Reduced-Outage-Probability Algorithms for Cross-Layer Call Admission Control in CDMA Beamforming Systems

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***Abstract*— A new call admission control (CAC) algorithm based on an approximated power control feasibility condition is proposed for the uplink of a cellular system. While power control feasibility can be expressed in closed-form for the case of single antennas, an approximated power control feasibility condition is required for multiple antenna systems. This approximation, however, increases outage probability in the physical layer. In this paper, we investigate the mitigation of the outage problem in the context of cross-layer performance, and propose CAC algorithms for code-division multiple access (CDMA) beamforming systems. More specifically, these new methods achieve a network-layer performance gain, in terms of low connection delay and low blocking probability, while simultaneously guaranteeing physical-layer performance in terms of outage probability. In this paper, several reduced- outage-probability (ROP) algorithms are proposed. Numerical examples illustrating the performance and properties of these ROP are presented and compared.**

I. INTRODUCTION

Recently, the problem of ensuring quality-of-service (QoS) by integrating the design in the physical layer and the call admission control in the network layer is receiving recent attention. In [1]- [3], an optimal semi-Markov decision process (SMDP)-based call admission control (CAC) policy is presented based on a linear-minimum-mean-square-error (LMMSE) multiuser receiver. These algorithms integrate the optimal CAC policy with a multiuser receiver, and as a result, are able to optimize the power control and the CAC across the physical and network layers. However, [1] [2] and [3] only consider single antenna systems, which lack the tremendous performance benefits provided by multiple antenna systems [4] - [6].

In a large system with multiple antennas, an exact power control feasibility condition (PCFC), as well as the feasible discrete state space [1] is hard to derive, while this feasible system space is necessary for an optimal SMDP-based CAC. Therefore, for multiple antenna systems, an approximated power control feasibility condition is required. This approximation increases outage probability, which is defined as the probability that a target bit-error-rate (BER) or packet-error-rate (PER), or equivalently, a target SIR, cannot be achieved.

To the best of our knowledge, cross-layer design considering SMDP-based optimal CAC policies for multiple antenna systems has not been addressed in the literature. In this paper, we derive an approximated power control feasibility condition (PCFC) for beamforming CDMA systems. After that, cross-layer CAC algorithms are proposed based on this approximated PCFC. Several reduced-outage-probability (ROP) algorithms are then presented to reduce the outage probability.

The rest of the paper is organized as follows. In Section II, we present the signal model. In Section III, an approximated PCFC is derived. The cross-layer CAC algorithms and the ROP algorithms are proposed in Sections IV and V, respectively. Simulation results are then presented in Section VI.

II. SIGNAL MODEL

A. Signal model at the physical layer

We consider the uplink of a single-cell multiuser beamforming system in which M antennas are employed at a base-station (BS) and a single antenna is employed at each mobile-station (user). A slow fading channel, consistent with current wideband CDMA channels, is considered in the following. The channel gain is assumed to be static during a symbol period, which can be estimated by using a training sequence [8]. The accuracy of this channel estimate is defined as $v_i \triangleq \frac{\xi_i^2}{|\bar{h}_i|^2}$, where $\bar{h}_i$ and ξ_i^2 denote the mean and the variance of the channel gain estimate, respectively. As in [1], the equivalent estimated average power gain for the channel of user i, is defined as $|\bar{h}_i|^2 = \sum_{d=1}^{D} |\bar{h}_{i,d}|^2$, where $\bar{h}_{i,d}$ represents the average link gain for the d^{th} path of user i, and D is the number of resolvable multi-paths.

In this paper, we use vector $\vec{a}_i$ to denote the normalized array response vector for user i, which contains the relative phases of the received signals at each array element and depends on the angle-of-arrival (AoA), denoted by θ_i. AoAs from different users are modeled as independent random variables uniformly distributed within $[0, 2\pi]$. In this paper, we also assume a synchronous system.

At the receiver, a spatial-matched-filter and temporal-MMSE receiver [5] is employed. For a system with large K and N, where N is the temporal spreading gain, by employing the large-system analysis in [8], we can obtain the asymptotic SIR for user k as follows

$$SIR_k = \frac{p_k |\bar{h}_k|^2 \phi_{kk}^2 \beta_k}{1 + p_k \xi_k^2 \phi_{kk}^2 \beta_k} \tag{1}$$

where p_k represents the transmitted power for user k, $k = 1, 2, .., K$, respectively; $\phi_{ik} \triangleq \vec{a}_i^H \vec{a}_k$, where $(.)^H$ denotes

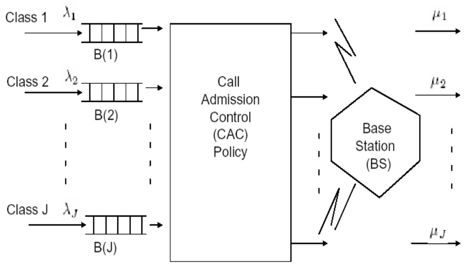

Fig. 1. Signal model at the network layer

transpose and hermitian, and β_k is the unique fixed point that satisfies

$$\beta_k = \{\phi_{kk}\sigma^2 + \frac{1}{N}\sum_{i=1,i\neq k}^{K} f_{i,k}\}^{-1} \tag{2}$$

in which σ^2 is the variance of the noise and

$$f_{i,k} = (D-1)I(p_i\phi_{ik}^2\xi_i^2, \beta_k) + I(p_i\phi_{ik}^2(\xi_i^2 + |\bar{h}_i|^2), \beta_k)$$

where $I(p,\beta) \triangleq \frac{p}{1+p\beta}$.

B. Signal model at the network layer

The signal model at the network-layer is shown in Figure 1. We consider a single-cell, power-controlled synchronous CDMA system which supports J classes of users. Each class of users shares a common buffer, and B_j denotes the buffer size of class j. Requests for connections are assumed to be Poisson distributed, with rates λ_j, $j = 1,..,J$. The call durations are assumed to have an exponential distribution with mean duration $\mu_j, j = 1,..,J$.

For each class j, where $j = 1,..,J$, there are K_j users, which have the same SIR constraints, γ_j, blocking probability constraints, Ξ_j, and connection delay constraints, Φ_j. It is also assumed that all users in class j have the same channel estimates, denoted as v_j.

III. APPROXIMATED POWER CONTROL FEASIBILITY CONDITION (PCFC)

In the following, we derive an approximated PCFC for beamforming CDMA systems.

First, we artificially divide the cell into L sectors, where L can be any integer from one to infinity. Sector i, where $i = 1,2,..,L$, represents an AoA range within $[2\pi(i-1)/L, 2\pi i/L]$.

Now consider a desired user k, which is assumed to be of class t and arrives with an AoA θ_k, which is in sector tt, where $t = 1,..,J$, and $tt = 1,2,..,L$.

Letting the received SIR in Equation (1) achieve its target value, γ_k, we have

$$\beta_k = \frac{\gamma_k}{p_k|\bar{h}_k|^2\phi_{kk}^2(1-\gamma_k v_k)}. \tag{3}$$

Imposing the assumption that $\beta_i = \beta_k$, where $i \neq k$, and employing (3), we can represent the transmitted power of the interfering user i by

$$p_i = \frac{\gamma_i p_k |\bar{h}_k|^2(1-\gamma_k v_k)\phi_{kk}^2}{\gamma_k|\bar{h}_i|^2\phi_{ii}^2(1-\gamma_i v_i)} \tag{4}$$

for any $i \neq k$.

Inserting (3) and (4) into (2), and employing the fact that $\phi_{ii}^2 = 1$ for any $i = 1,...,K$, we obtain a closed-form expression for the required transmitted power for user k

$$p_k = \frac{\sigma^2\gamma_k}{(1-\gamma_k v_k)(1-g_k)|\bar{h}_k|^2} \tag{5}$$

where

$$\begin{aligned} g_k \;&=\; \frac{1}{N}\sum_{i=1,i\neq k}^{K}(D-1)\frac{v_i\gamma_i\phi_{ik}^2}{1-\gamma_i v_i + \gamma_i v_i\phi_{ik}^2} + \\ &\quad \frac{1}{N}\sum_{i=1,i\neq k}^{K}\frac{(1+v_i)\gamma_i\phi_{ik}^2}{1-\gamma_i v_i + \gamma_i(1+v_i)\phi_{ik}^2}. \end{aligned} \tag{6}$$

By considering specific traffic classes and cell sectors, g_k can be expressed as

$$\begin{aligned} g_k \;&=\; \frac{1}{N}\sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{i=1,i\neq k}^{n_{j,l}}(D-1)\frac{v_j\gamma_j\phi_{ik}^2}{1-\gamma_j v_j + \gamma_j v_j\phi_{ik}^2} + \\ &\quad \frac{1}{N}\sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{i=1,i\neq k}^{n_{j,l}}\frac{(1+v_j)\gamma_j\phi_{ik}^2}{1-\gamma_j v_j + \gamma_j(1+v_j)\phi_{ik}^2} \\ &< \; 1 \end{aligned} \tag{7}$$

where $n_{j,l}$ denotes the number of the active users in class j and sector l. The last inequality combined with $\gamma_k v_k < 1$ ensures a positive p_k in (5).

When L is large enough, it is reasonable to assume that ϕ_{ik}^2 for all $1 \leq i \leq n_{j,l}$ and $i \neq k$ in (7) are approximately equal. Therefore, the fractions in (7) can be approximated by their mean values, and (7) can be further simplified as

$$\begin{aligned} &\frac{1}{N}\sum_{j=1}^{J}\sum_{l=1}^{L}n_{j,l}E\left[(D-1)\frac{v_j\gamma_j\phi_{ik}^2}{1-\gamma_j v_j + \gamma_j v_j\phi_{ik}^2}|k\right] + \\ &\frac{1}{N}\sum_{j=1}^{J}\sum_{l=1}^{L}n_{j,l}E\left[\frac{(1+v_j)\gamma_j\phi_{ik}^2}{1-\gamma_j v_j + \gamma_j(1+v_j)\phi_{ik}^2}|k\right] < 1 \end{aligned} \tag{8}$$

in which the conditional expectations are with respect to user i, whose class is j, and the AoA is in sector l.

Inequality (8) is the feasibility condition for desired user k in AoA sector tt. Summing all the active users in sector tt, and calculating the average, we obtain

$$\begin{aligned} &\frac{1}{N}\sum_{j=1}^{J}\sum_{l=1}^{L}n_{j,l}E[(D-1)\frac{v_j\gamma_j\phi_{ik}^2}{1-\gamma_j v_j + \gamma_j v_j\phi_{ik}^2} + \\ &\qquad\qquad \frac{(1+v_j)\gamma_j\phi_{ik}^2}{1-\gamma_j v_j + \gamma_j(1+v_j)\phi_{ik}^2}] < 1 \end{aligned} \tag{9}$$

where the expectation is with respect to users k and i, whose AoAs are in sectors tt and l, respectively.

By defining the expectation in (9) as $E^j_{tt,l}$, we have the following power control feasibility condition

$$\frac{1}{N}\sum_{j=1}^{J}\sum_{l=1}^{L} n_{j,l}E^j_{tt,l} < 1 \tag{10}$$

where $tt = 1, 2, .., L$.

The above L feasibility conditions can also be expressed in the following matrix form

$$\sum_{j=1}^{J}\mathbf{E}_j\alpha_j < 1 \tag{11}$$

in which $\alpha_j = [n_{j,1}/N, n_{j,2}/N, .., n_{j,L}/N]^t$, where $(.)^t$ denotes transpose, and

$$\mathbf{E}_j = \begin{bmatrix} E^j_{1,1} & E^j_{1,2} & \cdots & E^j_{1,L} \\ E^j_{2,1} & E^j_{2,2} & \cdots & E^j_{2,L} \\ \cdots & \cdots & \cdots & \cdots \\ E^j_{L,1} & E^j_{L,2} & \cdots & E^j_{L,L} \end{bmatrix}. \tag{12}$$

From (5) and the derivation of PCFC, the power of the class j and sector l user, denoted as p^j_l, can be obtained as

$$p^j_l = \frac{\sigma^2\gamma_j}{(1-\sum_{j=1}^{J}\mathbf{E}_j(l)\alpha_j)(1-\gamma_j v_j)|\bar{h}_j|^2} \tag{13}$$

where $\mathbf{E}_j(l)$ is the l^{th} row vector of $\mathbf{E}_j$.

For a multi-rate CDMA system, which employs M_j code-spreading sequences for a class j user, the above approximated power control feasibility condition can be expressed as follows

$$\sum_{j=1}^{J}\mathbf{E}_j M_j\alpha_j < 1 \tag{14}$$

as $K_j \to \infty$ and $N \to \infty$.

IV. CROSS-LAYER DESIGN OF CAC

In the physical layer, the PCFC in (14) can be used to formulate the feasible state space [1], in which the target SIR can be satisfied. This feasible space or the PCFC is then passed to the network layer to determine the cross-layer call admission control policy. In this work, we consider both complete-sharing (CS)-based and SMDP-based CAC.

For a simple complete-sharing (CS)-based CAC policy, when a call arrives, the power control feasibility condition in (14) is evaluated by incorporating information of this newly arrived call. If this feasibility condition holds, the call is accepted. Otherwise, the call is stored in a buffer, or blocked if the buffer is full. The shortcoming of this CAC policy is that QoS requirements in the network layer are ignored.

An optimal CAC algorithm, which is designed to satisfy the QoS requirements in both the physical and network layers, can be achieved by formulating the CAC problem as a SMDP, and then solving this SMDP. The computational complexity of a SMDP-based CAC problem increases exponentially with L. Thus, in this paper, we use the approximated PCFC in (14) with $L = 1$ to formulate the feasible state space of a SMDP-based CAC problem. The details on the formulation of a CAC problem by SMDP, as well as the solution to the SMDP, can be found in [1] [2] [9].

V. ROP ALGORITHMS

From the derivation of the approximated PCFC in (14), we observe that with increasing L, the approximated PCFC can be very accurate. This observation motivates an intuitive ROP algorithm, defined as ROP-I, in which the outage probability can be reduced by increasing L. With the increase of L, the outage can be reduced, but at the same time the blocking probability is also increased due to the strict PCFC. Furthermore, with the increase of L, the computational complexity for SMDP-based CAC increases exponentially. In the following, we propose two simple ROP algorithms, which we denote as ROP-II and ROP-III, respectively.

ROP-II and ROP-III aim at reducing the outage by leaving some margin for the target SIR. Both ROP-II and ROP-III work well for a small L, even $L = 1$, and hence are appropriate for both CS-based and SMDP-based CAC policies.

In ROP-II, for a given transmission scheme and target BER or PER, an equivalent SIR requirement for class j, where $j = 1, .., J$, can be calculated. The CAC and power control are then derived based on this target SIR, γ_j. At the transmitter, instead of using the original transmission scheme with target SIR γ_j, the transmitter adjusts its modulation and coding scheme to reduce the target SIR by a factor α_{dec}, where $\alpha_{dec} < 1$. Without loss of generality, we assume the same decrease-factor α_{dec} for all users. With an appropriate α_{dec}, the outage probability can be reduced to a tolerable level. This scheme achieves increased power efficiency at a cost of the spectral efficiency, due to the enhanced modulation and coding.

Unlike ROP-II, ROP-III reduces the outage probability by virtually increasing the target SIR. We use α_{inc} to denote the increase-factor, where $\alpha_{inc} > 1$. A virtual increased target SIR for class j is set to $\alpha_{inc}\gamma_j$. The CAC and power control algorithms are derived based on these virtual target SIRs. For simplicity, the increase-factor α_{inc} is same for all the users. The shortcoming of ROP-III is that the network layer performance in terms of blocking probability and connection delay degrades with the increase-factor α_{inc}.

We remark that in the case of ROP-II, the network-layer performance remains same with the decrease of α_{dec}. Therefore, the outage probability can be reduced to a very small level without affecting network-layer performance. The tradeoff in ROP-II is between the power efficiency and spectral efficiency, while ROP-I and ROP-III algorithms both encounter a tradeoff between network-layer and physical-layer performances.

VI. SIMULATION

In this section, we present the simulation results of the ROP algorithms for CS-based and SMDP-based CAC policies.

A. Simulation parameters

For the sake of comparison, we use the same simulation environment as [1] except that we employ a 6-element circular antenna array, instead of a single antenna at the BS. The

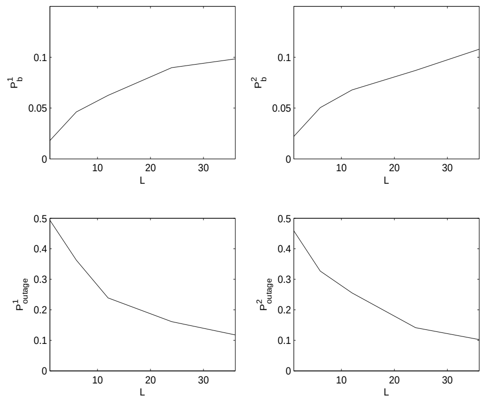

Fig. 2. Simulation results of ROP-I algorithm in beamforming systems.

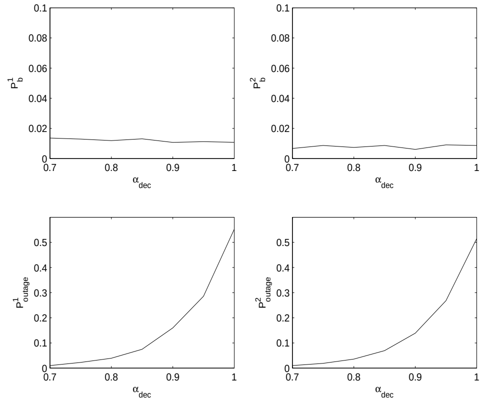

Fig. 3. Simulation results of ROP-II algorithm in beamforming systems with $B_1 = B_2 = 1$.

random variable ϕ_{ij}^2 in (9) can be written as [6]

$$\begin{aligned}\phi_{ij}^2 &= |\vec{a}_i^H \vec{a}_j|^2 \\ &= \frac{1}{M^2}\left|\sum_{q=0}^{M-1} e^{\sqrt{-1}\left(\frac{\pi\cos(\theta_i - q2\pi/M) - \pi\cos(\theta_j - q2\pi/M)}{2\sin(\frac{\pi}{M})}\right)}\right|^2 .\end{aligned} \tag{15}$$

In our simulations, a two-class multi-code CDMA system is considered with spreading gain $N = 128$ and $M_1 = M_2 = 16$ spreading codes per user. Due to the large N, the SIR convergence in (1) is accurate. A flat fading channel is assumed, i.e., $D = 1$. The channel estimates for class j users are assumed to be $\bar{h}_j = 1$ and $\xi_j^2 = 0.05$ for $j = 1, 2$, and as a result we have $v_1 = v_2 = 0.05$. The target SIR is $\gamma_1 = \gamma_2 = 10$, and the variance of the AWGN is $\sigma^2 = 0.01$.

The arrival and departure rates for class 1 and class 2 users are assumed to be $\lambda_1 = 1$, $\lambda_2 = 0.5$, $\mu_1 = 0.25$ and $\mu_2 = 0.1375$, respectively. In the network layer, the blocking probability and connection delay constraints for the two classes of users are $\Xi_1 = 0.2$, $\Xi_2 = 0.1$, $\Phi_1 = 2$ and $\Phi_2 = 0.3$, respectively.

B. Simulation results of ROP-I

For the given simulation parameters, the outage and the blocking probabilities for class j users, denoted as P_b^j and P_{outage}^j, where $j = 1, 2$, are presented as a function of L in Figure 2, in which the total number of arrivals/departures are $10,000$, buffer size is $B_1 = B_2 = 0$, and complete-sharing (CS)-based CAC is employed. It is observed that with an increase of L, the blocking probability degrades, while the performance in terms of outage probability improves. For example, as L is increased from 1 to 36, the outage probability is reduced from 0.5 to 0.1, while the blocking probability increases from 0.02 to 0.1. In ROP-I, it is obvious that the outage probability is reduced slowly with increasing L.

C. Simulation results of algorithm ROP-II

In ROP-II, the CAC and power control are derived by using the original target SIR $\gamma_1 = \gamma_2 = 10$. The reduced target SIR for class j, $\alpha_{dec}\gamma_j$, where $j = 1, 2$, can be implemented by adjusting the transmission schemes, e.g., lower the modulation level, and/or decreasing the coding rate.

For SMDP-based CAC policies with $L = 1$, the performance in terms of outage and blocking probabilities are presented in Figure 3. It is observed that even with a very small decrease in target SIR, the outage probability decreases significantly, while still maintaining the network-layer performance gain of beamforming. For example, $\alpha_{dec} = 0.8$, the outage probability is reduced from 0.5 to 0.035, while the blocking probability remains unchanged at around 0.025, which is much smaller than the achieved blocking probability in the case of single-antenna systems [1].

The above simulations provide the relationship between decrease-factor and the achieved outage probability. The reduced target SIR can be implemented by enhanced coding and modulation. In the following we give a simple example to illustrate the tradeoff between spectral efficiency and reduced outage probability.

In a system with adaptive modulation and coding (AMC) at the transmitter [7], we can adaptively reduce the target SIR. It is assumed that each user employs a QPSK convolution coded modulation scheme with coding rate $3/4$ and rate 1.5 bits/symbol. The target SIR for above AMC scheme is 10, which can achieve a target PER of 3.1468×10^{-6} with packet length 1080 [7]. In order to lower the outage probability for the $L = 1$ case, the transmission scheme can be adjusted to QPSK with coding rate $1/2$ or BPSK with coding rate $1/2$, which are denoted as enhanced scheme 1 and 2, respectively. The achieved outage and blocking probabilities are listed in Table I, in which SMDP-based CAC with $B_1 = B_2 = 0$ is employed. It is observed that the outage probability can be reduced to almost zero with a 0.5 bit/symbol rate loss, while the network-layer performance remains unchanged.

D. Simulation results of ROP-III

In ROP-III, CAC and power control are derived based on the increased virtual target SIRs, $\alpha_{inc}\gamma_j$, where $j = 1, 2$, and as a result, both the blocking probability and the outage probability are affected by the increase-factor α_{inc}.

For a CS-based CAC with $L = 1$, the outage-versus-α_{inc}, and the blocking-versus-α_{inc} are numerically presented in

TABLE I

Simulation results of ROP-II algorithm in beamforming systems with SMDP-based CAC and $B_1 = B_2 = 0$.

	P_b^1	P_b^2	P_{outage}^1	P_{outage}^2
Original scheme:	0.0283	0.0261	0.5438	0.5112
Enhanced scheme 1:	0.0240	0.0242	0.00008	0.00006
Enhanced scheme 2:	0.0220	0.0205	0	0

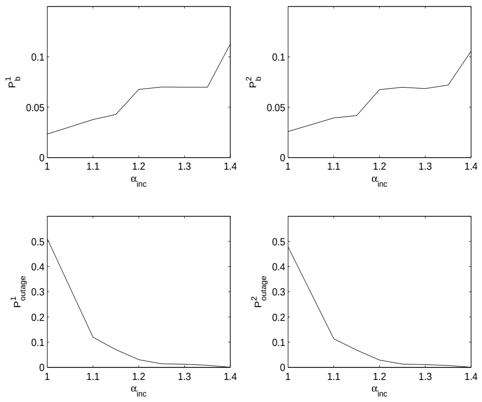

Fig. 4. Simulation results of ROP-III algorithm in beamforming systems with CS-based CAC.

Figure 4, in which the total number of arrivals/departures are $50,000$, and buffer size $B_1 = B_2 = 0$. It is observed that with an increase of α_{inc}, the outage probability decreases significantly. Although the blocking probability degrades with α_{inc}, fortunately it only degrades linearly. For example, with $\alpha_{inc} = 1.2$, the outage probability is improved dramatically from 0.5 to 0.03, while the blocking probability only increases linearly from 0.023 to 0.067.

E. Comparison of single-antenna and beamforming systems

We remark that single antenna systems retain the advantage of more precise power control to combat outage. In this section, we investigate the effect of reduced target SIR on both single and multiple antenna systems.

The simulation results for single-antenna and beamforming systems are shown in Tables II and III, respectively, in which the buffer size is $B_1 = B_2 = 0$, and the total number of arrivals/departures is $50,000$. It is observed that in a single antenna system, by adjusting the target SIR, the blocking probability can be improved very slowly, while in a beamforming system, the network-layer performance, in terms of blocking probability, can be improved dramatically by employing antenna arrays at the BS, and the outage probability can be mitigated to a very small value by reducing the target SIR. For example, when applying the reduced target SIR $\alpha_{dec}\gamma_j = 7$, where $j = 1, 2$, to a beamforming system, the blocking probability is around 0.02, and the outage probability can be reduced dramatically to 0.008. However, when applying the same reduced target SIR $\alpha_{dec}\gamma_j = 7$, where $j = 1, 2$, to a single antenna system, although the outage is always zero, the blocking probability may not even show improvement, and still remain at a large value of around 0.2.

TABLE II

Simulation results of ROP-II algorithm in single-antenna systems with CS-based CAC.

α_{dec}	P_b^1	P_b^2
0.9	0.2133	0.2257
0.7	0.2172	0.2137
0.49065	0.1553	0.1535
0.22876	0.0964	0.1011

TABLE III

Simulation results of ROP-II algorithm in beamforming systems with CS-based CAC.

α_{dec}	P_b^1	P_b^2	P_{outage}^1	P_{outage}^2
0.9	0.0244	0.0254	0.1428	0.1384
0.7	0.0239	0.0245	0.0083	0.0087
0.49065	0.0217	0.0209	0	0.00004
0.22876	0.0226	0.0241	0	0

VII. CONCLUSIONS

In this paper, we propose CAC algorithms based on an approximated PCFC for CDMA beamforming systems. The approximation of the PCFC leads to an outage probability. Several ROP schemes are proposed to reduce the outage probability. Simulation results show that these algorithms achieve a network-layer performance gain, in terms of low connection delay and low blocking probability, while simultaneously guaranteeing physical-layer performance.

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