Quality of Service Over Wireless ATM Links

Jeong Geun Kim and Marwan Krunz
Department of Electrical and Computer Engineering
University of Arizona
Tucson, AZ 85721
{jkkim, krunz}@ece.arizona.edu

Abstract— **Several technical issues must be resolved before ATM services can be efficiently extended to the wireless environment. Key issues include incorporating the characteristics of the time-varying wireless channel in the provisioning of the cell-level QoS, and improving the transport performance using error control mechanisms. In this paper, we analyze the cell loss and delay performance over a wireless ATM link. We consider both cases of a single and multiplexed ATM connections. The link capacity fluctuates according to a fluid version of Gilbert-Elliot channel model. Traffic sources are modeled as on-off fluid processes. Our analytical framework incorporates the effects of error control schemes (i.e., ARQ and/or FEC), which are used to improve the transport performance over the wireless link. For the single-stream case, we derive the mean delay and the cell loss rate (CLR) due to buffer overflow at the sender side of the wireless link. We also obtain a closed-form approximation for the corresponding** *wireless* **effective bandwidth. In the case of multiplexed streams, we obtain a good approximation for the CLR using the Chernoff-Dominant Eigenvalue (CDE) approach. The expressions for the CLR and effective bandwidth are then used to study the optimal FEC code rate that guarantees the requested QoS while maximizing the utilization of the wireless bandwidth. Numerical results and simulations are used to verify the adequacy of our analysis and to study the impact of error control on the allocation of bandwidth for guaranteed cell loss and delay performance.**

keywords: Wireless ATM networks, QoS, effective bandwidth, fluid analysis.

I. Introduction

Wireless asynchronous transfer mode (ATM) is emerging as a potential transport solution for broadband wireless networks [1], [2], [17]. It aims at extending ATM services to the wireless environment. To achieve this goal, wireless ATM must support the quality-of-service (QoS) requirements associated with various ATM services. The provisioning of QoS is particularly difficult in the wireless environment due to the scarcity of bandwidth and to the high and fluctuating bit-error rates (BER) of the radio channel.

The transport performance of a wireless ATM link can be improved by using error control schemes. Two classes of error control are commonly used in wireless communications: automatic repeat request (ARQ) and forward error correction (FEC) [5]. In general, ARQ is used to deliver data requiring higher reliability, whereas FEC is suitable for delay-sensitive traffic [5]. Recent studies suggest that hybrid ARQ/FEC might be more appropriate for a wireless ATM network [5], [14], particularly when the transported traffic streams exhibit diverse characteristics and QoS requirements. For instance, Available Bit Rate (ABR) connections with relaxed time constraints can use ARQ. In contrast, Constant Bit Rate (CBR) and Variable Bit Rate (VBR) connections that require low delay, jitter, and minimal cell loss may need a combination of FEC and ARQ with time-constrained retransmission [3].

Efficient provisioning of QoS guarantees in ATM networks can be achieved by employing the notion of effective bandwidth [7], [9]. Significant research has been done on computing the effective bandwidth over wireline links [6], [7], [9]. Guérin et al. proposed an approximate expression for the effective bandwidth of both individual and multiplexed connections, arguing that this approximation is necessary for real-time network traffic control [9]. Elwalid and Mitra studied the effective bandwidth for general Markovian traffic sources [7]. Elwalid et al. proposed an approximation for the cell loss rate (CLR) at an ATM multiplexer using a hybrid Chernoff-Dominant Eigenvalue (CDE) approach [8]. The research on effective bandwidth has generally been addressed in the context of high-speed (wired) ATM networks. Recently, Mohammadi et al. extended the concept of effective bandwidth to wireless ATM networks [16]. However, the impact of error control was not considered. Bandwidth allocation and FEC code optimization in wireless ATM networks were discussed in [19] using a simplified framework that did not involve traffic models and queuing analysis (traffic sources were characterized by their mean rates). In that study, the authors observed the existence of a tradeoff between FEC and the number of retransmitted cells. In [12], we started investigating the effective bandwidth for wireless ATM links. The current paper builds upon the work in [12], extending it in various directions.

In this work, we investigate the cell loss and delay performance of a wireless link. We consider two scenarios for transporting ATM traffic over a wireless link. In the first scenario, the wireless link is used to transport a single traffic stream. For example, the terrestrial link between the mobile terminal (MT) and an access point (AP) is used to transport the traffic stream. In the second scenario, multiple streams are multiplexed onto the same wireless link, which can be, for example, an intermediate satellite or microwave link. For both scenarios, we assume that the transmitter side of the wireless link maintains a finite-capacity cell buffer, which may occasionally overflow.

Delay and cell losses are aggravated by the ARQ retransmission process, leading to a reduction in the effec-

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tive service rate. Therefore, extra bandwidth must be assigned in order to compensate for the reduced service rate. This extra bandwidth can be assigned by increasing the service rate and/or the FEC rate. Increasing the service rate reduces the delay and CLR although the quality of the wireless channel stays unchanged. In contrast, increasing the effectiveness of FEC improves the quality of the wireless channel at the expense of extra bandwidth, which may in turn reduce the effective service rate. In general, adaptive coding yields the optimal throughput for a channel with variable error statistics [18].

In this study, we address the problem of obtaining the optimal bandwidth and FEC code rate for a guaranteed CLR. We refer to this bandwidth as the *wireless effective bandwidth*, which is similar in concept to the effective bandwidth in wireline ATM networks. To compute the wireless effective bandwidth, we first evaluate the cell loss performance at the transmitter, taking into account the channel behavior and the underlying error control schemes (ARQ and/or FEC). For this purpose, we model each traffic source by an on-off fluid process, and we use a fluid version of Gilbert-Elliott model to capture the behavior of the wireless channel. Using fluid-flow analysis, we compute the mean delay and the CLR due to buffer overflow for a single and multiplexed streams. In the single-stream case, we provide a closed-form approximation of the wireless effective bandwidth. Our results are used to study the impact of FEC on the effective bandwidth for a guaranteed CLR. Extensive simulations are conducted to verify the goodness of our analytical results.

The rest of the paper is organized as follows. In Section II we describe the general framework of our study. The cell loss and delay performance for a single stream is studied in Section III. The corresponding wireless effective bandwidth is analyzed in Section IV. The CLR for multiplexed streams is studied in Section V. Numerical results and simulations are reported in Section VI, followed by concluding remarks in Section VII.

II. Wireless ATM Link Model

In order to analyze the cell-level performance of a wireless ATM link, we consider the framework shown in Figure 1. In this framework, traffic streams from one or more ATM connections are fed into a finite-size FIFO buffer. A constant service rate c (in cells/second) is assigned to the wireless connection, whereas the actual drain rate observed at the buffer is reduced due to retransmissions and FEC overhead. The way of estimating the actual service rate will be discussed in the following section. In our study, we consider a particular hybrid ARQ/FEC approach in which the cyclic redundancy check (CRC) code is first applied to a cell, followed by FEC. We assume that the CRC code can alone detect all bit errors in a cell. In contrast, only a subset of the errors can be corrected by FEC. In addition, we impose a limit on the number of cell transmissions. Imposing such a limit can be used to provide delay guarantees for real-time traffic. Once a cell hits the limit, it will be discarded. We define the cell discarding rate (CDR) as

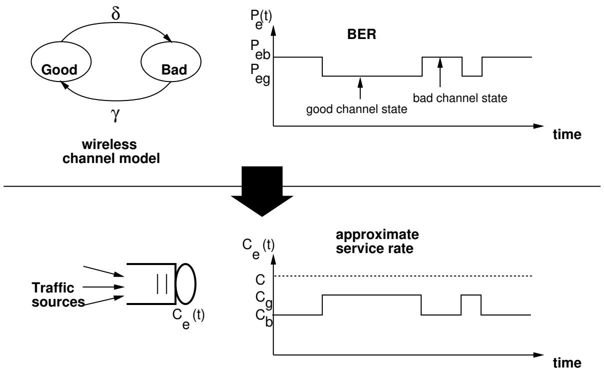

Fig. 2. Wireless channel model and corresponding service rate model.

the ratio of cells reaching the limit over the total number of transmitted cells (excluding lost cells due to buffer overflow). For simplicity, we ignore the overhead of the medium access control (MAC) layer.

The above model has three control parameters: the service rate (or assigned bandwidth), the FEC code rate, and the limit on the number of transmissions. These parameters can be adjusted during connection setup to satisfy certain QoS requirements. From the network point of view, the selection of these parameters is very crucial and requires thorough understanding of their impact on the cell-level performance. The main theme of this study is to investigate the cell-level performance of a wireless ATM link as a function of the assigned bandwidth, the limit on transmissions, and error control schemes.

III. Cell-Level Performance for a Single Stream

In this section, we introduce the queueing model that we use for analyzing the cell-level performance for a single traffic stream transported over a wireless ATM link. The traffic source is characterized by an on-off fluid model, with peak rate r and with exponentially distributed on and off periods with means $1/\alpha$ and $1/\beta$, respectively. The wireless channel is modeled using a fluid version of Gilbert-Elliott model, which is often used to investigate the performance of wireless links [10]. As explained in Figure 2, Gilbert-Elliott model is Markovian with two alternating states: *Good* and *Bad*. The bit error rates (BER) during the Good and Bad states are given by P_{eg} and P_{eb}, respectively, where $P_{eg} \ll P_{eb}$. The durations of the Good and Bad states are exponentially distributed with means $1/\delta$ and $1/\gamma$, respectively.

The FEC capability in the underlying hybrid ARQ/FEC mechanism is characterized by three parameters: the number of bits in a code block (n), the number of payload bits (k), and the maximum number of correctable bits in a code block (τ). Note that n consists of the k payload bits and the extra parity bits. The FEC code rate $e(\tau)$ is defined as

$$e(\tau) = \frac{k}{n(\tau)}.$$

Assuming that a FEC code can correct up to τ bits

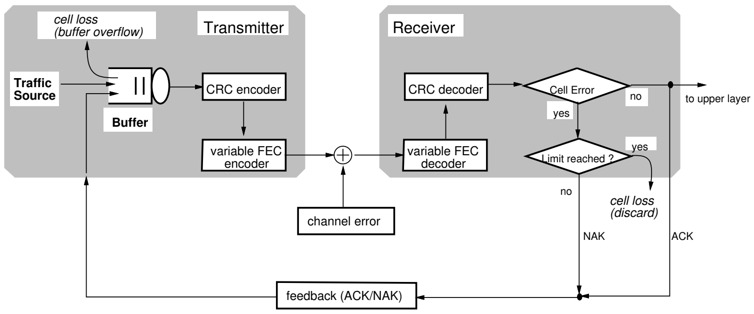

Fig. 1. Framework for analyzing the performance over a wireless ATM link.

and that bit errors during a given channel state are independent, the probability that a cell contains a non-correctable error is given by:

$$P_c(p_b, \tau) = \sum_{j=\tau+1}^{n(\tau)} \binom{n(\tau)}{j} p_b^j (1-p_b)^{n(\tau)-j} \quad (1)$$

where p_b is the bit error probability; $p_b \in \{P_{eg}, P_{eb}\}$. To account for the FEC overhead, we obtain the actual service rate c_e observed at the output of the buffer:

$$c_e = c \cdot e(\tau) \quad (2)$$

where c is the bandwidth assigned to the ATM connection.

The exact behavior of ARQ and FEC in the underlying queueing model is analytically intractable. To obtain analytically tractable results, we assume that the cell departure process follows a fluid process with a service rate that is modulated by the channel state (see Fig. 2). This approximation implies that there are two deterministic service rates: c_g during Good states and c_b during Bad states. We assume that the feedback delay for sending an acknowledgment from the receiver to the sender is negligible. Thus, a cell is successively retransmitted until it is received correctly at the destination or until the limit on the number of transmissions is reached. In this scenario, the total time needed to successfully transmit a cell conditioned on the channel state follows a truncated geometric distribution. Let N_{tr} denote the number of transmissions until the cell is successfully received or is discarded due to the limit on transmissions. For a given cell error probability P_c and a limit on transmissions N_l, the expectation of N_{tr} is given by:

$$E[N_{tr}] = \frac{1-P_c^{N_l}}{1-P_c}. \quad (3)$$

Thus, c_g and c_b correspond to the mean transmission rates of the truncated geometric trial with parameters $(P_{c,g}, N_l)$ and $(P_{c,b}, N_l)$, respectively, where $P_{c,g}$ and $P_{c,b}$ are the cell error probabilities in Good and Bad states, respectively, given by (1). Formally,

$$c_g = \frac{c \cdot e(\tau) \cdot (1-P_{c,g})}{1-P_{c,g}^{N_l}} \quad (4)$$

$$c_b = \frac{c \cdot e(\tau) \cdot (1-P_{c,b})}{1-P_{c,b}^{N_l}}. \quad (5)$$

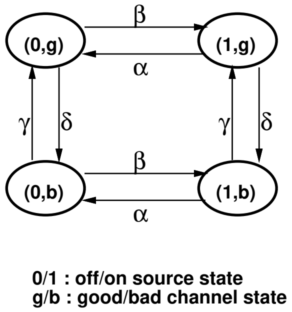

Fig. 3. State transition diagram.

It can be seen that the problem of determining the wireless effective bandwidth reduces to obtaining a service rate c that satisfies a required CLR. The system is Markovian with a state transition diagram that is shown in Figure 3. Let S denote the state space. Thus,

$$S = \{(0,g), (1,g), (0,b), (1,b)\}$$

where 0 and 1 denote the on and off states of a traffic source, respectively, and g and b denote Good and Bad channel states, respectively.

Following a standard fluid approach (see [4], for example), the evolution of the buffer content can be described by the following differential equation:

$$\frac{d\boldsymbol{\Pi}(x)}{dx}\boldsymbol{D} = \boldsymbol{\Pi}(x)\boldsymbol{M} \quad (6)$$

where $\boldsymbol{D} \triangleq \mathrm{diag}[-c_g, -c_b, r-c_g, r-c_b]$, $\boldsymbol{\Pi}(x) \triangleq [\ \Pi_{0,g}(x) \quad \Pi_{0,b}(x) \quad \Pi_{1,g}(x) \quad \Pi_{1,b}(x)\ ]$, $\Pi_s(x) \triangleq \Pr\{\text{buffer content} \leq x, \text{and the system } s \in S\}$, and $\boldsymbol{M}$ is the generator matrix of the underlying Markov chain:

$$\boldsymbol{M} = \begin{bmatrix} -(\beta+\delta) & \delta & \beta & 0 \\ \gamma & -(\beta+\gamma) & 0 & \beta \\ \alpha & 0 & -(\alpha+\delta) & \delta \\ 0 & \alpha & \gamma & -(\alpha+\gamma) \end{bmatrix}.$$

Throughout the paper, matrices and vectors are boldfaced.

The solution of (6) corresponds to the solution of the eigenvalue/eigenvector problem:

$$z\boldsymbol{\phi}\boldsymbol{D} = \boldsymbol{\phi}\boldsymbol{M} \quad (7)$$

which is generally given by

$$\mathbf{\Pi}(x) = \sum_{z_i \le 0} a_i \exp(z_i x)\phi_i \tag{8}$$

where a_i's are constant coefficients and the pairs $(z_i, \boldsymbol{\phi}_i), i = 1, 2, \cdots$, are the eigenvalues and the right eigenvectors of the matrix $\boldsymbol{M}\boldsymbol{D}^{-1}$ [4], [15].

In order to solve (7), we follow the approach used in [15]. The four-state Markov process is decomposed into two processes; one describes the on-off source and the other describes the state of the channel. We skip the detailed description on derivation which is available in [11], [12].

After obtaining the eigenvalues, the eigenvectors, and the coefficients, we can construct the stationary buffer content distribution $\mathbf{\Pi}(x)$. Consequently, the CLR due to buffer overflow $G(x)$ is given by:

$$G(x) \quad = \quad 1 - \mathbf{1}\mathbf{\Pi}(x). \tag{9}$$

Using Little's law, we also obtain the mean delay T_d give by:

$$T_d = \frac{\int_0^B G(x)dx}{\rho_s} \tag{10}$$

where ρ_s is the mean source rate.

IV. Wireless Effective Bandwidth

The expression for the CLR that was obtained in the previous section can, in principle, be used to compute the effective bandwidth. However, this requires expressing the service rate c as a function of other variables (CLR, buffer size, channel BERs, the number of correctable bits, etc.). In general, it is not possible to obtain an *exact* closed-form expression for the effective bandwidth, which would be useful in real-time traffic control[1]. Even for a single source (i.e., no multiplexing), the closed-form solution is not available without approximation [6], [9].

In this section, we derive an approximate expression for the effective bandwidth following the approach used in [7]. In [7] the authors consider the service rate c to be a variable parameter and the eigenvalues to be functions of c, i.e., $z = f(c)$. Since the problem is to obtain c for a given z, c can be expressed as the inverse function, i.e., $c = f^{-1}(z) \triangleq g(z)$. The key point in the analysis is that this inversion problem reduces to another eigenvalue problem (see [7] for details).

Consider (7). In this case, the drift matrix $\boldsymbol{D}$ can be written as

$$\boldsymbol{D} = r\boldsymbol{B}_r - ce(\tau)\boldsymbol{B}_c$$

where

$$\boldsymbol{B}_r = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \boldsymbol{B}_c = \begin{bmatrix} \eta_g & 0 & 0 & 0 \\ 0 & \eta_b & 0 & 0 \\ 0 & 0 & \eta_g & 0 \\ 0 & 0 & 0 & \eta_b \end{bmatrix} \tag{11}$$

[1] In this paper, we use the term 'effective bandwidth' in a general sense to refer to the minimum service capacity that is needed to achieve a given CLR. We use the term 'effective bandwidth approximation' to refer to the more specific definition of Elwalid et al. [7].

$\eta_g = 1 - P_c(P_{eg}, \tau)$, and $\eta_b = 1 - P_c(P_{eb}, \tau)$. Substituting $\boldsymbol{D}$ into (7), we obtain the following relation:

$$z\boldsymbol{\phi}(r\boldsymbol{B}_r - ce(\tau)\boldsymbol{B}_c) \quad = \quad \boldsymbol{\phi}\boldsymbol{M}. \tag{12}$$

Let $c \triangleq g(z)$. Then,

$$zr\boldsymbol{\phi}\boldsymbol{B}_r - zg(z)e(\tau)\boldsymbol{\phi}\boldsymbol{B}_c \quad = \quad \boldsymbol{\phi}\boldsymbol{M}. \tag{13}$$

Rearranging the previous equation, we obtain

$$g(z)e(\tau)\boldsymbol{\phi} \quad = \quad \boldsymbol{\phi}\left(-\frac{1}{z}\boldsymbol{M} + r\boldsymbol{B}_r\right)\boldsymbol{B}_c^{-1}. \tag{14}$$

Note that the problem of obtaining $g(z)$ translates into another eigenvalue problem. According to [7], the effective bandwidth is approximated by the maximal eigenvalue $g(z)$ satisfying (14).

From (14) and after some tedious algebraic manipulations, we obtain the following four eigenvalues:

$$g(z)e(\tau) = \begin{cases} \frac{C_1 - (\eta_g+\eta_b)C_2 \pm \sqrt{2(C_3 - C_2C_4)}}{4\eta_g\eta_b} \\ \frac{C_1 + (\eta_g+\eta_b)C_2 \pm \sqrt{2(C_3 + C_2C_4)}}{4\eta_g\eta_b} \end{cases}$$

where

$$\begin{aligned} C_1 &= (\eta_g + \eta_b)r - ((\alpha+\beta+2\gamma)\eta_g \\ &\quad +(\alpha+\beta+2\delta)\eta_b)\xi \\ C_2 &= \sqrt{(r-(\alpha-\beta)\xi)^2 + 4\alpha\beta\xi^2} \\ C_3 &= \eta_b^2((r-(\alpha+\delta)\xi)^2 + ((\beta+\delta)^2 + 2\alpha\beta)\xi^2) \\ &\quad -2\eta_g\eta_b(r^2 - (2\alpha+\delta+\gamma)r\xi \\ &\quad +((\alpha+\beta)(\alpha+\beta+\delta+\gamma) - 2\delta\gamma)\xi^2) \\ &\quad +\eta_g^2((r-(\alpha+\gamma)\xi)^2 + ((\beta+\gamma)^2 + 2\alpha\beta)\xi^2) \\ C_4 &= (\eta_g - \eta_b)(\eta_g(r-(\alpha+\beta+2\gamma)\xi) \\ &\quad -\eta_b(r-(\alpha+\beta+2\delta)\xi)) \\ \xi &= -B/\log p, \ B \text{ is buffer size and } p \text{ is CLR.} \end{aligned}$$

Thus, the maximal eigenvalue, corresponding to the wireless effective bandwidth approximation, is given by:

$$g(z) \quad = \quad \frac{C_1 + (\eta_g+\eta_b)C_2 + \sqrt{2(C_3 + C_2C_4)}}{4\eta_g\eta_b e(\tau)}. \tag{15}$$

Note that this is an asymptotic result, i.e., the buffer size is very large and the CLR is very small.

V. Cell Loss Performance for Multiplexed Streams

As discussed previously, it is also possible to multiplex several connections onto the same wireless link. In this section, we extend our previous cell loss analysis to the case of multiplexed streams.

The wireless ATM link is modeled as an ATM multiplexer with randomly varying service rate. This model is similar to the producer-consumer model investigated in [15]. In [15] the traffic generation (production) and the cell delivery (consumption) processes are coupled by a buffer, which enables their decomposition and consequently facilitates the analysis. For K multiplexed

Markovian fluid sources, the traffic generation part is governed by the following equation [15]:

$$z\boldsymbol{\phi}_s[\boldsymbol{\Lambda}_s - v\boldsymbol{I}] = \boldsymbol{\phi}_s\boldsymbol{M}_s \tag{16}$$

where $\boldsymbol{M}_s$ and $\boldsymbol{\Lambda}_s$ are the infinitesimal generator and rate matrices for the aggregate traffic, respectively. These matrices can be written as

$$\begin{aligned}\boldsymbol{M}_s &= \boldsymbol{M}_1 \oplus \boldsymbol{M}_2 \oplus \cdots \oplus \boldsymbol{M}_K \\ \boldsymbol{\Lambda}_s &= \boldsymbol{\Lambda}_1 \oplus \boldsymbol{\Lambda}_2 \oplus \cdots \oplus \boldsymbol{\Lambda}_K\end{aligned}$$

where $\boldsymbol{M}_i$ and $\boldsymbol{\Lambda}_i$ are the infinitesimal generator and rate matrices of the ith source, $i = 1, 2, \cdots, K$. In (16), z and $\boldsymbol{\phi}_s$ are the eigenvalue and eigenvector of the matrix $\boldsymbol{M}_s[\boldsymbol{\Lambda}_s - v\boldsymbol{I}]^{-1}$, respectively. The operator $\oplus$ denotes the Kronecker sum.

As for the cell delivery process, it is governed by [15]:

$$z\boldsymbol{\phi}_r[v\boldsymbol{I} - \boldsymbol{E}_c] \quad = \quad \boldsymbol{\phi}_r\boldsymbol{M}_r \tag{17}$$

where $\boldsymbol{M}_r$ is the generator matrix for the service process (the consumption part), and z and $\boldsymbol{\phi}_r$ are the corresponding eigenvalue and eigenvector, respectively.

Exact analysis of the producer-consumer system described by (16) and (17) was provided in [15] for on-off sources. The buffer consumption rates in [15] were taken as integer multiples of some unit rate. In our model, there are two consumption rates (c_b and c_g). But c_g is not necessarily an integer multiple of c_b. In [11], we provide the exact solution for the CLR based on Mitra's results,

While an exact solution for the CLR is feasible, the computational complexity associated with this solution is rather high. A much simpler approximate solution can be obtained, which is sufficiently accurate. In [8], Elwalid et al. proposed an approximation for the CLR at an ATM multiplexer for general Markovian sources using a combined Chernoff-dominant eigenvalue (CDE) approach. In this approximation, the CLR at the multiplexer with buffer size x is approximated by

$$G(x) \approx Le^{zx} \tag{18}$$

where z is the dominant eigenvalue and L is the corresponding coefficient. A procedure was presented for computing z and L at an ATM multiplexer with a constant service rate c. A similar procedure will be used in this paper to approximate the CLR at a wireless ATM link. Note that the service rate in our model fluctuates randomly depending on the channel state.

A. Calculation of the Dominant Eigenvalue

Adapting the results in [7] to our wireless link model, we establish the following proposition to obtain the dominant eigenvalue.

Proposition V.1: The dominant eigenvalue in the wireless ATM multiplexer model represented by (16) and (17) is the value of z satisfying the following equation:

$$\sum_{i=1}^{K} g_i(z) = \frac{z(c_g + c_b) - \delta - \gamma + \sqrt{Q_2(z)}}{2z} \tag{19}$$

where $g_i(z) =$ MRE$[\boldsymbol{\Lambda}_i - \boldsymbol{M}_i/z]$, MRE$[\boldsymbol{A}]$ denotes the maximal real eigenvalue of the matrix $\boldsymbol{A}$, and

$$Q_2(z) = (z(c_g - c_b) - (\delta - \gamma))^2 + 4\delta\gamma. \tag{20}$$

The proof of the previous proposition is available in [11].

B. Approximation of the Coefficient L Using Chernoff-Bound Approach

Prior studies have shown that the coefficient L in (18) plays a critical role in obtaining an accurate estimate of the CLR [6], [8]. In this section, we provide an approximation of L using a Chernoff-bound approach, in line of Elwalid et al.'s work [8] on analyzing the CLR at a multiplexer with a constant drain rate.

Following the discussion in [8] and the references therein, one can approximate the constant L by $G(0)$, implying that L is *approximately* the cell loss probability in a bufferless multiplexer:

$$G(0) \approx L. \tag{21}$$

In a bufferless multiplexer, cell losses occur when the input rate exceeds the service rate. Let χ_i denote the cell rate from source i at steady-state. The total traffic generation rate from K sources is denoted by χ where $\chi = \sum_{i=1}^{K} \chi_i$. For an ATM multiplexer with a fixed service rate R, L is estimated by

$$L \approx P[\chi \geq R].$$

Using Chernoff bound, Elwalid et al. [8] showed that as $R \to \infty$ with $K/R = o(1)$, $P[\chi \geq R]$ can be obtained as follows:

$$P[\chi \geq R] = \frac{\exp(-F(s^*))}{s^*\sigma(s^*)\sqrt{2\pi}}[1 + o(1)] \tag{22}$$

where

$$F(s) \triangleq sR - \sum_{i=1}^{K} \log N_i(s) \tag{23}$$

$$N_i(s) \triangleq E[\exp(s\chi_i)] \tag{24}$$

$$\begin{aligned}\sigma^2(s) &= \frac{\partial^2 \log E[\exp(s\chi)]}{\partial s^2} \\ &= \sum_{i=1}^{K}\left[\frac{N_i''(s)}{N_i(s)} - \left(\frac{N_i'(s)}{N_i(s)}\right)^2\right]\end{aligned} \tag{25}$$

and $F(s^*) = \sup_{s \geq 0} F(s)$.

In our case, R is not fixed, but can take one of two values (c_g and c_b). Losses will occur when χ exceeds c_g during the Good state and c_b during the Bad state. Thus, L in (18) is given by:

$$L \approx G(0) = P[\chi \geq c_g]w_g + P[\chi \geq c_b]w_b \tag{26}$$

where w_g and w_b are the steady-state probabilities that the channel is in Good and Bad states, respectively; $w_g = \gamma/(\delta + \gamma)$, $w_b = \delta/(\delta + \gamma)$. The probabilities $P[\chi \geq c_g]$ and $P[\chi \geq c_b]$ are obtained by substituting c_g and c_b for R in (22). For the case of K homogeneous on-off sources, we provide the expression for L in [11].

VI. Numerical Results and Simulations

In this section, we present numerical examples of our analytical results. We verify the adequacy of these results by contrasting them against more realistic simulations.

Similar to the analysis, the simulation results are obtained using on-off traffic sources with exponentially distributed on and off periods. The ARQ retransmission process is simulated in a more realistic manner, whereby a cell is transmitted repeatedly until it is received with no errors or it reaches the limit on the number of transmissions. The probability of a cell error is computed from (1) for both channel states. Transitions between Good and Bad states are assumed to occur only at the beginning of a cell transmission slot. A cell is retransmitted if it has uncorrectable errors. It is assumed that the propagation delay is small, so that the ACK/NAK message for a cell is received at the sender before the next transmission slot. Finally, we use a finite buffer size in our simulations, in contrast to the infinite-buffer assumption in the analysis.

In our experiments, we vary the buffer size and the BER during the Bad state (P_{eb}), and we fix the BER during the Good state at $P_{eg} = 10^{-6}$. We set the mean of the off period to ten times that of the on period. In addition, we take the parameters related to the wireless channel from [10]. We adopt Bose-Chaudhuri-Hocquenghem (BCH) code [13] for FEC. Since we treat the CRC code as part of the payload, the FEC code is applied to 424-bit data units (i.e., $k = 424$ bits). Refer to [11] for the size, the code rate, and the number of correctable bits of the BCH code used in our examples. All simulation results are reported with 95% confidence intervals. Table I summarizes the values of the various parameters in the simulations and numerical examples.

TABLE I

Parameter values used in the simulations and numerical results.

Parameter	Symbol	Value
peak rate	r	1 Mbps (2604.1667 cells/sec)
buffer size	B	$100 - 1000$ cells
mean on period	$1/\alpha$	0.02304 sec
mean off period	$1/\beta$	0.2304 sec
mean Good channel period	$1/\delta$	0.1 sec
mean Bad channel period	$1/\gamma$	0.0333 sec
BER in Good channel state	P_{eg}	10^{-6}
BER in Bad channel state	P_{eb}	$10^{-2} - 10^{-5}$
Limit on transmissions	N_l	$1 - \infty$

Figure 4 depicts the CLR versus the buffer size for a service rate $c = 900$ cells/sec ($P_{eb} = 10^{-2}, \tau = 0, 4, N_l = \infty$). As expected, the CLR increases as the buffer size decreases and as τ decreases. It is observed that the analytic results slightly underestimate the actual CLR. The gap is negligible over the whole range of buffer sizes. Figure 5 depicts the CLR as a function of the service rate c using different FEC code rates. The analytic results tend to slightly underestimate the CLR as c increases.

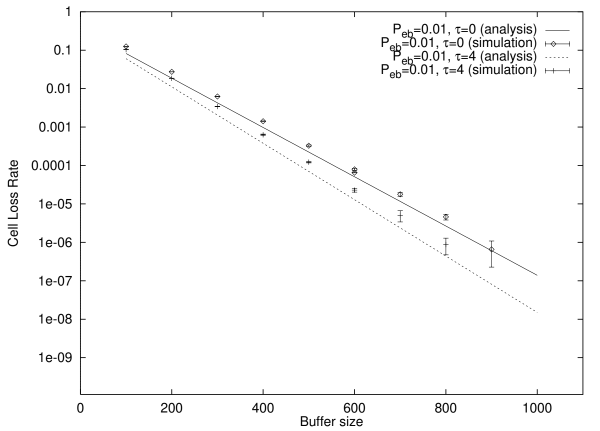

Fig. 4. Cell loss rate versus buffer size for a single stream ($c =$ 900 cells/sec, $P_{eb} = 10^{-2}, N_l = \infty$).

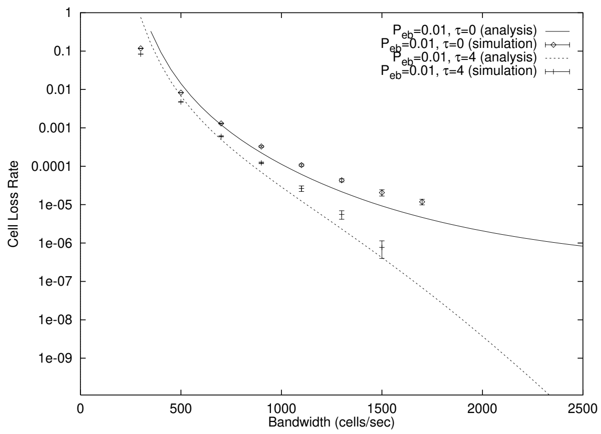

Fig. 5. Cell loss rate versus service rate c for a single stream ($B = 500$, $P_{eb} = 10^{-2}$, $N_l = \infty$).

However, the deviation of the analytical results is negligible, given that CLRs in ATM are contrasted in terms of the orders of magnitude by which they differ.

Figure 6 depicts the CLR and cell discarding rate (CDR) versus the limit on the number of transmissions (N_l) for the service rate $c = 900$ cells/sec ($P_{eb} = 10^{-2}, \tau = 2, B = 500$). It is observed that the CLR increases and CDR decreases as N_l decreases. In particular, the CDR is very sensitive to N_l whereas CLR becomes quite insensitive to N_l as N_l increases. This is due to the fact that $E[N_{tr}]$ in (3) quickly reaches its limit as N_l increases, thus causing little change in the service rate in Bad channel state. Note that the service rate in Good channel state is hardly affected by N_l.

Figure 7 depicts the mean delay versus the service rate when the buffer size $B = 500$ ($P_{eb} = 10^{-2}, \tau = 2, N_l = 4$). It is observed that the analytic results are almost identical to the simulation results. As expected, the mean delay decreases as the service rate increases. For some traffic classes, the tail of the delay distribution is considered more important than mean delay in provisioning QoS. This issue will be the subject of a subsequent paper.

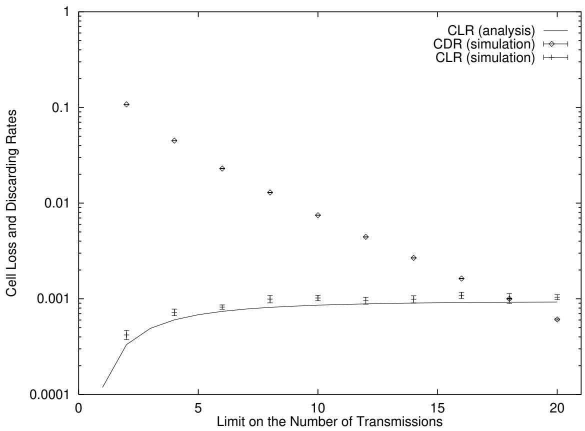

Fig. 6. Cell loss rate and cell discarding rate versus the limit on the number of transmissions.

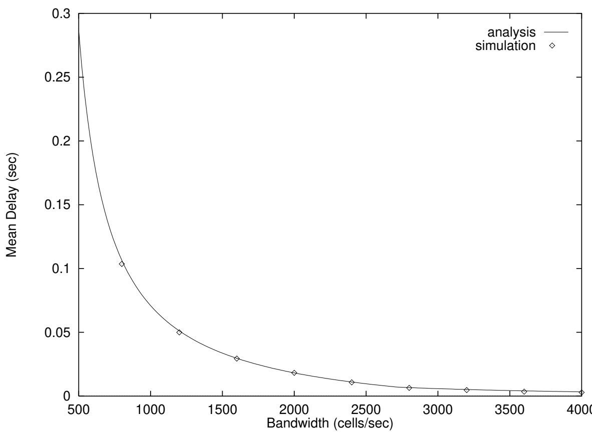

Fig. 7. Mean delay versus service rate (c).

Figures 8 shows the approximate wireless effective bandwidth versus the number of correctable bits τ for different target CLRs and for $P_{eb} = 0.01$. The buffer size B is fixed at 800 cells. These figures indicate the existence of an "optimal" code rate at which the allocated bandwidth is minimized for a given target CLR. For instance, to provide a target CLR of 10^{-6} when $P_{eb} = 0.01$, the minimum required bandwidth is $c = 868.23$ cells/sec, which is achieved when $\tau = 7$. Since at $P_{eb} = 0.01$ the mean number of bit errors in a cell is $4.82 < 5$, the advantage of correcting the excessive number of bit errors, i.e., more than seven, is overshadowed by the extra FEC bandwidth overhead. Note that the optimal code rate is always achieved at a nonzero τ, implying that resource allocation for a guaranteed CLR can always be improved using a combined ARQ/FEC approach. It is also observed that the optimal code rate increases with P_{eb}. The optimal code rate depends on the channel BERs and the target CLR. This suggests the need for adaptive FEC to continuously maintain an optimal code rate for a wireless channel with time-varying characteristics.

Next, we examine the CLR for multiplexed streams based on the results in Section V. We consider homogeneous on-off sources with the same target CLR. For

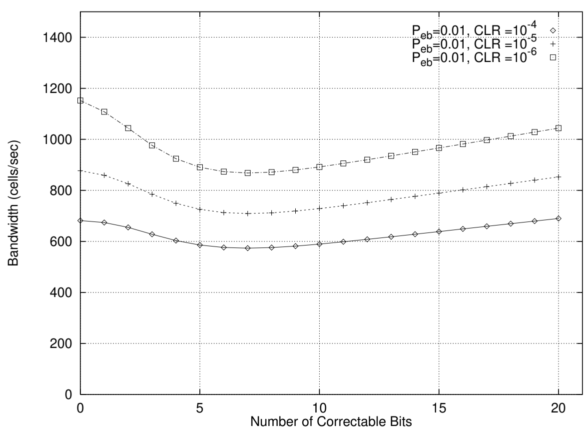

Fig. 8. Effective bandwidth versus τ for a single stream ($P_{eb} = 0.01$).

brevity, we report the results for ARQ only (i.e., $\tau = 0$). We set $P_{eb} = 10^{-3}$, $N_l = \infty$, and $c = 10$ Mbps. We vary the number of multiplexed streams. To test the goodness of our CLR analysis, which was obtained using the CDE approximation, we compare it to the exact analysis given in [11]. We also present the results based on two other approximations: the asymptotic and Binomial approximations. Both approximations rely on the dominant eigenvalue, similar to the CDE approach. However, they differ from it in the estimation of L; the coefficient associated with the dominant eigenvalue. In the asymptotic approximation, the exact value of L, denoted by L_a, is used, which is obtained from the exact analysis in [11]. The Binomial approximation estimates L by L_b, which is computed from the binomial distribution:

$$L_b \approx G(0) = P[\chi > c] = \sum_{i=j}^{K} \binom{K}{i} w_1^i w_0^{K-i}$$

where $j \triangleq \lceil c/r \rceil$ and w_1 and w_0 are the steady-state probabilities that a source is in on and off states, respectively.

Figures 9 depicts the CLR for 50 multiplexed connections with a total load of 54.5%. It is observed that the asymptotic approximation is quite accurate compared with the exact result. Thus, it can be argued that one eigenvalue is good enough to compute the CLR for multiplexed streams. In addition, it is also observed that the difference between the exact results and both the CDE and Binomial approximations tends to decrease as K increases. Both approximations provide upper bounds on the exact CLR, with the Binomial approximation being the tighter of the two. Since in our case only homogeneous on-off sources are considered, the binomial approximation is rather easy to compute. However, if we consider more general sources, it will incur substantial numerical complexity.

VII. Conclusions

In this paper, we investigated the mean delay and cell loss performance of a wireless ATM link. We used fluid

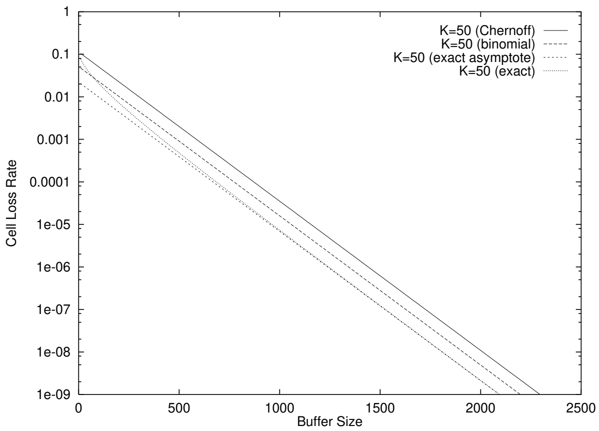

Fig. 9. Cell loss rate for 50 multiplexed streams.

models to capture the bursty nature of ATM traffic. The fluctuations of the wireless channel were appropriately captured using a fluid version of Gilbert-Elliot model. Error control schemes (ARQ and FEC) were incorporated. In the case of a single stream, the mean delay and the exact CLR were obtained. The solution was then used to obtain an approximation for the wireless effective bandwidth, which can be used as a valuable tool in resource allocation and admission control in wireless ATM networks. In the case of multiplexed streams, an approximate expression for the CLR was obtained. Our analytical results were contrasted with simulations of a wireless ATM link that implements a hybrid ARQ/FEC error control mechanism. We observed that in the case of a single stream (i.e., no multiplexing), the analytical expressions for the CLR and (approximate) wireless effective bandwidth are quite acceptable over a wide range of bit error rates. The approximate CLR for multiplexed streams is adequate under medium and high loads. A better approximation is needed when the load is light. We found that a combined ARQ/FEC is always more efficient than ARQ alone. The selection of the FEC code rate is very crucial to achieving optimal use of the wireless bandwidth and to the provisioning of QoS over a wireless ATM link. Our focus in this paper was on the cell loss rate and mean delay as the primary measures of QoS. In the future, we plan to investigate the delay distribution over the wireless ATM link under an imposed limit on the number of cell transmissions.

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