i} = \delta^a_{ij} \cdot \begin{bmatrix} \mathbf{0} & p^s_{01}\mathbf{H}^{i0} & \mathbf{0} & \cdots & \mathbf{0} \\ p^s_{10}\mathbf{H}^{i1} & \mathbf{0} & p^s_{12}\mathbf{H}^{i1} & \cdots & \mathbf{0} \\ \mathbf{0} & p^s_{21}\mathbf{H}^{i2} & \mathbf{0} & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & p^s_{(N-1)N}\mathbf{H}^{i(N-1)} \\ \mathbf{0} & \mathbf{0} & \cdots & p^s_{N(N-1)}\mathbf{H}^{iN} & \mathbf{0} \end{bmatrix}, \quad (6)$$

$$\mathbf{Q}_{i,i'} = \begin{bmatrix} p^a_{ii'} \cdot \delta^s_{00}\mathbf{H}^{i0} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & p^a_{ii'} \cdot \delta^s_{11}\mathbf{H}^{i1} \cdots & & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots p^a_{ii'} \cdot \delta^s_{NN}\mathbf{H}^{iN} & \end{bmatrix}, \quad (7)$$

where $\mathbf{0}$ is a $(K+1) \times (K+1)$ dimensional zero metrix, and $\mathbf{H}^{ij} = [H^{ij}_{l,l'}]$. Note that $\mathbf{H}^{ij} \cdot \mathbf{e}^T = \mathbf{e}$, where $\mathbf{e}$ is a $(K+1)$-dimensional unity row vector. Let λ^a_i and μ^a_i denote arrival rate and departure rate of the arrival MMDP in the state i, and λ^s_j and μ^s_j for service MMDP in the state j, respectively. Both the arrival MMDP and the service MMDP are birth-death processes. We can get the state transition probabilities for $\mathbf{P}^a$ and $\mathbf{P}^s$ matrices as follows.

$$p^a_{i,(i+1)} = \frac{\lambda^a_i}{\lambda^a_i + \mu^a_i}, \ (0 \leq i \leq M) \quad (8)$$
$$p^a_{i,(i-1)} = \frac{\mu^a_i}{\lambda^a_i + \mu^a_i}, \ (0 \leq i \leq M) \quad (9)$$
$$p^s_{j,(j+1)} = \frac{\lambda^s_j}{\lambda^s_j + \mu^s_j}, \ (0 \leq j \leq N) \quad (10)$$
$$p^s_{j,(j-1)} = \frac{\mu^s_j}{\lambda^s_j + \mu^s_j}, \ (0 \leq j \leq N) \quad (11)$$

where $\lambda^a_i = (M-i) \cdot \lambda_{nrt}, \mu^a_i = i \cdot \mu_{nrt}$, $\lambda^s_j = (N-j) \cdot \lambda_{rt}$, and $\mu^s_j = j \cdot \mu_{rt}$. The boundary conditions for equations from (8) to (11) are given by

$$\lambda_M^a = \lambda_N^s = \mu_0^s = \mu_0^a = 0. \quad (12)$$

The state transition diagram of the MMDP/MMDP/1/K system is given by Fig. 2, where δ_{ij}^a and δ_{ij}^s are obtained with the boundary conditions given by (12) as follows.

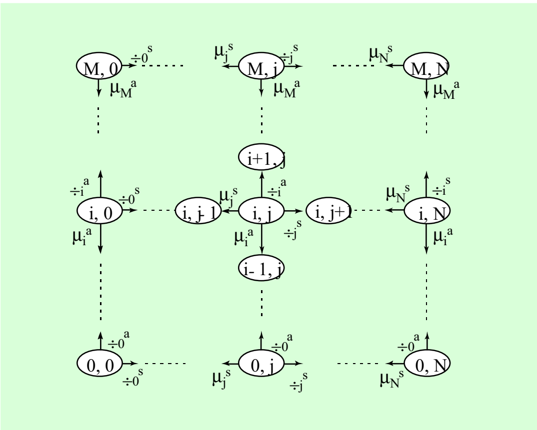

Fig. 2. State transition diagram for (M+1)-state MMDP/(N+1)-state MMDP process.

$$\delta_{ij}^a = \frac{\lambda_j^s + \mu_j^s}{\lambda_i^a + \mu_i^a + \lambda_j^s + \mu_j^s}, \quad (0 \le i \le M,\ 0 \le j \le N) \quad (13)$$

$$\delta_{ij}^s = \frac{\lambda_i^a + \mu_i^a}{\lambda_i^a + \mu_i^a + \lambda_j^s + \mu_j^s}, \quad (0 \le i \le M,\ 0 \le j \le N) \quad (14)$$

Therefore, the following equations are obtained for elements of matrices $\mathbf{Q}_{i,\,i}$ and $\mathbf{Q}_{i,\,i'}$ with the boundary conditions given by (12).

$$\delta_{ij}^a \cdot p_{j,\,(j+1)}^s = \frac{\lambda_j^s}{\lambda_i^a + \mu_i^a + \lambda_j^s + \mu_j^s}, \quad (0 \le i \le M,\ 0 \le j \le N) \quad (15)$$

$$\delta_{ij}^a \cdot p_{j,\,(j-1)}^s = \frac{\mu_j^s}{\lambda_i^a + \mu_i^a + \lambda_j^s + \mu_j^s}, \quad (0 \le i \le M,\ 0 \le j \le N) \quad (16)$$

$$p_{i,\,(i+1)}^a \cdot \delta_{ij}^s = \frac{\lambda_i^a}{\lambda_i^a + \mu_i^a + \lambda_j^s + \mu_j^s}, \quad (0 \le i \le M,\ 0 \le j \le N) \quad (17)$$

$$p_{i,\,(i-1)}^a \cdot \delta_{ij}^s = \frac{\mu_i^a}{\lambda_i^a + \mu_i^a + \lambda_j^s + \mu_j^s}, \quad (0 \le i \le M,\ 0 \le j \le N) \quad (18)$$

For the determination of $\mathbf{H}^{ij}$, let $H_{l,\,l'}^{ij}$ be an element of matrix $\mathbf{H}^{ij}$. Under the service renewal assumption, if $\Lambda_i > B_j (B_j > \Lambda_i)$, then the queue size will not decrease (not increase) during $[\tau_n,\ \tau_{n+1})$, and we have $Y_{n+1} \ge Y_n$ $(Y_{n+1} \le Y_n)$. We define the random variable $t_n \equiv \tau_{n+1} - \tau_n$ which is exponentially distributed with parameter $\gamma_i + \upsilon_j$. With the continuity assumption[15], the random variable $(\Lambda_i - B_j) \cdot t_n$ when $\Lambda_i > B_j$ (or $(B_j - \Lambda_i) \cdot t_n$ when $B_j > \Lambda_i$) has a geometric distribution over nonnegative integers with parameter $\rho_{ij} = exp\left(-\frac{(\gamma_i+\upsilon_j)}{\Lambda_i - B_j}\right)$ $\left(\text{or } \rho_{ij} = exp\left(-\frac{(\gamma_i+\upsilon_j)}{B_j - \Lambda_i}\right)\right)$. That is, $P\{[(\Lambda_i - B_j) \cdot t_n)] = \kappa\} = \rho_{ij}^{\kappa}(1-\rho_{ij})$ for $\kappa = 0,\ 1,\ \cdots$.

To compute $H_{l,\,l'}^{ij}$, we consider three cases. First, in the case of $B_j = \Lambda_i$, we note that if $Y_n = 0$ then Y_{n+1} can be either 0 (when $\tau_{n+1} - \tau_n < 1/\Lambda_i$) or 1 (when $\tau_{n+1} - \tau_n \ge 1/\Lambda_i$). However, if $Y_n > 0$ then Y_{n+1} must be equal to Y_n regardless of the value of $(\tau_{n+1} - \tau_n)$. Thus, for $\Lambda_i = B_j$, we have

$$H^{ij}_{l,l'} = \begin{cases} 1 - exp\left(-\dfrac{(\gamma_i + \upsilon_j)}{B_j}\right), & l = l' = 0, \\ exp\left(-\dfrac{(\gamma_i + \upsilon_j)}{B_j}\right) & l = 0,\ l' = 1, \\ 1 & l = l' > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{19}$$

where $\gamma_i = (M-i)\cdot\lambda_{nrt} + i\cdot\mu_{nrt}$ and $\upsilon_j = (N-j)\cdot\lambda_{rt} + j\cdot\mu_{rt}$.

In the case of $\Lambda_i < B_j$, $\mathbf{H}^{ij}$ is a lower triangular matrix with element $H^{ij}_{l,l'}$ being given as

$$H^{ij}_{l,l'} = \begin{cases} \rho^l_{ij} & l \ge l' = 0, \\ \rho^{l-l'}_{ij}(1-\rho_{ij}) & 0 < l' \le l, \\ 0 & l' > l, \end{cases} \tag{20}$$

where $\rho_{ij} = exp\left(-\dfrac{(\gamma_i + \upsilon_j)}{B_j - \Lambda_i}\right)$.

Similarly, in the case of $\Lambda_i > B_j$, $H^{ij}_{l,l'}$ is given as

$$H^{ij}_{l,l'} = \begin{cases} \rho^{K-l}_{ij} & l \ge l' = K, \\ \rho^{l'-l}_{ij}(1-\rho_{ij}) & l \le l' < K, \\ 0 & l' < l, \end{cases} \tag{21}$$

where $\rho_{ij} = exp\left(-\dfrac{(\gamma_i + \upsilon_j)}{\Lambda_i - B_j}\right)$.

Now, we consider how to compute the cell loss probability, P_{loss}, from the steady-state probabilities. Let π_{ijl} be the steady-state probability of (A_n, S_n, Y_n) in state (i, j, l). We define the probability vector $\mathbf{\Pi} \equiv (\mathbf{\Pi}_0, \mathbf{\Pi}_1, \cdots, \mathbf{\Pi}_M)$, where $\mathbf{\Pi}_i \equiv (\mathbf{\Pi}_{i0}, \mathbf{\Pi}_{i1}, \cdots, \mathbf{\Pi}_{iN})$, $(0 \le i \le M)$, and $\mathbf{\Pi}_{ij} = (\pi_{ij0}, \pi_{ij1}, \cdots, \pi_{ijK})$, $(0 \le i \le M,\ 0 \le j \le N)$. Since all elements of $\mathbf{H}^{ij}$, $(i = 0, 1, \cdots, M$ and $j = 0, 1, \cdots, N)$ have been calculated, and (N_n, S_n, Y_n) is finite and irreducible, $\mathbf{\Pi}$ is uniquely determined from the balance equations as follows.

$$\mathbf{\Pi} = \mathbf{\Pi}\cdot\mathbf{Q}, \tag{22}$$

$$\mathbf{\Pi}\cdot\mathbf{E}^T = 1, \tag{23}$$

where $\mathbf{E}$ is a unity row vector of an $(M+1)\times(N+1)\times(K+1)$ dimension, and $\mathbf{E}^T$ is its transpose.For the computation of the P_{loss} from the steady-state probability π_{ijl}, let $N_{i,j,l}$ be the total number of cells arrived during a period $[\tau_n, \tau_{n+1})$, given that $A_n = i$, $S_n = j$, $Y_n = l$. The random variable $N_{i,j,l}$ has a geometric distribution over nonnegative integers with parameter $exp\left(-\dfrac{(\gamma_i + \upsilon_j)}{\Lambda_i}\right)$. Thus,

$$E[N_{i,j,l}] = \frac{exp\left(-\dfrac{(\gamma_i+\upsilon_j)}{\Lambda_i}\right)}{1 - exp\left(-\dfrac{(\gamma_i+\upsilon_j)}{\Lambda_i}\right)}. \tag{24}$$

When $(\gamma_i + \upsilon_j)/\Lambda_i$ is sufficiently small, $E[N_{i,j}] \approx \Lambda_i/(\gamma_i + \upsilon_j)$.

Let $R_{i,j,l}$ be the total number of cells rejected in the same period. We now consider the distribution of $R_{i,j,l}$. When $\Lambda_i \le B_j$, $\mathrm{P}[R_{i,j,l} = 0] = 1$. If $\Lambda_i > B_j$, we have $R_{i,j,l} = \max\,(0, [(\Lambda_i - B_j)\cdot t_n] - K - l)$. That is,

$$P[R_{i,j,l} = \kappa] = \rho^{K-l+\kappa}_{ij}\cdot(1-\rho_{ij}),\ \kappa = 1, 2, \cdots, \tag{25}$$

which gives

$$P[R_{i,j,l}] = \frac{\rho_{ij}^{K-l+1}}{1-\rho_{ij}}, \text{ for } \Lambda_i > B_j, \qquad (26)$$

where ρ_{ij} is defined as in (21).

To estimate the cell loss probability P_{loss}, or the long-run proportion of cells rejected, we have

$$P_{loss} = \frac{\sum_{(i,j)\in V} \sum_{l=0}^{K} E[R_{i,j,l}]\pi_{ijl}}{\sum_{i=0}^{M}\sum_{j=0}^{N}\sum_{k=0}^{K} E[N_{i,j,l}]\pi_{ijl}}, \qquad (27)$$

where $V = \{(i, j) : \Lambda_i > B_j\}$.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we evaluate the cell loss probability of nrt-VBR traffic under the condition of coexistence with rt-VBR traffic which has higher priority for service. Throughout this section we assume that the link capacity of the multiplexer is 155 Mbits/s, the buffer size for nrt-VBR traffic is 100 cells, and the traffic load of rt-VBR is maintained at 20 % of the output link capacity.

For parameters of an MMDP model, an on-off traffic is characterized by Λ_p, μ^{-1}, and λ^{-1}. However, the on-off traffic may be described by a set of peak rate Λ_p bits/s (or average rate Λ_{av} bits/s), burstiness $b(=\Lambda_p/\Lambda_{av})$, and average burst length, BL,

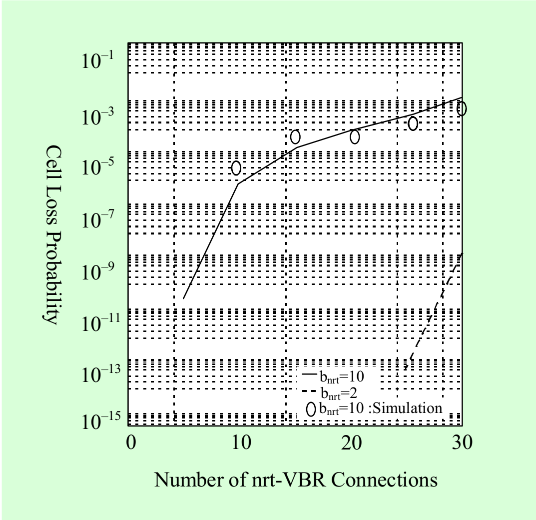

Fig. 3. Cell loss probability versus the number of nrt-VBR connections: ρ_{rt} = 0.2, N_{rt} = 10, b_{rt} = 2, BL_{rt} = 1000 cells, Λ_{av} = 2 Mbits/s, b_{nrt} = 2 or 10, BL_{nrt} = 1000 cells, K = 100 cells, C = 155 Mbits/s, payload = 53 byte.

where BL is the average number of cells generated during an active period. These parameters are related by the formulas: $\mu^{-1} = 424 \cdot BL/\Lambda_p$, and $\lambda^{-1} = (b-1)\cdot\mu^{-1}$, since one cell size is 53 octets.

In Fig. 3 - Fig. 6, we present the cell loss probabilities versus the number of nrt-VBR connections for different parameter values, and compare with computer simulation results. Fig. 3 is the case that the one on-off source for nrt-VBR traffic has Λ_{av} = 2 Mbits/s, the burstiness, b_{nrt} = 2 or 10, and the burst length, BL_{nrt} = 1000 cells under the condition of rt-VBR traffic N_{rt} = 10, b_{rt} = 2, and BL_{rt} = 1000 cells. If we set the required QoS of the nrt-VBR traffic

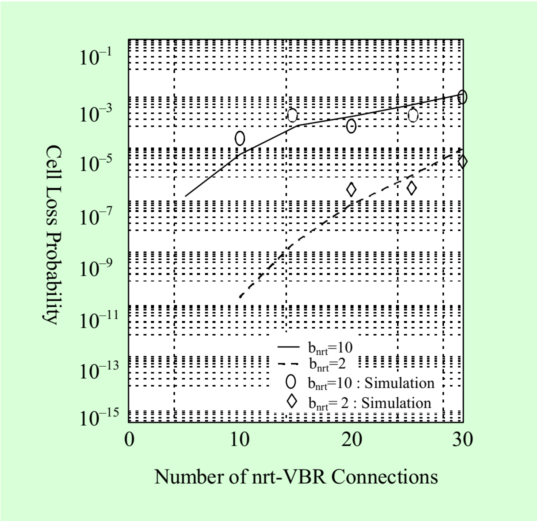

Fig. 4. Cell loss probability versus the number of nrt-VBR connections: $\rho_{rt} = 0.2$, $N_{rt} = 10$, $b_{rt} = 4$, $BL_{rt} = 1000$ cells, $\Lambda_{av} = 2$ Mbits/s, $b_{nrt} = 2$ or 10, $BL_{nrt} = 1000$ cells, $K = 100$ cells, $C = 155$ Mbits/s, payload = 53 byte.

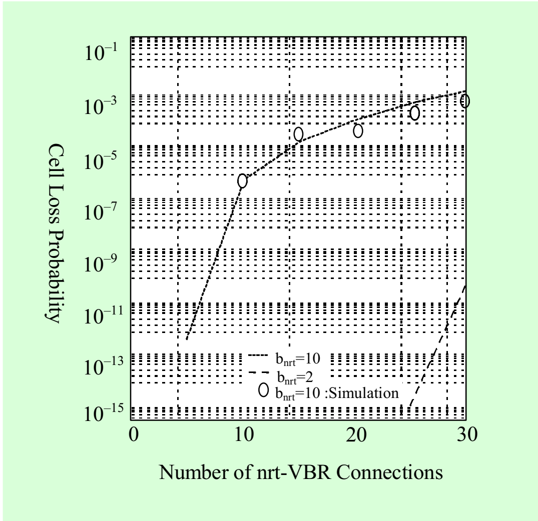

Fig. 5. Cell loss probability versus the number of nrt-VBR connections: $\rho_{rt} = 0.2$, $N_{rt} = 20$, $b_{rt} = 2$, $BL_{rt} = 1000$ cells, $\Lambda_{av} = 2$ Mbits/s, $b_{nrt} = 2$ or 10, $BL_{nrt} = 1000$ cells, $K = 100$ cells, $C = 155$ Mbits/s, payload = 53 byte.

as 10^{-3} for CAC, the number of admitted nrt-VBR connections is 20 when the burstiness of the nrt-VBR traffic is 10. In this case the peak rate, average rate and equivalent bandwidth of the nrt-VBR traffic are 20 Mbits/s, 2 Mbits/s, and 6 Mbits/s, respectively.

Fig. 4 is the same case as in Fig. 3 except that the burstiness of rt-VBR traffic, b_{rt}, is changed to 4. As the burstiness of rt-VBR increases from 2 to 4, the equivalent bandwidth for rt-VBR traffic becomes larger. As a result, the number of admitted connection decreases from 20 to 18 to maintain the cell loss probability at 10^{-3}. The difference between Fig. 3 and Fig. 5 is that the number of rt-VBR connections increases from 10 to 20 while maintaining the load of rt-VBR at 20 %. In this case, there is no difference for the CAC of nrt-VBR connections. We tried the analysis and simulation using several BL_{rt} and BL_{nrt} values. However, the burst length affects little to the cell loss probabilities.

Fig. 7 and Fig. 8 show the relationship between cell loss probabilities and the burstiness of nrt-VBR connections with computer simulation results. We can see that there is a threshold value of burstiness over which cell loss probabilities increases approximately linearly in proportional to the burstiness. This is because of the ap-

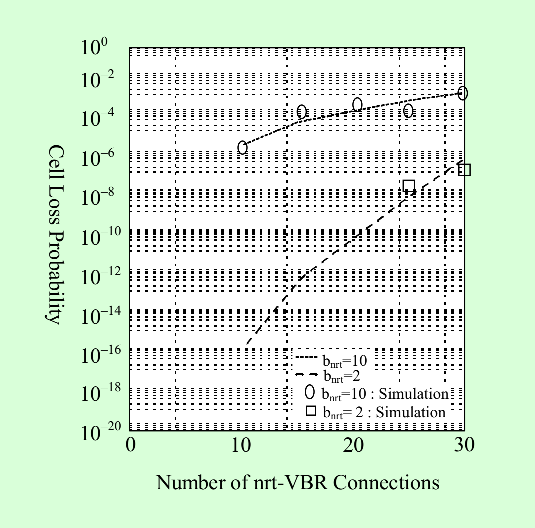

Fig. 6. Cell loss probability versus the number of nrt-VBR connections: $\rho_{rt} = 0.2$, $N_{rt} = 20$, $b_{rt} = 4$, $BL_{rt} = 1000$ cells, $\Lambda_{av} = 2$ Mbits/s, $b_{nrt} = 2$ or 10, $BL_{nrt} = 1000$ cells, $K = 100$ cells, $C = 155$ Mbits/s, payload = 53 byte.

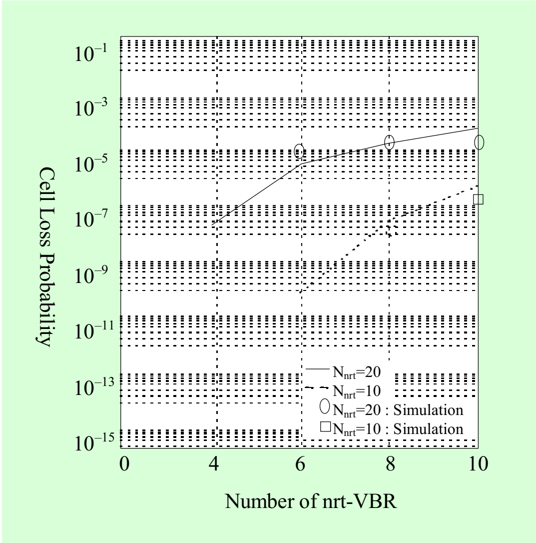

Fig. 7. Cell loss probability versus the burstiness of nrt-VBR connections: $\rho_{rt} = 0.2$, $N_{rt} = 10$, $b_{rt} = 2$, $BL_{rt} = 1000$ cells, $N_{nrt} = 10$ or 20, $\Lambda_{av} = 2$ Mbits/s, $BL_{nrt} = 1000$ cells, $K = 100$ cells, $C = 155$ Mbits/s, payload = 53 byte.

proximate linear increase of the equivalent bandwidth of VBR traffic by the increase of burstiness.

The simulation is implemented using the assumption of M independent sources for nrt-VBR and N independent sources for rt-VBR traffic feeding an ATM multiplexer with the defined parameters. The simulation is event-driven and each has its own random number generator. The criterion for stopping the simulation is that the width of the 95 % confidence interval should be less than 5 % of the estimated cell loss probability.

V. CONCLUSION

In this paper, we have proposed a new queuing model, $MMDP/MMDP/1/K$, for ATM multiplexers with multiple QoS VBR traffic. Using the model we are able to estimate the cell loss probability in an ATM multiplexer and the equivalent bandwidth of bursty VBR traffic. The major advantages of this approach are simplicity in analysis, accuracy of analysis by comparison of simulation, and numerical stability.

For the computational efficiency, how the $(M+1)-$ state $MMDP/(N+1)-$ state $MMDP/1/K$ model is ap-

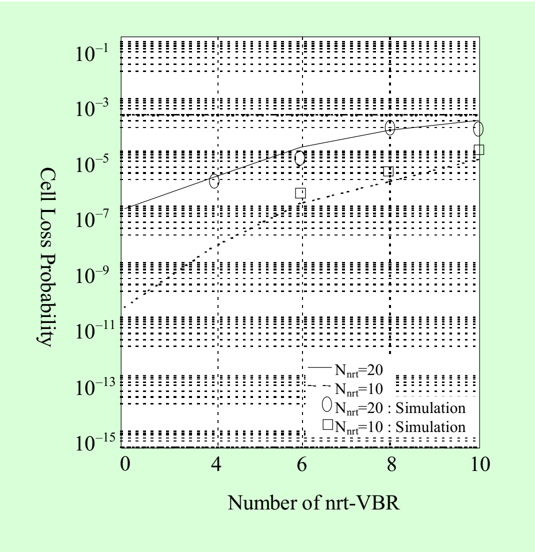

Fig. 8. Cell loss probability versus the burstiness of nrt-VBR connections: $\rho_{rt} = 0.2$, $N_{rt} = 10$, $b_{rt} = 4$, $BL_{rt} = 1000$ cells, $N_{nrt} = 10$ or 20, $\Lambda_{av} = 2$ Mbits/s, $BL_{nrt} = 1000$ cells, $K = 100$ cells, $C = 155$ Mbits/s, payload = 53 byte.

proximated to $m-$ state $MMDP/n-$ state $MMDP/1/K$ model, where m is between 1 and $M+1$ and n is between 1 and $N+1$, is for further study.

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