Cross-Layer Design and Analysis of Wireless Networks Using the Effective Bandwidth Function

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***Abstract*— In this paper, we propose a useful framework for the cross-layer design and analysis of wireless networks where ARQ (Automatic Repeat reQuest) and AMC (Adaptive Modulation and Coding) schemes are employed. To capture the joint effect of the packet transmission error rate at the PHY layer and the packet loss probability at the MAC layer, we introduce the effective bandwidth function of the packet service process. Base on queueing analysis with this effective bandwidth function, our cross-layer design tries to satisfy the required packet loss probability by each user and minimize the average packet transmission error rate. Numerical examples are provided to show the usefulness and characteristics of our framework.**

***Index Terms*— Adaptive modulation and coding (AMC), cross-layer design, effective bandwidth function, quality of service (QoS), wireless channel.**

I. Introduction

With rapid adoption of wireless technology combined with the explosive growth of the Internet, the demand for high data rates and QoS (Quality-of-Service) in wireless networks is rapidly growing. Since the radio spectrum available for wireless services is very limited, spectral efficiency is of primary concern in the design of future wireless networks. To increase the spectral efficiency of wireless networks, the Adaptive Modulation and Coding (AMC) scheme [1] and cross-layer design [2]–[6] have been extensively studied.

The aim of this paper is to propose a useful framework for the cross-layer design of wireless networks where ARQ (Automatic Repeat reQuest) and AMC are employed. We suppose that ARQ requests retransmissions for packets in error and all packets are eventually transmitted once stored in the queue at the MAC layer. Thus, packet losses can occur due to buffer overflow at the MAC layer and can consequently be considered as measuring the performance of the MAC layer. On the other hand, the performance of the PHY layer can be estimated by the packet error rate (PER) due to the AMC scheme employed at the PHY layer. Therefore, assuming that a user requires a certain level of packet loss probability, it is very important to design an AMC scheme which satisfies the required packet loss probability at the MAC layer while maintaining the PER at the PHY layer as low as possible, which is the main objective of our cross-layer design.

In this study, to investigate the queueing performance at the MAC layer, we introduce the notion of effective bandwidth functions of the service and arrival processes [7]–[9], [11]. Through the effective bandwidth function of the service process we can investigate the effect of the AMC scheme on system performances both at the MAC layer and at the PHY layer, and accordingly it is a useful device for our study.

Before closing this section, it is worth mentioning the work in [4] where the authors considered a similar problem. However, there are two main differences between our model and the model in [4]. The first is that [4] did not consider the packet retransmissions at the MAC layer, and the second is that [4] used the constraint that the target PER at the PHY layer is achieved for each AMC mode, while we use a less restrictive constraint that the target *average* PER is achieved over AMC modes.

The remainder of this paper is organized as follows: In Section II, we describe the system model. In Section III, we introduce effective bandwidth functions of the service and arrival processes and analyze the system for performance evaluation. In Section IV, we present our cross-layer design framework, and in Section V we provide numerical examples to examine the usefulness and characteristics of our cross-layer design framework. Conclusions are drawn in Section VI.

II. System Model

We consider a connection between a server (source) and a subscriber (destination), which includes a wireless link with a single-transmit and a single-receive antenna. We focus on the downlink in this paper, although our framework is also applicable to the uplink. There is a finite size queue at the MAC layer of the transmitter, and the service discipline of the queue is first-in-first-out (FIFO). The system employs an AMC scheme with N transmission modes as given in Table I where we have $N = 7$. The AMC scheme in Table I is the same as given in Table I of [3].

A. Physical Layer Model

At the PHY layer, transmissions are performed PHY frame-by-frame, where each PHY frame duration is fixed with length T_f (sec). The PHY frame duration T_f is considered to be unit time in our model, and accordingly we assume that time axis is divided into unit times and time is indexed by t ($t = 0, 1, \ldots$). We also assume that the channel condition is slowly varying and remains invariant per PHY frame. As a consequence, the transmission mode in the AMC scheme is adjusted on

Manuscript received March 24, 2006; revised August 18, 2006 and November 28, 2006; accepted February 2, 2007. The associate editor coordinating the review of this letter and approving it for publication was V. Lau. This research was supported by the MIC (Ministry of Information and Communication), Korea, under the ITRC (Information Technology Research Center) support program supervised by the IITA (Institute of Information Technology Assessment).

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Digital Object Identifier 10.1109/TWC.2007.06030108.

TABLE I
THE AMC SCHEME WITH 7 MODES [3]

Mode	Modulation	rate	a_n	g_n	γ_{pn}
1	BPSK	1	67.7328	0.9819	6.3281
2	QPSK	2	73.8279	0.4945	9.3945
3	8-QAM	3	58.7332	0.1641	13.9470
4	16-QAM	4	55.9137	0.0989	16.0938
5	32-QAM	5	50.0552	0.0381	20.1103
6	64-QAM	6	42.5594	0.0235	22.0340
7	128-QAM	7	40.2559	0.0094	25.9677

rate = bits/symbol

a PHY frame-by-frame basis. When transmission mode n is used, d_n MAC frames in the queue of the MAC layer are mapped into a PHY frame and transmitted simultaneously in the corresponding PHY frame. We assume that $d_0 < d_1 < \cdots < d_N$. A good example set of $\{d_n\}_{n=0}^N$ can be found in [3].

We assume that the slowly varying wireless channel is modeled by the Nakagami-m model where the received SNR (signal-to-noise ratio) γ per frame is a random variable with Gamma probability density function:

$$p_\gamma(\gamma) = \frac{m^m \gamma^{m-1}}{\overline{\gamma}^m \Gamma(m)} \exp\left(-\frac{m\gamma}{\overline{\gamma}}\right), \tag{1}$$

where $\overline{\gamma} = \mathrm{E}[\gamma]$ is the average received SNR, $\Gamma(m) = \int_0^\infty t^{m-1}\exp(-t)dt$ is the Gamma function, and m is the Nakagami fading parameter ($m \geq 1/2$).

Since the AMC scheme employed has N transmission modes, we partition the entire SNR range into $N+1$ non-overlapping intervals with boundary values denoted as $\{\gamma_n\}_{n=0}^{N+1}$ with $\gamma_0 = 0$ and $\gamma_{N+1} = \infty$. When the received SNR γ is in the interval $[\gamma_n, \gamma_{n+1})$ $(n = 1, \ldots, N)$, the transmission mode n is chosen. To avoid deep channel fades, no data are sent when $\gamma_0 \leq \gamma < \gamma_1$, that is, $d_0 = 0$ for mode 0. Then, the design objective for the AMC scheme is to determine the set of boundary values $\{\gamma_n\}_{n=1}^N$.

We now model the wireless channel state by a Finite State Markov Chain (FSMC) $\{m(t)|t = 0, 1, \cdots\}$ with state space $\{0, 1, \cdots, N\}$ as in [3] where $m(t) = n$ when transmission mode n is selected at time t. Let $\boldsymbol{P} = (p_{i,j})$ be the transition probability matrix of the FSMC $\{m(t)\}$ where $p_{i,j}$ denotes the conditional probability that the FSMC $\{m(t)\}$ is in state j at time $t+1$, given that it is in state i at time t. To save space, we omit a detailed derivation of the matrix $\boldsymbol{P}$ (for the detailed derivation, see [4]).

For later use, let π_n $(n \in \{0, 1, \cdots, N\})$ denote the stationary probability that the FSMC is in state n, i.e., $\pi_n > 0, \sum_{i=0}^N \pi_i p_{i,j} = \pi_j, 0 \leq j \leq N$ and $\sum_{n=0}^N \pi_n = 1$. Then by definition

$$\pi_n = \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma, \qquad n = 0, \ldots, N,$$

where $p_\gamma(\gamma)$ is given by (1), and it can be easily shown that, for $0 \leq n \leq N$

$$\pi_n = \frac{\Gamma(m, m\gamma_n/\overline{\gamma}) - \Gamma(m, m\gamma_{n+1}/\overline{\gamma})}{\Gamma(m)}, \tag{2}$$

where $\Gamma(m, x) = \int_x^\infty t^{m-1}\exp(-t)dt$ is the complementary incomplete Gamma function.

B. MAC Layer Model

For the service process for MAC frames in the queue at the MAC layer, we assume the following: If a MAC frame is received incorrectly at the receiver after error detection, this information is immediately fed back to the transmitter and the transmitter retransmits the MAC frame in the next PHY frame. On the other hand, if a MAC frame is received correctly at the receiver after error detection, this information is immediately fed back to the transmitter and the transmitter removes the MAC frame from the queue. For convenience, a MAC frame is referred to as a packet from now on.

To model the packet service process at the MAC layer, we first consider the packet error process at the physical layer in our model. From the assumptions and the settings we made so far, the PER at the PHY layer is expressed as a function of the transmission mode selected by the AMC controller. Let $\mathrm{PER}_n(\gamma)$ denote the packet error rate at the PHY layer when the mode n is used and the received SNR is equal to γ. For the AMC modes in Table I, when the packet length is 1080 bits, Liu *et al.*[3] showed that $\mathrm{PER}_n(\gamma)$ can be approximated as

$$\mathrm{PER}_n(\gamma) \approx \begin{cases} 1 & (0 < \gamma < \gamma_{pn}), \\ a_n \exp(-g_n\gamma) & (\gamma \geq \gamma_{pn}), \end{cases} \tag{3}$$

where a_n, g_n, and γ_{pn} are the mode-dependent parameters and are given in Table I. In practice, we have $\gamma_n > \gamma_{pn}$.

Next, to model the packet service process at the MAC layer, we define r_n $(n = 1, \ldots, N)$ to be the PER at the PHY layer when the mode n is used. Then, r_n $(n = 1, \ldots, N)$ is approximately given by [3], [4]

$$\begin{aligned} r_n &= \frac{1}{\pi_n}\int_{\gamma_n}^{\gamma_{n+1}} a_n \exp(-g_n\gamma) p_\gamma(\gamma) d\gamma \\ &= \frac{a_n m^m}{\pi_n \Gamma(m)\overline{\gamma}^m} \frac{\Gamma(m, b_n\gamma_n) - \Gamma(m, b_n\gamma_{n+1})}{b_n^m}, \end{aligned}$$

where π_n is given by (2) and $b_n = m/\overline{\gamma} + g_n$. Since we assume that we do not transmit any packet when mode 0 is selected, for notational convenience, we define $r_0 = 1$.

We now assume that packet errors occur independently on a packet-by-packet basis with probability r_n when mode n is chosen. The PER averaged over all transmission modes, called the average PER, is then given by

$$\frac{\sum_{n=1}^N \pi_n d_n r_n}{\sum_{n=1}^N \pi_n d_n}. \tag{4}$$

We are now ready to describe the packet service process at the MAC layer. Let $c_n(t)$ $(n = 0, \ldots, N; t = 0, 1, \ldots)$ denote a random variable representing the number of packets correctly transmitted at time t when the transmission mode n is selected. Under the assumptions we have made so far, $\{c_n(t)\}$ is a sequence of independent random variables and the probability mass function of $c_n(t)$ is given by

$$\mathrm{P}\{c_n(t) = k\} = \binom{d_n}{k}(1 - r_n)^k r_n^{d_n - k}, \quad k = 0, \ldots, d_n.$$

Then the packet service process is given by $\{c_{m(t)}(t)\}$. That is, when the wireless channel state at time t is n, i.e., $m(t) = n$, the number of successfully transmitted packets is $c_n(t)$. Since

$\{m(t)\}$ is a Markov chain, the service process $\{c_{m(t)}(t)\}$ is a Markov modulated process.

Finally, we focus on the queueing process at the MAC layer. Let $q(t)$ $(t = 0, 1, \ldots)$ denote a random variable representing the queue length (i.e., the number of packets in the queue) at time t. Let $a(t)$ $(t = 0, 1, \ldots)$ denote a random variable representing the number of packets newly arriving just after time t. If we assume the early arrival model [10] for our discrete time queueing system at the MAC layer, i.e., new packets are serviced immediately upon arrival if possible, then the queueing process $\{q(t)\}$ evolves according to the following recursion [10], [11]:

$$q(t+1) = \max\{0, q(t) + a(t) - c_{m(t)}(t)\}. \qquad (5)$$

III. Effective Bandwidth Function and Queueing Performance

In this section, we define the effective bandwidth function (EBF) of the service process as a device to describe the effect of AMC on the PHY layer as well as the MAC layer, and provide a useful expression for the EBF. For detailed and theoretical descriptions of the EBF, see e.g., [2], [7]–[9], [11] and references therein.

Let $C(t)$ $(t = 0, 1, \ldots)$ denote a random variable representing the cumulative service process during the interval $[0, t)$, i.e., $C(t) = \sum_{s=0}^{t-1} c_{m(s)}(s)$. Let $\Lambda_C(\theta)$ denote the Gärtner-Ellis limit of the cumulative service process $C(t)$, i.e., $\Lambda_C(\theta) = \lim_{t\to\infty} t^{-1} \log \mathrm{E} \exp(\theta C(t))$, provided that the limit exists. Then the EBF of the service process is defined by $\xi_C(\theta) = -\frac{\Lambda_C(-\theta)}{\theta}$ [2], [11].

To compute the EBF of the service process, let $\phi_n(\theta) = \mathrm{E}\exp(\theta c_n(t))$ $(n = 0, \ldots, N)$ and $\boldsymbol{\phi}(\theta)$ be the diagonal matrix with diagonal elements $\{\phi_0(\theta), \phi_1(\theta), \ldots, \phi_N(\theta)\}$. Since the service process $\{c_{m(t)}(t)\}$ is a Markov modulated process, it can be shown that the EBF of the service process is given by

$$\xi_C(\theta) = -\frac{\log \delta_C(-\theta)}{\theta},$$

where $\delta_C(\theta)$ is the Perron-Frobenius (PF) eigenvalue of the matrix $\boldsymbol{C}(\theta) = \boldsymbol{\phi}(\theta)\boldsymbol{P}$. For the proof, refer to [7], [11].

Similarly, we define the EBF $\xi_A(\theta)$ of the arrival process by

$$\xi_A(\theta) = \frac{\Lambda_A(\theta)}{\theta},$$

where $\Lambda_A(\theta) = \lim_{t\to\infty} t^{-1} \log \mathrm{E}\exp(\theta A(t))$ and $A(t) = \sum_{n=0}^{t-1} a(n)$ [11].

Now we are ready to investigate the queueing performance with the help of the EBFs of the service and arrival processes. Let $q(\infty)$ denote a random variable representing the queue length evolved by (5) in steady state. It is known that under some conditions, the tail distribution $\mathrm{P}(q(\infty) > x)$ of the queue length in steady state is approximately given by [2], [11], [12]

$$\mathrm{P}(q(\infty) > x) \approx \mathrm{P}(q(\infty) > 0) \exp(-\theta^* x), \qquad (6)$$

where θ^* is the unique real solution of the equation

$$\Lambda_A(\theta) + \Lambda_C(-\theta) = 0,$$
$$(\text{ or equivalently }) \; \xi_A(\theta) - \xi_C(\theta) = 0. \qquad (7)$$

IV. Cross-Layer Design

In this section, we present our framework for a cross-layer design. As mentioned before, we use the packet loss probability and the average PER as estimates of the performances of the MAC and PHY layers, respectively. In addition, we assume that the packet loss probability is well approximated by the tail probability $\mathrm{P}(q(\infty) > x)$ of the queue length at the MAC layer, and we use (6) to compute $\mathrm{P}(q(\infty) > x)$. Note that the tail probability overestimates the packet loss probability in general, but for simplicity we use the approximation (6) in this study. In fact, as seen later our framework can use any approximation formula for the packet loss probability based on the EBFs of the service and arrival processes. The exact derivation of the packet loss probability is beyond the scope of this study.

Now assume that each user requires a specific level of packet loss probability $\hat{P}_{\mathrm{loss}}$. Our cross-layer design aims to maximize the transmission efficiency while guaranteeing the required packet loss probability for each user. Here, the transmission efficiency is defined to be the ratio of the number of correctly received packets to the total number of transmitted packets, and is computed by $1 - P_{\mathrm{target}}$ where P_{target} denotes the average PER given in (4).

In what follows, we present a procedure to determine the AMC scheme, i.e., the set of boundary values $\{\gamma_n\}_{n=1}^N$ for our cross-layer design. For each target average PER, we select a suitable AMC scheme which maximizes its corresponding EBF among AMC schemes considered in the algorithm below. This is because the resulting packet loss probability decreases with an increase in the EBF of the corresponding service process for each AMC scheme. Refer to equations (6) and (7). Next, we compute the tail probability $\mathrm{P}(q(\infty) > x)$ for the selected AMC scheme. We continue the same procedure by changing the value of the target average PER. Then, bearing in mind that a lower value of the target average PER leads to greater transmission efficiency, we consider the set of target average PERs which result in the packet loss probabilities being lower than the required packet loss probability, and finally we select the minimum target average PER in the set and its corresponding AMC scheme.

To describe the detailed algorithm, we first consider the packet loss probability $P_{\mathrm{loss}}(x)$, the set of boundary values $\{\gamma_n(x)\}_{n=0}^{N+1}$ and the resulting average PER $\mathrm{PER}(x)$ as functions of the target average PER x as follows:

1) Let $x =$ the target average PER, and set Δ to an appropriate value where Δ is a positive design parameter.
2) Set $k = 1$ and initialize the boundary values:
$$\gamma_0^{(0)} = 0, \qquad \gamma_{N+1}^{(0)} = \infty,$$
$$\gamma_n^{(0)} = \frac{1}{g_n} \log \frac{a_n}{x} \quad (n = 1, \ldots, N).$$
3) Decrease the boundary values: for $n = 1, \ldots, N$,
$$\gamma_n^{(k)} = \gamma_n^{(k-1)} - \frac{1}{\Delta}(\gamma_n^{(0)} - \gamma_{n-1}^{(0)}),$$
$\gamma_0^{(k)} = 0$ and $\gamma_{N+1}^{(k)} = \infty$.
4) Calculate π_n and r_n $(n = 1, \ldots, N)$ with $\gamma_n = \gamma_n^{(k)}$.
5) Use (4) to calculate the average PER.

6) If the calculated average PER is greater than x, then set $\gamma_n(x) = \gamma_n^{(k-1)}$ $(n = 0, \ldots, N+1)$, estimate the packet loss probability $P_{\text{loss}}(x)$ and the resulting average PER $\text{PER}(x)$ with the set of boundary values $\{\gamma_n(x)\}_{n=0}^{N+1}$ using (6) and (4), respectively. Otherwise increase k by one, i.e., $k = k + 1$, and go to Step 3.

Note that, if we choose Δ sufficiently large, we have $\text{PER}(x) \approx x$. The procedure for our cross-layer design is then described as follows:

- Define a function $f(x)$ by $f(x) = P_{\text{loss}}(x) - \hat{P}_{\text{loss}}$.
- Find a zero x_0 of the function $f(x)$ by a numerical algorithm such as the bisection method.
- The set of boundary values $\{\gamma_n\}_{n=1}^{N}$ is then given by $\gamma_n = \gamma_n(x_0)$ $(n = 0, \ldots, N+1)$. The average PER achieved by our cross-layer design is given by $\text{PER}(x_0) \approx x_0$.

Remark 1. The initial set of boundary values $\{\gamma_n^{(0)}\}_{n=0}^{N+1}$ determined by Step 2 is the same as used in [3]. Note that the constraint in our cross-layer design is less restrictive than that in [3]. Hence, the initial set of boundary values determined by Step 2 satisfies the condition that the resulting average PER is less than the target average PER, i.e., $\text{PER}(x) \leq x$.

Remark 2. Note that when the boundary values decrease as $\gamma_n^{(k+1)} \leq \gamma_n^{(k)}$ $(n = 1, \ldots, N)$, the resulting service rate to a given SNR increases and the resulting PER also increases. While the increase in service rate increases the EBF of the service process, the increase in PER decreases the EBF of the service process. Consequently, Step 3 may increase or decrease the EBF of the service process. In our numerical studies, we have observed that Step 3 increases the EBF of the service process, although we will not provide a theoretical proof for this observation in this paper. One of the reasons is that in our model, the increase in service rate has a greater impact on the EBF of the service process than the increase in PER. In the next section, we will provide numerical examples to show that decreasing boundary values increases the EBF of the service process. Note here that the increase in EBF of the service process decreases the packet loss probability.

Remark 3. From Remark 2, we can conjecture that there is a trade-off between the target average PER and the packet loss probability in our framework. In other words, if we allow a large average PER, we can attain a low packet loss probability in our framework. In the next section, we will provide a numerical example to show the trade-off. From our conjecture, we see that the AMC scheme with boundary values $\gamma_n = \gamma_n(x_0)$ $(n = 0, \ldots, N+1)$ obtained from the above procedure satisfies our cross-layer design objective.

Remark 4. Our framework does not provide the *global* optimal AMC scheme over all possible AMC schemes which satisfy the packet loss probability requirement. However, considering all possible AMC schemes seems to be impossible and time-consuming. In our framework, we give a *simple and efficient* algorithm which can provide a *better (not the best)* AMC scheme. Due to its simplicity and efficiency, we believe our framework is quite useful in practice.

V. Numerical Examples

In this section, we provide some numerical examples to show the usefulness of our framework, and the correctness of our observation and conjecture in Remark 3. Unless otherwise mentioned, we will use the following parameters in the numerical examples.

- the frame length $T_f = 2$ ms
- the sequence $\{d_n\}$ of service rates for AMC modes : $d_n = 2n, 0 \leq n \leq N$
- the Nakagami fading parameter $m = 1$
- the average SNR $\bar{\gamma} = 15$ dB
- the Doppler frequency $f_d = 10$ Hz

First we confirm that when the boundary values decrease as $\gamma_n^{(k+1)} \leq \gamma_n^{(k)}$ $(n = 1, \ldots, N)$ in Step 3, the EBF of the service process increases. Figs. 1 and 2 show the behavior of the EBF of the service process with the increase of k. We set $\Delta = 100$ in the figures. From the figures, we see that Step 3 increases the EBF of the service process, as mentioned in Remark 2.

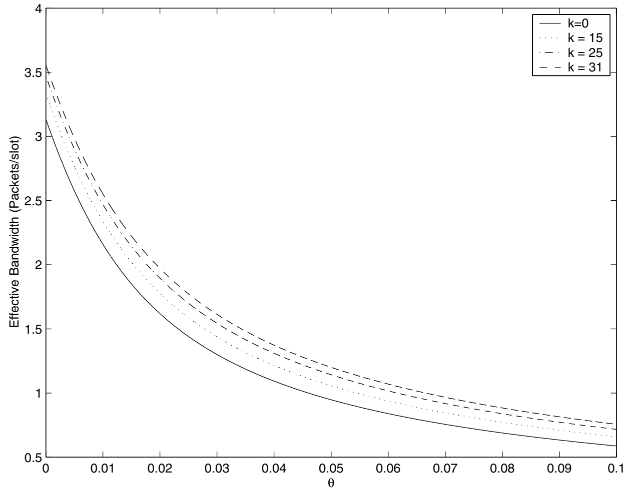

Fig. 1. The behavior of the effective bandwidth function ($P_{\text{target}} = 0.01$).

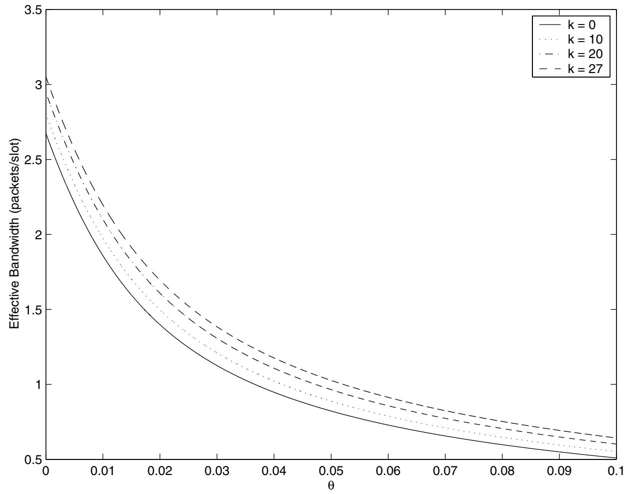

Fig. 2. The behavior of the effective bandwidth function ($P_{\text{target}} = 0.001$).

Next we examine the accuracy of the approximation formula (6). We simulate our system where the transition matrix and the packet error rates $\{r_n\}_{i=1}^{N}$ obtained in Section II are used to model the wireless channel. The results are given in Figs. 3 and 4. In the figures, simulation results are obtained by

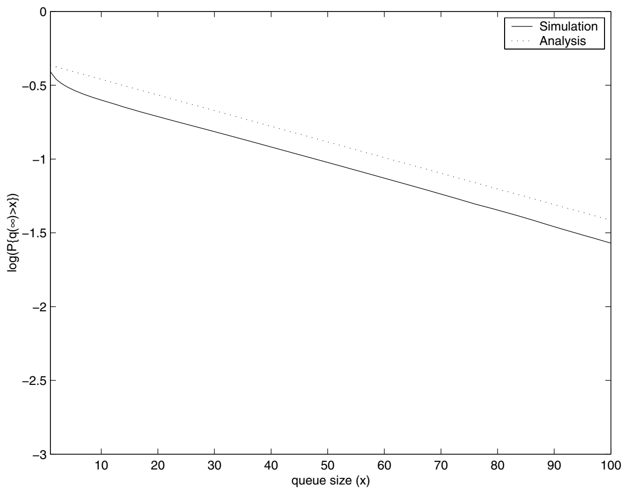

Fig. 3. The tail probabilities for a Poisson process ($P_{\text{target}} = 0.01$).

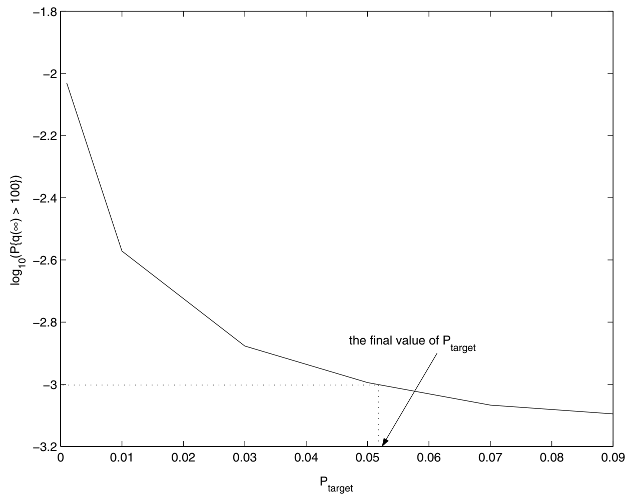

Fig. 5. Packet loss probabilities versus target average packet error rate.

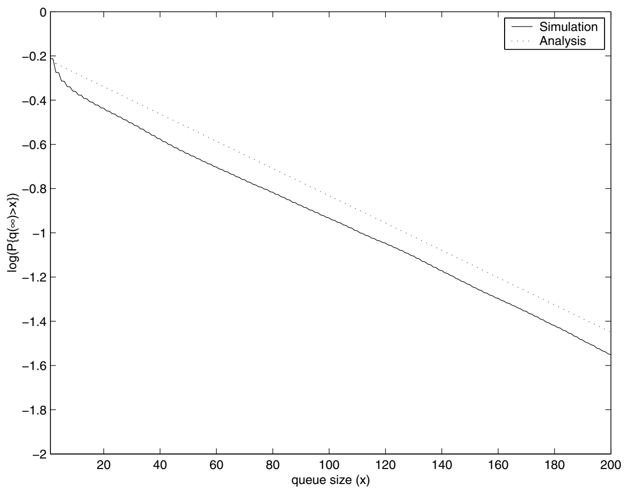

Fig. 4. The tail probabilities for an ON and OFF process ($P_{\text{target}} = 0.001$).

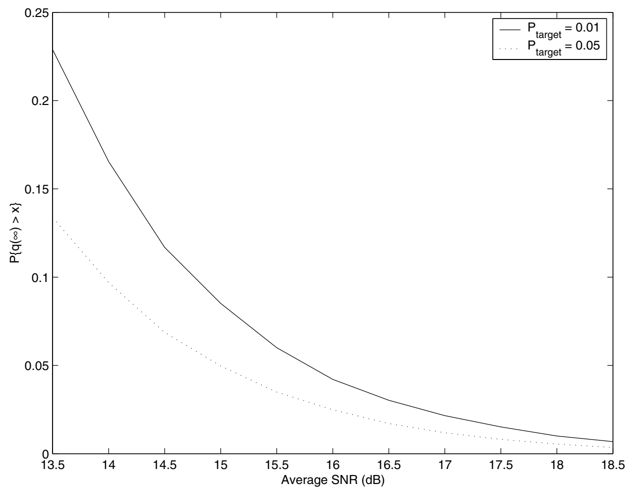

Fig. 6. Packet loss probabilities versus Average SNR (dB).

averaging values from five simulation runs. The arrival process in Fig. 3 is a Poisson process with rate $\lambda = 2.5/T_f$ and the arrival process in Fig. 4 is an ON and OFF process with the following parameters: The transition probability from the ON state (resp. OFF state) to the OFF state (resp. ON state) is 0.35 (resp. 0.55), and the number of packets arriving in unit time with an ON state (resp. OFF state) is 6 (resp. 0). The tail probabilities estimated by our approximation formula are denoted by "Analysis" and those estimated by simulation are denoted by "Simulation" in the figures. As seen in the figures, the tail probabilities estimated by our approximation formula (6) are close to those estimated by simulation.

We next illustrate the trade-off between the target average PER and the packet loss probability in our framework, as conjectured in Remark 3. Fig. 5 displays the packet loss probabilities achieved by our framework as a function of the target average PER P_{target} when the size of the queue is 100. The arrival process in Fig. 5 is a Poisson process with rate $\lambda = 2/T_f$. In this figure, we observe that there is a trade-off between the target average PER and the packet loss probability in our framework. Thus, in our framework, if we allow larger average PER, we can achieve lower packet loss probability. In addition, using Fig. 5 we can determine the AMC scheme satisfying our objective as follows: Assume that the required packet loss probability is 0.001. From the figure, when the value of P_{target} is 0.051, our cross-layer design objective is achieved. Hence, we select the AMC scheme with boundary values $\{\gamma_n\}_{n=0}^{N+1}$ which corresponds to $P_{\text{target}} = 0.051$.

Finally, we examine the effect of the average SNR on the packet loss probability achieved by our framework. Fig. 6 displays the packet loss probability as a function of the average SNR for the target average PERs $P_{\text{target}} = 0.01, 0.05$. The arrival process in Fig. 6 is a Poisson process with rate $\lambda = 2/T_f$. As seen in the figure, the packet loss probability achieved by our framework is quite sensitive to changes in the average SNR, and it decreases with an increase in the average SNR.

VI. Conclusions

In this paper, we propose a new framework for the cross-layer design of wireless networks where ARQ and AMC are employed. To capture the joint effect of the packet transmission error rate at the PHY layer and the packet loss probability at the MAC layer, we introduce the effective bandwidth function of the packet service process. With the help of the effective bandwidth function, we characterize the wireless channel and analyze the queueing system. Based on the analytical result, our cross-layer design tries to satisfy the packet loss probability required by each user and maximize the transmission efficiency. In numerical examples, we show how to achieve our cross-layer design objective and we investigate the characteristics of our framework.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for valuable comments which significantly improved the presentation of this paper.

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