This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2008 proceedings.

An Optimal Admission Control Policy for CDMA Multiple Antenna Systems with QoS Constraints

Wei Sheng and Steven D. Blostein
Department of Electrical and Computer Engineering
Queen's University, Kingston, Ontario, Canada
Emails: wsheng@ee.queensu.ca, Steven.Blostein@queensu.ca

***Abstract*— An optimal admission control (AC) policy is proposed for a CDMA multiple antenna system, which can maximize the system throughput while simultaneously guaranteeing all quality-of-service (QoS) requirements in both physical and network layers. While previous research can only ensure the QoS requirements for appropriately chosen automatic-retransmission-request (ARQ) parameters, the proposed AC policy aims to ensure the QoS requirements for arbitrary ARQ parameters, which saves system resources. Numerical examples show that the proposed AC policy can achieve a significant performance gain in terms of network layer performance as well as system throughput.**

I. Introduction

In current third generation (3G) systems such as high speed uplink packet access (HSUPA), a threshold-based admission control (AC) policy is employed, which admits a user request if the load reported is below the AC threshold. Although the AC decision can be improved upon by taking advantage of resource allocation information [1], and it is simple to implement, this threshold-based AC policy cannot guarantee long-term QoS requirements in the network layer [2], such as blocking probability.

Recently there are several admission control (AC) policies proposed in the literature, which can guarantee QoS constraints in both physical and network layers [2]- [3]. To employ the powerful error-control capability, a suboptimal packet admission control (PAC) problem is studied in [4], which includes the impact of an automatic-retransmission-request (ARQ) scheme. To the best of our knowledge, [4] is the first paper in the literature which addresses the cross-layer AC design by including ARQ schemes. However, the solution in [4] depends on an approximate power control feasibility condition (PCFC) and as a result is only a suboptimal solution. Furthermore, in [4], ARQ parameters, such as the number of allowed retransmissions and target packet-error-rate (PER), should be chosen appropriately to meet the QoS requirements, which adds to system complexity. To overcome this problem, an optimal AC policy for arbitrary ARQ parameters is desired.

In our companion paper [7], the optimal AC problem is studied for multiple antenna systems, in which an outage probability constraint as well as all the other QoS constraints are incorporated into the semi-Markov decision process. For simplicity, however, error-control schemes are ignored in [7]. In this paper, by considering the impact of ARQ schemes, we further investigate optimal and suboptimal AC policies with QoS constraints. The proposed AC policies can guarantee the QoS for arbitrary ARQ parameters and maximize the overall system throughput. A truncated ARQ scheme is employed in this paper, which retransmits an error packet until correctly received or a maximum number of retransmissions is reached.

We remark that the proposed work in this paper differs from the existing algorithms in [4] in the following aspects: a) a separate reduced-outage-probability (ROP) algorithm is necessary in [4], while the proposed AC policies in this paper do not require any ROP algorithm, saving system resources; b) In [4], ARQ is employed to reduce outage, while in our proposed AC policy, with a guaranteed outage probability constraint, ARQ is employed to increase user capacity, which results in improved network layer performance; c) In [4], the AC policy is derived to optimize network layer performance only, while in this paper we aim to optimize average throughput which represents the overall system performance across different layers.

The proposed AC policy can be derived offline and then stored in a lookup table. Whenever an arrival or departure occurs, an optimal action can be obtained by table lookup, resulting in low enough complexity for admission control at the packet level. Similar to call/connection level admission control, in a packet-switched system a packet admission control policy decides if an incoming packet can be accepted or blocked in order to meet quality-of-service (QoS) requirements. In a packet-switched network, blocking a packet instead of blocking the whole user connection can be more spectrally efficient. In this paper, we consider the packet level AC problem.

The rest of this paper is organized as follows. The signal model and problem formulation are presented in Section II. Section III investigates the physical layer performance and provides an analytical expression for outage probability. Optimal CAC policies are proposed in Section IV. Numerical results are presented in Section V.

II. Signal Model

A. Signal model in the physical layer

A single-cell uplink CDMA beamforming system is considered which has M antennas at the BS. A spatial matched filter receiver is employed, and the system can support J classes of packets. Different classes of packets are characterized by different QoS requirements. Let K denote the total number of packets in the system.

The received signal-to-interference ratio (SIR) for a desired

1525-3511/08/$25.00 ©2008 IEEE

packet k, where $k = 1, .., K$, can be written as [8]

$$SIR_k = \frac{W}{R_k} \frac{p_k \phi_{kk}^2}{\sum_{i \neq k} p_i \phi_{ik}^2 + \eta_0 W} \quad (1)$$

where W and R_k denote the bandwidth and data rate for packet k, respectively, and the ratio $\frac{W}{R_k}$ represents the processing gain; $p_k = P_k G_k^2$ denotes the received power, in which P_k and G_k denote the transmitted power and link gain, respectively; η_0 denotes the one-sided power spectral density of background additive white Gaussian noise (AWGN); ϕ_{ik}^2 denotes the fraction of packet i's signal passed by the beamforming weights for desired packet k , which can be expressed as $\phi_{ik}^2 = \left|\mathbf{a}_k^H \mathbf{a}_i\right|^2$, in which $\mathbf{a}_i$ denotes the normalized array response vector for packet i, and $(.)^H$ denotes conjugate transpose.

The QoS requirement in the physical layer can be represented by outage probability, defined as the probability that a target SIR, or equivalently, a target packet-error-rate (PER) cannot be satisfied. We discuss two types of long-run outage probability constraints: worst-state-outage-probability (WSOP) and average-outage-probability (AOP). The WSOP constraint ensures that at any time instant and any system state the outage probability constraint cannot be violated, while the AOP constraint is more aggressive, which only ensures a long-run average outage probability constraint.

B. Signal model in the network layer

The arrival process of the aggregate connections is modeled by a Poisson process with rate λ_j for each class j, where $j = 1, .., J$.

When an incoming packet arrives, the pre-determined AC policy decides if this packet can be accepted, buffered or blocked. If a packet is deemed to be accepted, this packet will generate its first transmission round. Then the receiver will send back an acknowledgement (ACK) signal to the transmitter. A positive ACK indicates that the packet is correctly received while a negative ACK indicates an incorrect transmission.

If a positive ACK is received or the maximum number of re-transmissions, denoted by L_j for class j, is reached, the packet releases the server and departs. Otherwise the packet will be retransmitted. Therefore, the service time of a packet in class j can comprise at most $L_j + 1$ transmission rounds. Each transmission round, including the actual transmission time of the packet and the waiting time of an ACK signal (positive or negative), is assumed to have an exponential distribution with mean duration $\frac{1}{\mu_j}$ for class j packets. However, in this paper, a sub-optimal solution is also provided for a generally distributed duration.

If the packet is not accepted by the AC policy, it will be stored in a queue buffer provided that the queue buffer is not full, otherwise the packet will be blocked. Whenever a packet in the system releases the server, the packet queued in the buffer can be made active, i.e., transmitted immediately. The buffer size for class j is denoted by B_j.

We note that there are two types of buffers in the system: queue buffers and server buffers. Queue buffers accommodate queued incoming packets, while server buffers accommodate transmitted packets in the server in case any packet in the server requires retransmission. For simplicity, we assume that the size of the server buffers is large enough such that all the packets in the server can be stored. In the following, the term 'buffer' refers to the queue buffer.

The QoS requirements in the network layer can be represented by blocking probability and connection delay [5], which is the waiting time in the queue buffer. By Little's theorem, the connection delay can also be represented equivalently by the average queue length [5].

C. Problem formulation

The average system throughput, defined as the number of correctly received packets per second, can be evaluated by [10]

$$\text{Throughput} = \sum_j (1 - P_b^j)(1 - P_{out}^{av})(1 - PER_j)\lambda_j \quad (2)$$

where P_b^j, P_{out}^{av} and PER_j denote the blocking probability, the average outage probability, and the packet-error-rate for class j, respectively.

By including the impacts of an truncated ARQ scheme with maximum number of retransmissions L_j, we aim to design an optimal packet-admission-control (PAC) policy by including error-control schemes such as ARQ. The optimal AC policy is capable of maximizing the overall system throughput, while simultaneously guaranteeing QoS requirements in terms of outage probabilities, blocking probability and connection delay.

To solve the above optimization problem, we first analyze the outage probability for a given number of packets in the system, which is then passed to the network layer to decide the AC policy by formulating a constrained Markov decision process.

III. Outage probability for a given system state in the presence of ARQ

The system state s can be represented by

$$s = [\underbrace{n_q^1, k^{1,1}, .., k^{1,L_1+1}}, ..., \underbrace{n_q^J, k^{J,1}, ..., k^{J,L_J+1}}]^T \quad (3)$$

where $k^{j,i}$ denotes the number of active packets in class j which is under the i^{th} transmission round, or equivalently, under the $(i-1)^{th}$ retransmission; n_q^j denotes the queue length, i.e., the number of packets in the queue buffer of class j. The number of class j packets can be obtained as $n_s^j = \sum_{i=1}^{L_j+1} k^{j,i}$, and the total number in the system is obtained as $K = \sum_{j=1}^{J} n_s^j$.

In this section, we derive the outage probability for a given system state s by including the impact of ARQ.

A. Derivation of target SIR

From [4], we know that ARQ affects the outage probability by reducing the target SIR requirement in the physical layer. In the following, we derive the target SIR which can achieve a target PER requirement, denoted by ρ_j for class j packets.

We define two kinds of packet-error-rates (PERs): overall PER and instantaneous PER. Overall PER, denoted by $PER_{overall}^j$, is defined as the probability that a class j packet is incorrectly received after its maximum number of retransmissions is reached, i.e., an error occurs in each of the $L_j + 1$ transmission rounds, where L_j denotes the maximum number of retransmissions. Instantaneous PER, denoted as $PER_{in}^j(l)$, is defined as the probability that an error occurs in a single transmission round l of a class j packet.

Under the assumption that each retransmission round is independent from the others, the achieved overall PER can be expressed as [10]

$$PER_{overall}^j = \prod_{l=1}^{L_j+1} PER_{in}^j(l) \leq \rho_j \quad (4)$$

where ρ_j denotes the target PER for class j.

To ensure the above inequality, we require

$$PER_{in}^j(l) \leq (\rho_j)^{\frac{1}{L_j+1}}. \quad (5)$$

In general, given the above target instantaneous PER, it is not an easy task to derive the target signal-to-interference ratio (SIR). Fortunately, there are approximations in the literature. For example, the instantaneous PER for packet length N_p bits can be approximately expressed in terms of instantaneous SIR as [10]

$$PER_{in}^j(l) = a\exp(-g \times SIR_j) \quad (6)$$

for $SIR_j \geq \gamma_0$ dB, where SIR_j is the achieved SIR, given in (1); a, g, and γ_0 are constants depending on the chosen modulation and coding scheme. In the above expression, the interference is assumed to be additive white Gaussian noise, which is reasonable in a system with a large number of interferers.

Combining (5) and (6), we have

$$SIR_j \geq \frac{1}{g}[\ln a - \ln((\rho_j)^{\frac{1}{L_j+1}})] \quad (7)$$

where $\ln(.)$ denotes natural logarithm, and the right hand side of the above inequality is the target SIR, denoted by

$$\gamma_j = \frac{1}{g}[\ln a - \ln((\rho_j)^{\frac{1}{L_j+1}})]. \quad (8)$$

B. Approximate outage probability

From Perron-Frobenius theorem, the outage probability for a state s, defined as the probability that the target SIR γ_j, given in (8), cannot be satisfied, can be derived as [9]

$$P_{out}(s) = \text{Prob}\{\upsilon(\mathbf{Q}_s\mathbf{F}_s) \geq 1\} \quad (9)$$

where Prob$\{A\}$ denotes the probability of event A, $\upsilon(.)$ denotes the maximum eigenvalue, $\mathbf{Q}_s$ is a K-dimensional diagonal matrix with the i^{th} non-zero element as $\frac{\gamma_i R_i}{W}$, $i = 1,..,K$, and $\mathbf{F}_s$ is a K by K matrix in which the element at the i^{th} row and the j^{th} column can be expressed as $F_{ij} = \frac{\phi_{ij}^2}{\phi_{ii}^2}$ for $i \neq j$, and $F_{ij} = 0$ for $i = j$.

Equation (9) provides an exact expression for the outage probability, which can only be evaluated numerically. In the following, we derive an approximate outage probability.

TABLE I
NUMERICAL VALUES OF $E[F_{ij}]$ AND $Var[F_{ij}]$ FOR A BEAMFORMING SYSTEM.

M	1	2	3	4
$E[F_{ij}]$	1.0000	0.54628	0.39504	0.32405
$Var[F_{ij}]$	1.0000	0.42735	0.24374	0.21897

Owing to the properties of nonnegative matrices, the eigenvalue $\upsilon(\mathbf{Q}_k\mathbf{F}_k)$ can be estimated by [8],

$$\upsilon(\mathbf{Q}_k\mathbf{F}_k) = \frac{1}{\sum_{j=1}^{J} n_s^j} \sum_{j=1}^{J} \left[\frac{R_j\gamma_j}{W} \sum_{m=t_j+1}^{t_j+n_s^j} \sum_{i=1}^{K} F_{mi} \right]$$

where $t_j = \sum_{l=1}^{j-1} n_s^l$ for $j > 1$, and $t_j = 0$ for $j = 1$.

As shown in [9], by using the central limit theorem, random variable $\upsilon(\mathbf{Q}_k\mathbf{F}_k)$ has an approximately Gaussian distribution. Therefore, the outage probability in (9) becomes

$$P_{out}(s) = Q\left[\frac{1 - E[\upsilon]}{\sqrt{Var(\upsilon)}}\right] \quad (10)$$

where $Q(\alpha) = \frac{1}{\sqrt{2\pi}}\int_{\alpha}^{\infty} e^{-\frac{x^2}{2}}dx$, $E[\upsilon]$ and $Var(\upsilon)$ denote the expectation and variance of random variable $\upsilon(\mathbf{Q}_k\mathbf{F}_k)$, which can be obtained as follows:

$$E[\upsilon] = \sum_{j=1}^{J} \frac{1}{W}\gamma_j R_j n_s^j E[F_{ij}]$$
$$E[\upsilon] = \frac{1}{K}\sum_{j=1}^{J} n_s^j [\frac{1}{W}\gamma_j R_j]^2 Var[F_{ij}] \quad (11)$$

where $E[F_{ij}]$ and $Var[F_{ij}]$ denote the expectation and variance of F_{ij}, which can be evaluated numerically. Table I presents these numerical values for a uniform circle array, which are derived in [9].

The accuracy of the above outage probability approximation is discussed in [9]. In this paper, to highlight the optimal PAC design in the presence of ARQ, we use the above approximate outage probability for simplicity. However, the proposed PAC policies can be applied straightforwardly to any other outage probability expressions.

IV. SMDP AND GSMP-BASED AC POLICIES

Based on the outage analysis in the physical layer, we next derive an optimal SMDP-based AC policy as well as a low-complexity generalized semi-Markov process (GSMP)-based AC policy by including a truncated ARQ scheme.

A. SMDP-based AC policy

In the system under consideration, the duration of each packet may include several transmission rounds due to ARQ retransmissions, and as a result, the time duration until the next system state may not be exponentially distributed. Therefore, the SMDP formulation approach discussed in [2] [3], which assumes an exponentially distributed duration, cannot be applied here.

As shown in [4], if the decision epoch is chosen as the arrival and departure of each transmission round instead of the arrival/departure of each packet, the time duration until the next state remains exponentially distributed. In this case, the AC problem can be formulated as a SMDP, and linear programming approach provides an optimal solution.

SMDP components

The components of a semi-Markov decision process, such as state space, action space, dynamic statistics, policy, performance criterion and average cost function, are now briefly described.

The state space can be formulated as

$$S = \{s, \text{ where } P_{out}(s) \le \delta_w, \text{and } n_q^j \le B_j\}.$$

where $P_{out}(s)$ is given in (10), and δ_w, n_q^j and B_j denote the target WSOP, the queue length and the buffer size, respectively.

At each state s, an action $a \in A_s$ is chosen that determines how the admission control will perform at the next decision moment [4], where A_s is the admissible action space for state s.

The state dynamics of a SMDP are completely specified by stating the transition probabilities of the embedded chain $p_{sy}(a)$ and the expected holding time $\tau_s(a)$: $p_{sy}(a)$ is defined as the probability that the state at the next decision epoch is y if action a is selected at the current state s, while $\tau_s(a)$ is the expected time until the next decision epoch after action a is chosen in the present state s. The detailed derivations and expressions of A_s, $\tau_s(a)$ and $p_{sy}(a)$ can be found in [4].

A policy R defines a mapping rule from state space S to action space A. In this paper, we take the average cost as the performance criterion. For any policy R with an initial state s_0, the average cost can be expressed as [6]

$$J_R(s_0) = \lim_{t \to \infty} \frac{1}{T} E\left\{ \int_0^T c(s(t), a(t))dt \right\} \qquad (12)$$

where $E[.]$ denotes expectation, and $c(s(t), a(t))$ is the expected cost function which represents the expected cost until the next decision epoch when $a(t)$ is chosen at the current system state $s(t)$.

When the average cost in (12) represents blocking probability, connection delay, outage probability or throughput, respectively, the corresponding expected cost functions, denoted by $c_b^j(s,a)$, $c_d^j(s,a)$, $c_{out}(s,a)$ and $c_{thr}(s,a)$, respectively, can be derived as [5] [7]

$$\begin{aligned} c_b^j(s,a) &= (1-a_j)(1-\zeta(B_j - n_q^j)) && (13)\\ c_d^j(s,a) &= n_q^j && (14)\\ c_{out}(s,a) &= P_{out}(s) && (15)\\ c_{thr}(s,a) &= \sum_{j=1}^{J} \lambda_j (1 - c_b^j(s,a))(1 - c_{out}(s,a)) && (16) \end{aligned}$$

where a_j denotes the action for class j traffic, and $P_{out}(s)$ is given in (10). Function $\zeta(x)$ is equal to 1 for $x > 0$, and 0 otherwise. The detailed derivation can be found in [7].

Deriving an optimal policy by solving the SMDP

An optimal AC policy can be obtained by using the decision variables $z_{sa}, s \in S, a \in A_s$, in solving the following linear programming (LP) problem:

$$\max_{z_{sa} \ge 0, s, a} \sum_{s \in S} \sum_{a \in A_s} \sum_{j=1}^{J} c_{thr}(s,a)\tau_s(a) z_{sa} \qquad (17)$$

subject to the set of constraints

$$\begin{aligned} \sum_{a \in A_m} z_{ma} - \sum_{s \in S} \sum_{a \in A_s} p_{sm}(a) z_{sa} &= 0, m \in S \\ \sum_{s \in S} \sum_{a \in A_s} \tau_s(a) z_{sa} &= 1 && (18)\\ \sum_{s \in S} \sum_{a \in A_s} (1-a_j)(1-\zeta(B_j - n_q^j))\tau_s(a) z_{sa} &\le \Psi_j && (19)\\ \sum_{s \in S} \sum_{a \in A_s} P_{out}(s)\tau_s(a) z_{sa} &\le \delta_{av} && (20)\\ \sum_{s \in S} \sum_{a \in A_s} n_q^j \tau_s(a) z_{sa} &\le \Xi_j && (21) \end{aligned}$$

where ψ_j, δ_{av} and Ξ_j denote the target blocking probability, target average outage probability and target connection delay, respectively.

In the above LP formulation, $\tau_s(a) z_{sa}$ represents the steady-state probability that the system is at state s and an action a is chosen. The first constraint is the balance equation, and the second constraint ensures the sum of all the steady-state probabilities to be one. The latter three constraints represent the QoS requirements in terms of blocking probability, average-outage-probability, and connection delay respectively.

B. GSMP-based AC policy

In the above SMDP formulation, in order to maintain the Markov properties required by SMDP, the decision epoch is chosen as the arrival and departure for each transmission round. For large J and number of retransmissions L_j, the above SMDP formulation leads to a computation problem of excessive size [4].

To reduce the complexity, the decision epoch can be chosen as the time instances that a packet arrives or departs. Based on these decision epoches, the classical Markov assumptions are not maintained, and the AC problem can be formulated as a generalized semi-Markov process (GSMP) [2]. While an optimal solution for this GSMP problem is hard to obtain, the linear programming approach in (17) provides a sub-optimal solution [2]. In this section, we briefly discuss the suboptimal GSMP-based PAC policy.

With GSMP formulation, the duration of the class j packets may have a general distribution, with mean $\frac{1}{\mu_j}(1 + \rho_j + .. + \rho_j^{L_j})$, where μ_j denotes the departure rate for each transmission round for the class j packets. The state space can be expressed as $S = \{s = [n_s^1, .., n_s^J], \text{ where } P_{out}(s) \le \delta_w\}$. The detailed derivations for action space A_s and dynamic statistics $\tau_s(a)$ and $p_{sy}(a)$ can be found in the literature, e.g., [5]. For the reason of comparisons, here we use the same performance criterion and average cost criterion as in SMDP case which is discussed in Section IV-A. The suboptimal AC policy can be obtained by solving the general LP problem in (17) with GSMP components S, A_s, $\tau_s(a)$ and $p_{sy}(a)$.

By formulating the AC problem as a GSMP, the dimension of the state space is reduced from $2J + \sum_{j=1}^{J} L_j$ to $2J$ and as a result the computation complexity can be dramatically reduced. Although the GSMP approach only provides a sub-optimal AC policy, in a low instantaneous PER region, the GSMP-based solution is very close to the SMDP-based AC policy. Intuitively, when the PER is very low, retransmission occurs only occasionally, and the duration of a packet would be very close to an exponential distribution. In this case, the LP approach would provide a nearly optimal solution to the above GSMP.

We remark that unlike the SMDP-based AC policy in which the transmission round is assumed to have an exponential distribution, the GSMP-based AC policy discussed in the sub-section can be applied to a system with a generally distributed transmission round.

V. Numerical Examples

In the following examples, a two-class system is considered. The data rates are set to $R_1 = 144$ kbps and $R_2 = 384$ kbps. The arrival and departure rates for class 1 and class 2 packets are denoted by $\lambda_1 = 0.5$, $\lambda_2 = 0.25$, $\mu_1 = 0.3$, and $\mu_2 = 0.2$, respectively. The blocking probability constraints are given as $\Psi_1 = 0.05$ and $\Psi_2 = 0.05$, respectively, unless specified otherwise, and the connection delay constraints for class 1 and class 2 packets are set to 1.67 and 3.5 seconds, respectively. The average outage probability constraint is set to $\delta_{av} = 0.05$ and the worst-state outage probability is $\delta_w = 0.5$. Two antennas are employed at the BS, i.e., $M = 2$. The total bandwidth is 3.84 MHz. Without loss of generality, we consider a QPSK and convolutionally coded modulation scheme with coding rate $\frac{1}{2}$ and a packet length $N_p = 1080$. Under this scheme, the parameters of a, g and γ_0 in Equation (6) can be obtained from [10].

We investigate the long-run average performance in terms of blocking probability, average outage probability, delay and overall system throughput. The average-outage-probability is derived by averaging the state outage probability for a long term, where the state outage probability is derived by using the approximation in (10).

A. *Performance of the proposed AC policies*

We first investigate the performance for a SMDP-based AC policy, in which $L_1 = 0$, $L_2 = 1$, $\rho_1 = \rho_2$, and no buffer is employed. Figure 1 compares the performance for the system with ARQ and the system without ARQ when the SMDP formulation is employed. In both cases, the QoS requirements in terms of blocking probability and average outage probability, denoted by P_b^j and P_{out}^{av}, $j = 1, 2$, respectively, can be satisfied. The connection delay is zero since no buffer is allowed. It is observed that the performance can be significantly improved by allowing retransmissions.

Figure 2 compares the performance between SMDP and GSMP AC policies, in which $L_1 = 0$, $L_1 = 1$, and no buffer is employed. Figure 2 demonstrates that for a small number of retransmissions, SMDP and GSMP-based AC policies have similar performance. Although performance comparison for large L_j is not presented here since a SMDP-based AC policy would involve excessive computation, it is expected that for low PER, these two AC policies would still have similar performance. For a high PER, however, the packet duration is far from exponentially distributed, and thus linear programming cannot provide an optimal solution to a GSMP and its performance would be inferior to that of SMDP.

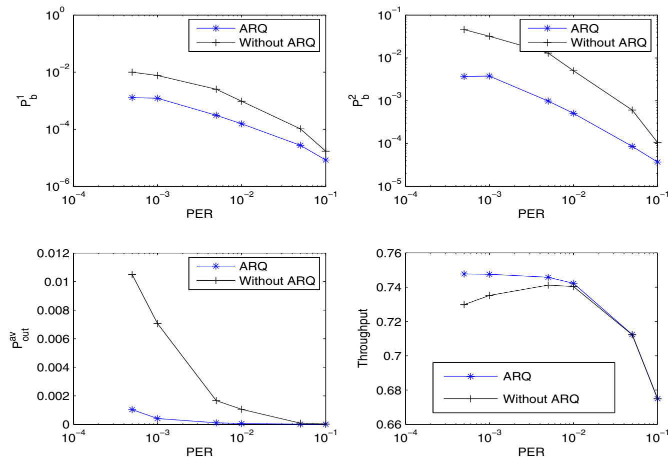

Fig. 1. Performance of a SMDP-based AC policy.

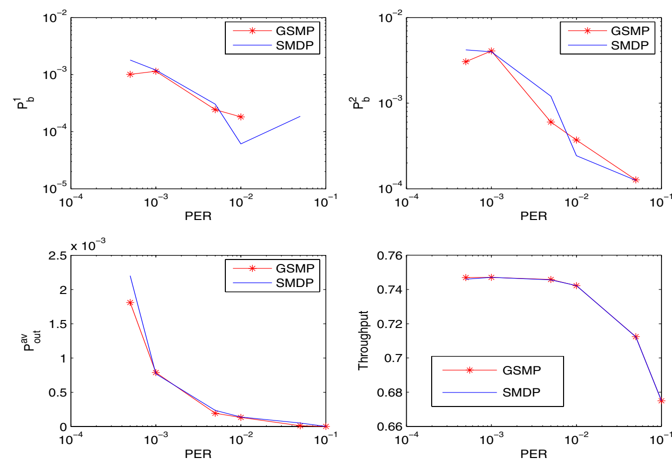

Fig. 2. Performance comparison between SMDP and GSMP-based AC polices.

Now we study the performance for a GSMP-based AC policy in which $\rho_1 = \rho_2$, $L_1 = L_2$, and $B_1 = B_2 = 1$. We investigate the performance for $L_j = 0, 1$ and 2, respectively. The results for large L_j can be extended straightforwardly. Table II compares the overall blocking probability, denoted by P_b, for difference L_j. We observe that for a small target PER region, which is reasonable in a practical system, the blocking probability can be dramatically reduced with an increased L_j. Figure 3 shows the delay, the outage probability and the throughput for different L_j. The delay presented here is the overall delay which is the sum of the connection delay and the mean transmission delay. It is observed that although ARQ increases the transmission delay as well as the overall

TABLE II
BLOCKING PROBABILITY FOR A GSMP-BASED AC POLICY.

Target PER	5×10^{-4}	5×10^{-3}	1×10^{-2}
P_b with $L_j = 0$	1.15×10^{-2}	1.19×10^{-3}	1.1×10^{-3}
P_b with $L_j = 1$	5.43×10^{-4}	6.19×10^{-5}	1.86×10^{-4}
P_b with $L_j = 2$	1.24×10^{-4}	0	6.79×10^{-5}

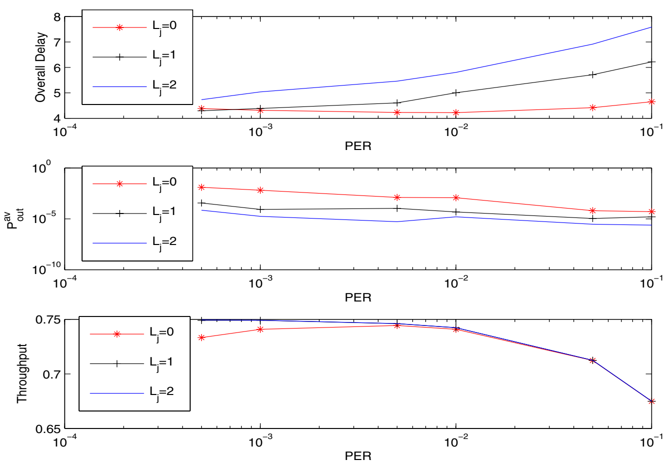

Fig. 3. Performance of a GSMP-based AC policy.

delay, this delay degradation can be very small in a small PER region due to the only occasionally occurred retransmissions. From this figure, it is also observed that outage probability and throughput can be improved by increasing L_j. However, when L_j is increased beyond a certain level, e.g., $L_j = 1$ in the investigated system, the throughput improvement is very small.

B. Comparison with the existing PAC policy

Figure 4 compares the performance between our proposed PAC policy and the existing PAC policy in [4] in which $L_j = 1$, $B_j = 0$, $j = 1, 2$, and GSMP formulation is employed. Although the average outage probability for the proposed PAC policy is inferior to the PAC policy in [4], it is observed that our proposed PAC algorithm is able to achieve a lower blocking probability and a higher throughput. This inferior average outage probability is due to the fact that for the proposed policy only a require outage probability is ensured and no excessive outage probability reduction is desired, while in [4], the PAC policy allows excess outage probability reduction, which wastes system resources. Therefore, in our proposed PAC, the resources can be more efficiently utilized to maximize the overall system throughput. Another advantage of our proposed PAC is that we can guarantee all QoS requirements for an arbitrary choice of ARQ parameters, while the PAC in [4] can only ensure the QoS requirements under certain ARQ parameters.

VI. CONCLUSIONS

In this paper, we propose a cross-layer optimal packet admission control policy with QoS constraints in both physical and network layers. While the previous research on PAC

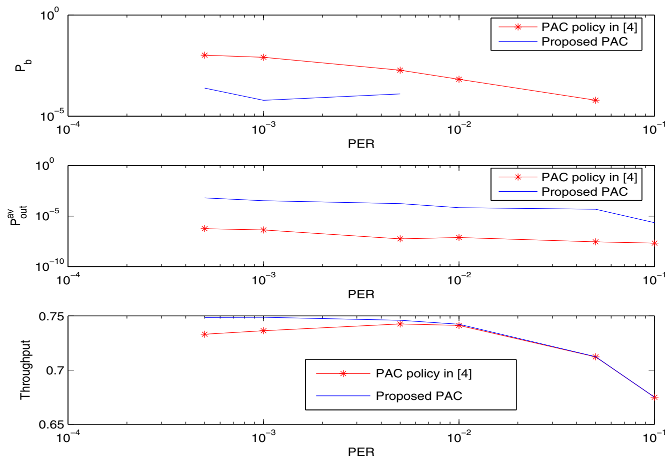

Fig. 4. Comparison between proposed and existing PAC policies.

policy needs to adjust ARQ parameters to guarantee the QoS requirements, our proposed PAC policy is able to ensure all QoS requirements for any ARQ parameters. The proposed PAC policy provides a more flexible way to handle the QoS, and as a result, is capable of achieving an improved system throughput. A possible future direction would be the joint optimization of the AC policy and ARQ parameters in order to further improve the system performance.

ACKNOWLEDGMENT

This research has been partially supported by Natural Sciences and Engineering Research Council Discovery Grant 41731.

REFERENCES

[1] S. Brueck, E. Jugl, H. Kettschau, M. Link, J. Mueckenheim, and A. Zaporozhets, "Radio Resource Management in HSDPA and HSUPA", *Bell Labs Technical Journal*, 11(4), pp. 151167, 2007.

[2] S. Singh, V. Krishnamurthy, and H. V. Poor, "Integrated voice/Data call admission control for wireless DS-CDMA systems", *IEEE Trans. Signal Processing*, vol. 50, no. 6, pp. 1483-1495, June 2002.

[3] W. Sheng and S. D. Blostein, "Cross-layer call admission control for a CDMA uplink employing a base-station antenna array", *Proc. IEEE Globecom 2007*, November 2007.

[4] W. Sheng and S. D. Blostein, "Cross-layer Admission Control Policy for CDMA Beamforming Systems", *EURASIP Journal on Wireless Communications and Networking, Special Issue on Smart Antennas*, July 2007.

[5] C. Comaniciu and H. V. Poor, "Jointly optimal power and admission control for delay sensitive traffic in CDMA networks with LMMSE receivers", *IEEE Trans. Signal Processing*, vol. 51, no. 8, pp. 2031-2042, August 2003.

[6] F. Yu, V. Krishnamurthy, and V. C. M Leung, "Cross-layer optimal connection admission control for variable bit rate multimedia trafiic in packet wireless CDMA networks", *IEEE Trans. Signal Processing*, vol. 54, no. 2, pp. 542-555, Feburary 2006.

[7] W. Sheng and S. D. Blostein, "A Maximum-Throughput Call Admission Control Policy for CDMA Beamforming Systems", *To Appear in Proc. IEEE WCNC 2008*, March 2008.

[8] G. Song and K. Gong, "Performance comparison of optimal beamforming and spatial matched filter in power-controlled CDMA Systems", *Proc. ICC 2002*, vol. 1, pp. 455-459, 2002.

[9] G. Song and K. Gong, "Approximate formula for evaluating Erlang capacity of CDMA systems with smart antennas", *Electronics letters*, vol. 36, no. 12, pp. 1001-1002, June 2000.

[10] Q. Liu, S. Zhou, and G. B. Giannakis, "Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links", *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1746-1755, Sep. 2004.