Cross-Layer-Based Modeling for Quality of Service Guarantees in Mobile Wireless Networks

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ABSTRACT

In this article we propose a cross-layer approach to investigate the impact of the physical-layer infrastructure on the data-link-layer QoS performance in mobile wireless networks. At the physical layer, we take the MIMO diversity schemes as well as AMC into account. At the data-link layer, our focus is on how this physical-layer infrastructure influences the real-time multimedia QoS provisioning performance such as delay-bound violation and buffer-overflow probabilities. To achieve this goal, we first model the physical-layer service process as a finite state Markov chain. Based on this FSMC model, we then characterize the QoS performance at the data-link layer using the *effective capacity* approach, which turns out to be critically important for the statistical QoS guarantees in mobile wireless networks. The numerical and simulation results obtained demonstrate that the proposed cross-layer model can efficiently characterize the interaction between the physical layer infrastructure and upper layer protocols' QoS provisioning performance.

INTRODUCTION

The explosive development of wireless services such as wireless Internet, mobile computing, and cellular telephoning motivates an unprecedented revolution in wireless networks. This also presents great challenges to system designers since the time-varying fading channel has the significant impact on supporting the quality of service (QoS) requirements for heterogeneous mobile users. A large number of interesting schemes are developed at the physical layer to overcome the impact of wireless fading channels. Among them, the multiple-input multiple-output (MIMO) infrastructure [1] and adaptive modulation and coding (AMC) [2] are promising techniques that have received significant research attention in recent years.

There have been a great deal of research efforts on applying both MIMO and AMC to improve the spectral efficiency at the physical layer. However, the problems of how to efficiently employ the unique nature of such techniques for designing upper-layer protocols and the impact of this physical layer revolution on supporting diverse QoS requirements, have been neither well understood, nor thoroughly studied. Consequently, it becomes increasingly important to develop the *cross-layer* scheme to integrate the QoS provisioning algorithms/protocols at higher network layers with MIMO and AMC implemented at the physical layer.

In this article we propose a cross-layer approach to investigate the impact of physical layer characteristics on data link layer QoS performance in mobile wireless networks. Some relevant work can be found in [3–5]. At the physical layer, we integrate the MIMO diversity with AMC, while at the data link layer, our focus is on how this physical layer infrastructure influences the QoS provisioning performance. To achieve this goal, we first model the physical-layer service process as a finite state Markov chain (FSMC). Based on this FSMC model, we then characterize the QoS provisioning performance at the data link layer by applying the technique of the *effective capacity* [3]. The effective capacity approach enables us to analyze the statistical QoS metrics such as delay bound violation and buffer overflow probabilities, which are critically important for QoS guarantees over real-time multimedia mobile wireless networks. Extending and applying the theories of the effective capacity, we show how it can act as a bridge that connects across the physical layer with the upper layer protocols. The numerical and simulation results obtained demonstrate that our approach can efficiently capture the interaction across different layers and accurately characterize the QoS provisioning performance.

The rest of this article is organized as follows. We introduce the physical layer system model

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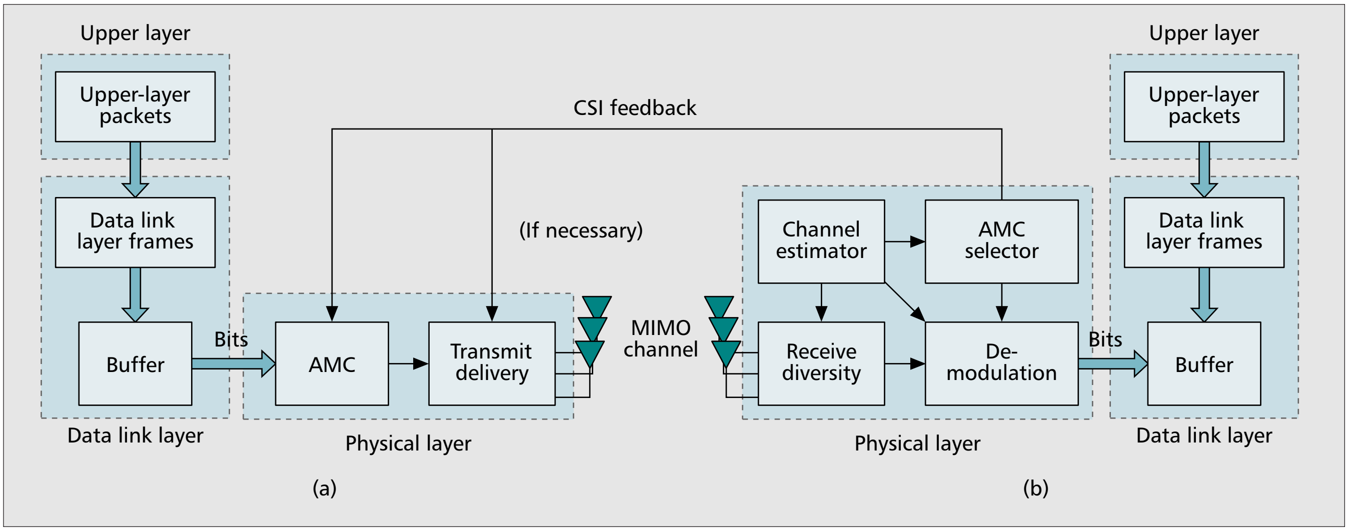

Figure 1. *The system model: a) base station transmitter; b) mobile wireless receiver.*

for the point-to-point wireless link. We propose effective-capacity-based cross-layer modeling for wireless QoS guarantees. We evaluate our proposed cross-layer design system model. The article is then concluded.

THE PHYSICAL LAYER SYSTEM MODEL

In this article we concentrate on the point-to-point wireless downlink transmission with N_t antennas (Tx) at the base station transmitter and N_r antennas (Rx) at the mobile receiver. This system model, as shown in Fig. 1, can be considered as cellular networks where we only focus on the transmission from a base station to a single mobile receiver over a point-to-point wireless link. Note that in real wireless networks it is also important to consider the end-to-end QoS provisioning. However, in this article we focus on the point-to-point QoS mainly for the following reasons. First, the investigation of point-to-point QoS provisioning provides fundamental studies for end-to-end QoS guarantees. Second, the bottleneck of most current wireless networks (e.g., cellular networks) is typically located at the last wireless hop, which can be simplified and modeled as a point-to-point QoS provisioning problem. As shown in Fig. 1, the upper layer packets are first divided into frames at the data link layer. The frames are stored at the transmit buffer and then split into bitstreams at the physical layer, where AMC and MIMO diversity are employed, respectively, to enhance the system performance. The reverse operations are implemented at the receiver side. Also, the channel state information (CSI) is estimated at the receiver and fed back to the transmitter for AMC and MIMO diversity deployments (if necessary, depending on the specific MIMO diversity scheme used).

MIMO SYSTEMS

The wireless fading channel is characterized by its random fluctuations from the transmitted signal strength over time, frequency, and space. To overcome severe performance deterioration due to channel fading in mobile wireless networks, various diversity techniques can be utilized to efficiently improve system performance. While conventional time and frequency diversities have been successfully implemented in current wireless systems, the use of spatial diversity by deploying multiple antennas at the transmitter and/or receiver is still receiving a great deal of research attention in recent years. In general, MIMO techniques can be classified into two categories:

- Improving reliability by spatial diversity
- Enhancing throughput by spatial multiplexing

Due to the hardware limitations and power constraints of the mobile terminal (MT), the number of receive antennas at the MT is limited to a small number. Therefore, the benefit of using spatial multiplexing is restricted and at the cost of complexity in the MT. In contrast, it is practically more attractive to apply spatial diversity, especially the base station transmit diversity technique [1], in mobile wireless networks. Thus, in this article we only focus on the first category, spatial-diversity-based MIMO systems.

There are a number of promising transmit/receive diversity schemes. For example, when CSI is available at both sides of the wireless link, maximal ratio transmission (MRT, also known as transmit beamforming) and maximal ratio combining (MRC) are known as the optimal transmit and receive diversity schemes, respectively. When CSI is not available at the transmitter side, space-time block coding (STBC) is a powerful approach to achieve transmit diversity. Moreover, selection combining (SC) at either the transmitter or receiver side emerges as a good trade-off between performance and complexity. In this article we consider a general model for different diversity schemes. The diversity schemes on which we focus include MRT, STBC, MRC, and transmit/receive SC, as well as the integrations of those schemes.

We propose to use the effective bandwidth and effective capacity as the controlling functions for cross-layer modeling. The characterizations of the QoS performance guarantees are equivalent to investigating the dynamics of the QoS exponent θ, which turns out to be a very simple and efficient cross-layer modeling approach

ADAPTIVE MODULATION AND CODING

The AMC technique, where transmission parameters such as constellation size and coding rate are dynamically adapted to the time-varying fading channel, has emerged as one of the key solutions to increase the spectral efficiency of wireless networks. In [2] the authors did pioneering work in this area and investigated the AMC scheme combined with power and rate adaptations. In [4] the authors studied adaptive modulation integrated with convolutional codes.

In this article we follow the AMC parameters developed in [4] for convenience. The specific modulation and coding modes for the AMC scheme used are constructed as follows. We partition the entire signal-to-noise ratio (SNR) range by, say, $K = 7$ nonoverlapping consecutive intervals, resulting in $K + 1$ boundary points denoted $\{T_k\}_{k=0}^{K}$, where $T_0 < T_1 < \ldots < T_K$ with $T_0 = 0$ and $T_K = \infty$. Correspondingly, the AMC is selected to be in mode k if the SNR, denoted γ, falls into the range $T_k \leq \gamma < T_{k+1}$, where $k = 0, 1, \ldots, K - 1$. More specifically, the code rates of the available modes are 0, 0.5, 0.5, 0.75, 0.5625, 0.75, and 0.75, respectively, and their corresponding constellations are "outrage," binary phase shift keying (BPSK), quaternary PSK (QPSK), QPSK, 16-quadrature amplitude modulation (QAM), 16-QAM, and 64-QAM, respectively. Thus, with code rates ranging from 0 to 0.75 and the modulations ranging from "outrage" to 64-QAM, the corresponding system's spectral efficiency of each mode is 0, 0.5, 1.0, 1.5, 2.25, 3.0, and 4.5 b/s/Hz, respectively. As the SNR increases, the system selects the AMC mode with higher spectral efficiency to transmit data. On the other hand, as the SNR gets worse, the system decreases the transmission rate to adapt to the degraded channel conditions. In the worst case, the transmitter can stop transmitting data, which corresponds to the "outrage" mode of the system.

The boundary points $\{T_k\}_{k=1}^{K-1}$ are determined by the reliability QoS requirement of the specific services. More specifically, for any given packet size and packet error rate (PER), the boundaries $\{T_k\}_{k=1}^{K-1}$ can be derived numerically by using the probability density function (pdf) of the SNR with the different MIMO diversity schemes and PER expressions of convolutional codes, which are detailed in [4].

THE FSMC MODEL FOR WIRELESS SERVICE PROCESSES

In [6] the authors proposed using FSMCs to model the wireless fading channel. This model has since been extensively studied and successfully applied in various scenarios to evaluate QoS performance over wireless links. In this article we extend and develop the FSMC model to characterize the variation of the MIMO diversity and AMC-based wireless service process. We assume that the channel is invariant within a data link layer frame's time duration T_f but varies in duration from frame to frame. This assumption is valid when the frame duration is not too long and the mobility of the mobile user is not too high. Thus, a discrete time FSMC can be developed to characterize the fading channel process. Each state of our FSMC corresponds to a mode of AMC. The state-transition probability can be well approximated using the level-crossing rate (LCR) evaluated at the AMC boundary points of the SNR process [7]. In general, the transition matrix of our developed FSMC, denoted $\mathbf{P} = [p_{ij}]_{K \times K}$, can also be derived numerically according to the specific AMC and MIMO diversity schemes deployed at the physical layer.

THE EFFECTIVE CAPACITY FOR QOS GUARANTEES

STATISTICAL QOS GUARANTEES

Real-time multimedia services such as video and audio require the bounded delay or, equivalently, the guaranteed bandwidth. Once a received real-time packet violates its delay bound, it is considered useless and discarded. However, over mobile wireless networks, a hard delay bound guarantee is practically infeasible to achieve due to the impact of time-varying fading over wireless channels. For example, over a Rayleigh fading channel, the only lower bound of the system bandwidth that can be *deterministically* guaranteed is a bandwidth of zero. Thus, we consider an alternative solution by providing *statistical* QoS guarantees, where we guarantee the delay bound with a small violation probability.

During the early 1990s, statistical QoS guarantee theories were extensively studied in the context of the so-called *effective bandwidth theory* with emphasis on wired asynchronous transfer mode (ATM) networks. The asymptotic results in [9] showed that for stationary and ergodic arrival and service processes under sufficient conditions, the probability that queue size Q exceeds a certain threshold B (i.e., the buffer overflow probability) decays exponentially fast as the threshold B increases; that is,

$$\Pr\{Q > B\} \approx e^{-\theta B}, \text{ for a large } B, \tag{1}$$

where θ is a certain positive constant called the QoS exponent, detailed below. For a small B, the following approximation is shown to be more accurate [3]:

$$\Pr\{Q > B\} \approx \alpha e^{-\theta B}, \tag{2}$$

where α denotes the probability that the buffer is not empty. Furthermore, when delay bound is the main QoS metric of interest (i.e., when the focus is on delay bound violation probability), a set of expressions similar to Eqs. 1 and 2 can also be obtained in the same manner.

From Eqs. 1 and 2 we observe that the parameter θ plays an important role in statistical QoS guarantees, which indicates the decaying rate of the QoS violation probability. A smaller θ corresponds to a slower delaying rate, which implies that the system can only provide a looser QoS requirement, while a larger θ leads to a faster delaying rate, which means a more stringent QoS requirement can be guaranteed. Due to its close relationship with statistical QoS provisioning, θ is called the *QoS exponent* [3].

THE FUNDAMENTALS OF EFFECTIVE CAPACITY

In [3] the authors proposed an interesting concept termed *effective capacity*, which turns out to be the *dual problem* of effective bandwidth. In particular, effective capacity is defined as the *maximum arrival rate* a given service process can support in order to guarantee a QoS requirement specified by θ, while effective bandwidth is defined as the *minimum service rate* required by a given arrival process for which the QoS exponent θ is fulfilled. From the definition of effective capacity, we observe that effective capacity relates wireless channel service rate to network QoS provisioning performance through the QoS exponent θ. Thus, we can use it as a bridge in cross-layer design modeling between the physical layer system infrastructure and the upper-layer network protocols' statistical QoS performance.

Based on the duality between effective bandwidth and effective capacity, we have analytically shown that the effective capacity function, denoted $E_C(\theta)$, has the following properties:

- $E_C(\theta)$ is a *monotonically decreasing* function of θ.
- $\lim_{\theta \to 0} E_C(\theta)$ converges to the *average service rate*.
- $\lim_{\theta \to \infty} E_C(\theta)$ converges to the *minimum service rate*.

Intuitively, these properties can be explained as follows. As the QoS constraint becomes more and more stringent, the given channel can support lower and lower traffic arrival rates in order to guarantee the more stringent delay QoS requirement. This is why the effective capacity is a decreasing function of θ. On the other hand, when the system can tolerate long delay, the maximum arrival rate a given channel can support is equal to its average service rate. However, if the arrival rate increases beyond the average service rate, from queuing theory we know that a large queue will build up and the queue size will eventually approach to infinity. This is the reason effective capacity converges to its average service rate when $\theta \to 0$. When the system cannot tolerate any delay, we can only restrict the arrival rate to be equal to or less than the minimum service rate to ensure that the queue will never build up. That is why the effective capacity converges to the minimum service rate as $\theta \to \infty$.

To help demonstrate the principles and identify the relationship between effective bandwidth and effective capacity, let us consider two cases illustrated in Fig. 2, which are elaborated on, respectively, as follows.

Case I — *Service process (ii) is given with arrival process (i) having higher bandwidth than that of arrival process (ii)*. For the fixed service process (ii) in Fig. 2, a higher-bandwidth traffic arrival process (i), plotted in terms of effective bandwidth, intersects with $E_C(\theta)$ at the QoS exponent θ_1, while a lower-bandwidth traffic arrival process-(ii), also plotted according to the effective bandwidth function, intersects with $E_C(\theta)$ at the QoS exponent θ_2. Clearly, Fig. 2 shows $\theta_1 < \theta_2$. This implies that the given service process (ii) can support a more stringent QoS for the slower arrival process (ii) than can for the faster arrival process (i), which is expected since intuitively the higher-bandwidth arrival process (i) results in larger QoS violation probability.

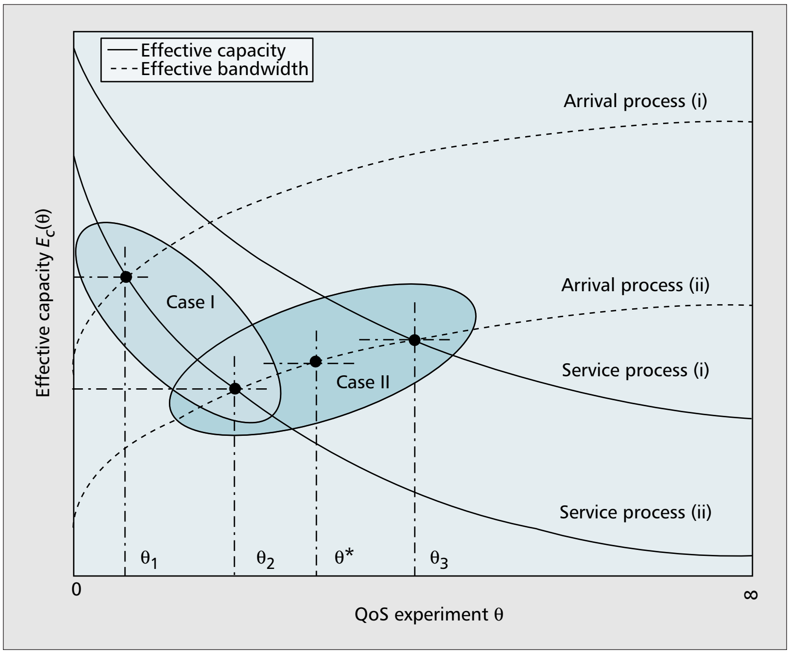

Figure 2. *Relationship between effective bandwidth and effective capacity as a function of the QoS exponent θ.*

Case II — *Arrival process (ii) is given with service process (i) having higher bandwidth than that of service process (ii)*. For the fixed arrival process (ii) in Fig. 2 , we specify its statistical QoS requirement as the QoS exponent θ^*. Then the higher-bandwidth service process (i) can guarantee the required statistical QoS since the intersection θ_3 between arrival process (ii) and service process (i) satisfies $\theta_3 > \theta^*$, while the lower-bandwidth service process (ii) cannot support the required QoS provisioning, because the intersection θ_2 between arrival process (ii) and service process (ii) results in $\theta_2 < \theta^*$.

From the above observations and analyses, we propose to use the effective bandwidth and effective capacity as the controlling functions for cross-layer modeling. The characterizations of the QoS performance guarantees are equivalent to investigating the dynamics of the QoS exponent θ, which turns out to be a very simple and efficient cross-layer modeling approach, elaborated on below.

EFFECTIVE CAPACITY OF THE PROPOSED SCHEME

As described above, effective capacity is the dual problem of effective bandwidth. Thus, utilizing the well established effective bandwidth theory, it is feasible to formulate the effective capacity problem analytically. Using the duality between effective bandwidth and effective capacity, we can show that the effective capacity function $E_C(\theta)$ is determined by the following equation:

$$E_c(\theta) = -\frac{1}{\theta}\log\left(\rho\{\mathbf{P}\Phi(\theta)\}\right), \quad \theta > 0, \qquad (3)$$

where **P** is the transition matrix of our developed FSMC, $\Phi(\theta)$ is a $K \times K$ diagonal matrix with the kth diagonal entry $\phi_k(\theta) = \exp(-R_k\theta)$, where R_k is the number of bits transmitted per

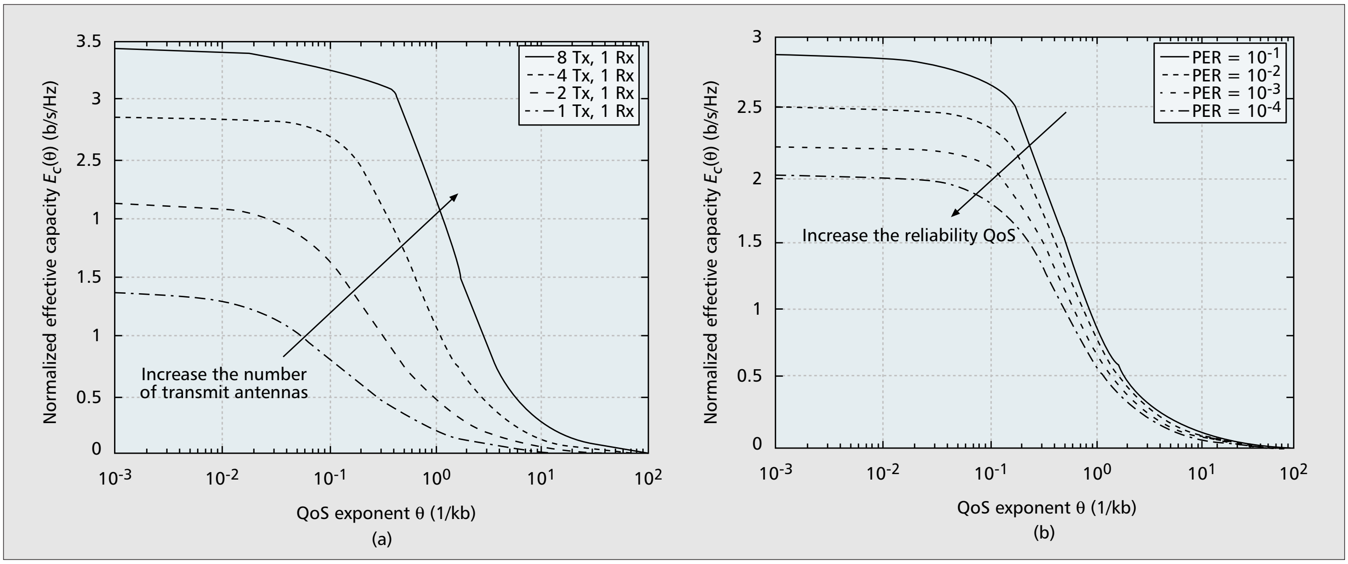

Figure 3. *Effective capacity* $E_c(\theta)$ *as a function of QoS exponent* θ *with the different physical layer diversity schemes and parameters: a) beamforming/MRC; b) STBC/MRC.*

frame by using the kth AMC mode, and $\rho\{\cdot\}$ denotes the spectral radius of the matrix. Note that the spectral radius of a matrix is defined as the maximum of the absolute values of the eigenvalues for that matrix. We derived Eq. 3 following a similar manner as shown in [9]. Notice that the derivation of Eq. 3 is not exactly the same as the procedure used in [9], but the spirit is similar.

The above cross-layer modeling establishes the analytical framework to investigate the impact of the physical layer infrastructure variations on the statistical QoS provisioning performance at the upper layer protocols through the effective capacity function $E_C(\theta)$. This analytical framework is critically important since, based on our developed cross-layer model, the upper layer protocols, such as various admission control, scheduling, and adaptive resource allocation algorithms [8, 10, 11], can be designed correspondingly to guarantee the desired QoS requirements, depending on the different wireless schemes used at the physical layer.

PERFORMANCE EVALUATIONS

We first evaluate the effective capacity function by numerical solutions under different physical layer diversity schemes and parameters used, as shown in Fig. 3, where we set the example system bandwidth $W = 100$ kHz, the frame duration $T_f = 2$ ms, the average SNR $\overline{\gamma}$ =10 dB, and the maximum Doppler frequency $f_d = 5$ Hz. Moreover, we use the following assumptions:

- The CSI is perfectly estimated at the receiver and reliably fed back to the transmitter.
- The MIMO channel is flat-fading and independent identically Rayleigh distributed between each transmit/recive antenna pair in mobile wireless networks.

Figure 3a shows the effective capacity $E_C(\theta)$ with the different numbers of transmit antennas, where we fix the total transmit power when increasing the number of transmit antennas. The number of receive antennas is set to $N_r = 1$ and the average PER = 10^{-3}. From Fig. 3a, we can observe that increasing the number of transmit antennas at the physical layer can significantly improve effective capacity, which verifies the superiority of employing spatial diversity in supporting statistical QoS for upper layer protocols. Figure 3b studies the relationship between effective capacity and QoS reliability requirements for PER, where we set the number of transmit and receive antennas $N_t = N_r = 2$ and use the Alamouti STBC scheme [1] in the system. As shown by Fig. 3b, more stringent reliability QoS (lower PER) results in lower effective capacity, which is expected since the system needs to decrease the transmission rate to guarantee reliability. From Fig. 3, we can observe that physical layer variations have a significant impact on effective capacity, and thus on the QoS provisioning performance of wireless networks at higher layer protocols.

We observe that the numerical results shown in Fig. 3 are also consistent with the properties of effective capacity mentioned above. Specifically, all $E_C(\theta)$s are monotonically decreasing functions of the QoS exponent θ. When the QoS exponent θ gets near 0, the spectral efficiency of effective capacities can be shown to be equal to the average rates of service processes. On the other hand, as the QoS exponent θ gets large, the effective capacity converges to 0, which corresponds to the minimum service-rate (i.e., the outage mode of AMC).

We also conduct simulations to verify the correctness and validity of our proposed cross-layer modeling technique and QoS provisioning performance. In the simulations we generate two types of real-time services. The first type simulates the low speed audio service, where we model the arrival traffic by the well-known ON-OFF model. The probability of ON and OFF states are 49 percent and 51 percent, respectively. The ON state traffic is modeled as a constant rate of 16 kb/s. The system bandwidth for the audio service is set to $W = 10$ kHz. The second one simulates a high-speed video traffic flow.

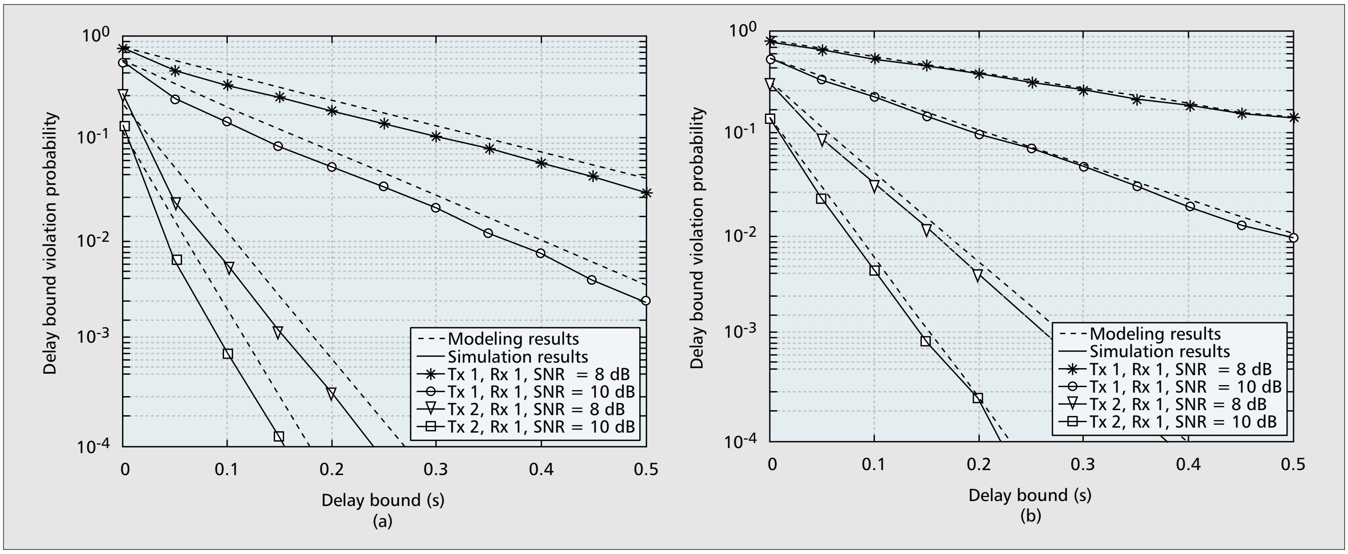

Figure 4. *The modeling and simulation results of the delay bound violation probability for audio and video traffic services: a) audio traffic services (ON-OFF traffic model); b) video traffic services (AR traffic model).*

We employ a first-order auto-regressive (AR) process to simulate video traffic characteristics [12]. The mean and standard deviation of the arrival video traffic are 72.7 kb/s and 6.95 kb/s, respectively. The system bandwidth for the video service is set to $W = 100$ kHz. In the simulation the transmitter employs Alamouti's STBC scheme when the number of transmit antennas $N_t = 2$.

Figures 4a and 4b show the QoS violation (delay bound violation) probability vs. the delay bound threshold for audio and video traffic services, respectively. In order to obtain the modeling results, we derive the effective capacity of the channel and the effective bandwidth of the traffic, respectively. Then the intersection between the effective capacity and effective bandwidth determines the QoS exponent θ, which then determines the slope of the exponential decay rate for the modeling results in the figure. In the simulations we simulate the arrival traffic and wireless channel based on the parameters described above. Finally, we calculate the probability of the queuing delay exceeding the delay bound threshold. As expected, the delay bound violation probabilities for both types of services decay exponentially as the delay bound increases. When increasing the number of transmit antennas or transmit power (SNR increases), the QoS provisioning performance can be improved. As shown in both Figs. 4a and 4b, our modeling results agree well with the simulation results, especially for video services. Thus, Fig. 4 confirms the correctness and accuracy of our developed cross-layer modeling.

CONCLUSIONS

We propose a cross-layer design approach to study the interaction between the physical layer AMC and MIMO diversity, and the higher-layer protocols on the statistical QoS performance of the mobile wireless networks. We identify the relationship between effective bandwidth and effective capacity, and obtain the effective capacity function in our proposed system model. The numerical and simulation results show that AMC and MIMO diversity employed at the physical-layer have significant impact on the statistical QoS performance at the upper layer protocols. The proposed cross-layer modeling accurately characterizes the influence of the physical layer infrastructure on statistical QoS performance at the higher protocol layers.

While in this article we only investigate single-user QoS provisioning, our developed cross-layer modeling technique can be readily extended to scenarios with multiple users sharing the wireless media in time-division multiple access (TDMA) systems. More important, our developed cross-layer modeling technique also offers a practical and effective approach to develop highly efficient admission control, scheduling, and adaptive resource allocation schemes to guarantee QoS for real-time multimedia traffic over mobile wireless networks.

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> *Our developed cross-layer modeling technique offers the practical and effective approach to develop the highly-efficient admission-control, scheduling, and adaptive resource-allocation schemes to guarantee the QoS for real-time multimedia traffics over mobile wireless networks.*