Cross-Layer Call Admission Control for a CDMA Uplink Employing a Base-Station Antenna Array

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***Abstract*— A novel cross-layer call admission control policy is proposed for a general CDMA beamforming system. In contrast to previously proposed call admission control (CAC) policies which focus on large systems and specific receiver structures, in this paper we aim to design an optimal CAC policy in a more general CDMA beamforming system. The effects due to mutual coupling and multi-path scattering are also taken into account. Based on this more realistic signal propagation model, an optimal semi-Markov decision process (SMDP)-based CAC policy is proposed, which is then evaluated and compared with single antenna systems. Numerical examples demonstrate that compared with the case in single antenna systems, our proposed CAC policy for beamforming systems is capable of achieving a significant performance gain, while simultaneously guaranteeing quality-of-service (QoS) requirements.**

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 has been receiving much attention. In [1] [2], optimal semi-Markov decision process (SMDP)-based CAC algorithms are presented, which are able to optimize power control and admission control across physical and network layers. However, these approaches only consider single antenna systems, which lack the performance benefits provided by multiple antenna systems [3] - [5].

In [6] and [7], the cross-layer admission control problem is extended to multiple antenna systems, in which a large-size system with a linear-minimum-mean-square-error (LMMSE) receiver is assumed, and no mutual coupling and scattering are considered. The specific signal model employed in [6] [7] limits the application of the proposed CAC policies. Also, the ignorance of mutual coupling and scattering makes the predicted performance too optimistic. Although there are several papers investigating the effects of mutual coupling and scattering, e.g, [5], these work only focus on physical layer performance. This motivates the investigation of cross-layer CAC design for a general CDMA beamforming system.

In this paper, we consider an uplink CDMA beamforming system in which mutual coupling and scattering are taken into account. We aim to employ the benefits provided by multiple antennas, and discuss the CAC problem which can optimize the network layer performance while satisfying QoS requirements.

We first derive the power control feasibility condition (PCFC). The outage probability, which is defined as the probability that a target SIR cannot be satisfied, can be reduced by a simple reduced-outage-probability (ROP) algorithm proposed in [7]. The PCFC, combined with the ROP algorithm, are then passed to the network layer to formulate a semi-Markov-decision process (SMDP). An optimal CAC policy can be obtained by solving this SMDP via a linear programming (LP) approach.

The rest of this paper is organized as follows. In Section II, we present the signal model. In Section III, an exact PCFC is derived, which is then simplified to an approximated PCFC. A simple ROP algorithm is also addressed in this section. The cross-layer CAC algorithms are discussed in Section IV. Numerical results are then presented in Section V.

II. SIGNAL MODEL

A. Signal model at the physical layer

We consider an uplink CDMA beamforming system, which supports J classes of users. Let K_j denote the number of users for class j, where $j = 1, .., J$. There are M antennas employed at the BS and a single antenna is employed for each user. There are totally K users in the system, where $K = \sum_{j=1}^{J} K_j$.

Let $\vec{a}_i$ denote the normalized array response vector for user i, where i=1, .., K. The array response vector contains the relative phases of the received signals at each array element, which depends on the array geometry as well as the angle of arrival (AoA) for user i, denoted by θ_i.

To characterize the fraction of user i's signal passed by the beamforming weights, the beamforming pattern for a desired user k can be accomplished by

$$\phi_{ik}^2 = \left|\vec{\omega}_k^H \vec{a}_i\right|^2 \tag{1}$$

where $\vec{\omega}_k$ denotes the beamforming weight vector for a desired user k, and $(.)^H$ denotes conjugate transpose.

The above expressions neglect the effects of mutual coupling and scattering. For a desired user k, when mutual coupling and scattering are taken into account, Equation (1) can be modified to [5]

$$\phi_{ik}^2 = \left|\frac{(\mathbf{Z}^{-1}\vec{\omega}_k)^H}{\|\mathbf{Z}^{-1}\vec{\omega}_k\|}\frac{(\mathbf{Y}_i\vec{a}_i)}{\|\mathbf{Y}_i\vec{a}_i\|}\right|^2 \tag{2}$$

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where $\|.\|$ denotes norm, $\mathbf{Z}^{-1}$ is the inverse of mutual impedance matrix $\mathbf{Z}$ [5], and $\mathbf{Y}_i$ is a diagonal matrix with elements $\{\upsilon_i r_{i1}, .., \upsilon_i r_{iM}\}$, in which υ_i denotes the path loss and shadowing effects factor for user i, and r_{im} represents Rayleigh fading random variables for user i at array element m , where $m = 1, .., M$, which depends on the given angle spread, $\triangle$. The detailed calculation of ϕ_{ik}^2 can be found in [5].

Given the above beamforming signal model, the SIR for user i can be written as

$$SIR_i = \frac{B}{R_i} \frac{p_i \phi_{ii}^2}{\sum_{l \neq i} p_l \phi_{il}^2 + \eta_0 B} \quad (3)$$

where B is the total bandwidth, η_0 is the one-sided power spectral density of background additive white Gaussian noise, p_i and R_i represent the received power and transmission rate for user i, respectively. The parameters ϕ_{ii}^2 and ϕ_{ik}^2, defined in (2), capture the effects of beamforming, which take into account mutual electromagnetic coupling of antenna array elements and scattering due to multipath propagation.

In the following, we consider a spatially matched filter receiver, i.e., $\vec{\omega}_k = \vec{a}_k$. The QoS requirements in the physical layer can be represented by outage probability, defined as the probability that the target SIR cannot be satisfied. It is assumed that the users in class j have the same target SIR and outage probability constraints.

B. Signal model in the network layer

In the network layer, 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 $\frac{1}{\mu_j}, j = 1, .., J$. Whenever an incoming user arrives, the CAC policy decides if this user can be accepted, stored in the buffer, or blocked if the buffer is full. Each class of users shares a common buffer with size B_j for class j.

The QoS requirements in the network layer can be characterized by blocking probability and connection delay. It is assumed that the users in class j have the same blocking probability and connection delay constraints.

III. Power control feasibility condition (PCFC)

PCFC ensures a positive power solution to achieve target SIRs, and can be employed to formulate the state space, which is necessary for an optimal CAC policy. We next derive this PCFC.

The SIR requirements of user i can be written as

$$SIR_i \quad \geq \quad \gamma_i \quad (4)$$

where γ_i denotes the target SIR for user i, where $i = 1, .., K$.

Letting SIR_i in Equation (4) achieve its target value, γ_i, we have the following matrix form [8]

$$[\mathbf{I} - \mathbf{QF}]\vec{P} = \mathbf{Q}\vec{U} \quad (5)$$

where $\mathbf{I}$ is the identity matrix, $\vec{P} = [p_1, .., p_K]^t$, $\vec{U} = \eta_0 B[1, .., 1]^t$,

$$\mathbf{Q} = diag\left\{\frac{\gamma_1 R_1/B}{1 + \gamma_1 R_1/B}, .., \frac{\gamma_K R_K/B}{1 + \gamma_K R_K/B}\right\} \quad (6)$$

and

$$\mathbf{F} = \begin{bmatrix} F_{1,1} & F_{1,2} & ... & F_{1,K} \\ F_{2,1} & F_{2,2} & ... & F_{2,K} \\ ... & ... & ... & ... \\ F_{K,1} & F_{K,2} & ... & F_{K,K} \end{bmatrix} \quad (7)$$

in which $F_{ij} = \frac{\phi_{ij}^2}{\phi_{ii}^2}$.

To ensure a positive solution for power vector $\vec{P}$, we have the following power control feasibility condition [8],

$$\rho(\mathbf{QF}) < 1 \quad (8)$$

where $\rho(.)$ denotes the maximum eigenvalue.

The outage probability can be obtained as the probability that the above condition is violated. Although the state space, required by an optimal CAC policy, can be formulated by evaluating the above outage probability, this evaluation relies on the number of users as well as the distribution of AoAs for all the users in the system, and thus results in a very high computation complexity. An approach to evaluate the above outage probability with reasonably low complexity is currently under investigation.

In this paper, we propose an alternative solution, which employs an approximated PCFC, and as a result can dramatically simplify the formulation of the state space.

A. Approximated power control feasibility condition

Without loss of generality, we consider an arbitrary user i in class 1, where $i = 1, .., K_1$. By considering specific traffic classes and letting SIR achieve its target value, the expression in (3) can be written as follows,

$$\gamma_i = \frac{p_i \phi_{ii}^2 \frac{B}{R_1}}{\sum_{l=1, l \neq i}^{K_1} p_l \phi_{il}^2 + \sum_{l=1}^{K_2} p_l \phi_{il}^2 + .. \sum_{l=1}^{K_J} p_l \phi_{il}^2 + \sigma^2}$$

where $\sigma^2 \triangleq \eta_0 B$ denotes the noise variance, and p_i represents the received power for user i.

It is not difficult to show that users in the same class have the same received power. By denoting the received power in class j as p_j, the above expression can be written as

$$\gamma_i \quad = \quad \frac{p_1 \phi_{ii}^2 \frac{B}{R_1}}{p_1(K_1 - 1)\beta_1 + \sum_{j=2}^{J} p_j K_j \beta_j + \sigma^2} \quad (9)$$

where $\beta_1 = \frac{1}{K_1 - 1} \sum_{l=1, l \neq i}^{K_1} \phi_{il}^2$ and $\beta_j = \frac{1}{K_j} \sum_{l=1}^{K_j} \phi_{il}^2$ for $j = 2, .., J$.

By exchanging the numerator and denominator, Equation (9) is equivalent to

$$\frac{p_1(K_1 - 1)\beta_1 + \sum_{j=2}^{J} p_j K_j \beta_j + \sigma^2}{p_1 \frac{B}{\gamma_1 R_1}} \quad = \quad \phi_{ii}^2 \quad (10)$$

where $i = 1, .., K_1$.

Summing the above K_1 equations, and calculating the sample average, we obtain

$$\frac{p_1(K_1 - 1)\alpha_1 + \sum_{j=2}^{J} K_j p_j \alpha_j + \sigma^2}{p_1 \frac{B}{\gamma_1 R_1}} = \frac{1}{K_1} \sum_{i=1}^{K_1} \phi_{ii}^2 \quad (11)$$

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where $\alpha_1 = \frac{1}{K_1}\sum_{i=1}^{K_1}\beta_1$ and $\alpha_j = \frac{1}{K_1}\sum_{i=1}^{K_1}\beta_j$.

When the number of users is large enough, the above $\alpha_1, .., \alpha_J$ can be approximated by their mean values, and (11) can be further simplified as

$$E_1[\phi_{des}] = \frac{p_1(K_1-1)E_{11}[\phi_{int}] + \sum_{j=2}^{J} K_j p_j E_{1j}[\phi_{int}] + \sigma^2}{p_1\frac{B}{\gamma_1 R_1}} \quad (12)$$

in which $E_{mn}[\phi_{int}]$ is the expected fraction of an interferer user in class n passed by a beamforming weight vector for a desired user in class m, where $m, n = 1, .., J$, while $E_j[\phi_{des}]$ is the expected fraction of a desired user in class j passed by its beamforming weight vector, where $j = 1, .., J$.

The AoAs of active users in the system are assumed to have identically independent distributions, which are independent of a user's specific class. Therefore, it is reasonable to assume that $E_{mn}[\phi_{int}]$ is also independent of specific classes m and n, which can be denoted by $E[\phi_{int}]$. Similarly, $E_j[\phi_{des}]$ is independent of class j, and can be denoted by $E[\phi_{des}]$. $E[\phi_{des}]$ and $E[\phi_{int}]$ represent the expected fractions of the desired user's power and interference, respectively.

From the above discussion, (12) can be written as

$$\frac{p_1(K_1-1)E[\phi_{int}] + \sum_{j=2}^{J} K_j p_j E[\phi_{int}] + \sigma^2}{p_1\frac{B}{\gamma_1 R_1}} = E[\phi_{des}].$$

By exchanging the numerator and denominator of the above equation, we have

$$\frac{p_1\frac{B}{\gamma_1 R_1}}{p_1(K_1-1)\frac{E[\phi_{int}]}{E[\phi_{des}]} + \sum_{j=2}^{J} K_j p_j \frac{E[\phi_{int}]}{E[\phi_{des}]} + \frac{\sigma^2}{E[\phi_{des}]}} = 1. \quad (13)$$

The QoS requirement for class 1 in (13) can be extended to any class j,

$$\frac{p_j\frac{B}{\gamma_j R_j}}{p_j(K_j-1)\frac{E[\phi_{int}]}{E[\phi_{des}]} + \sum_{m=1,m\neq j}^{J} K_m p_m \frac{E[\phi_{int}]}{E[\phi_{des}]} + \frac{\sigma^2}{E[\phi_{des}]}} = 1 \quad (14)$$

where $j = 1, .., J$.

The power solution can be obtained by solving the above J equations [9]

$$p_j = \frac{\frac{\sigma^2}{E[\phi_{int}]}}{(1+\frac{B}{\gamma_j R_j \frac{E[\phi_{int}]}{E[\phi_{des}]}})[1-\sum_{j=1}^{J}\frac{K_j}{1+\frac{B}{\gamma_j R_j \frac{E[\phi_{int}]}{E[\phi_{des}]}}}]} \quad (15)$$

where $j = 1, .., J$.

Positivity of power solution implies the following power control feasibility condition

$$\sum_{j=1}^{J}\frac{K_j}{1+\frac{B}{\gamma_j R_j \frac{E[\phi_{int}]}{E[\phi_{des}]}}} \leq 1. \quad (16)$$

As shown in [5], $E[\phi_{int}]$ and $E[\phi_{des}]$ can be determined numerically from Equation (1) for a beamforming system without mutual coupling and scattering, or from (2) when mutual electromagnetic coupling of antenna array elements and scattering due to multipath propagation are both taken into account.

In the derivation of the above PCFC, it is assumed that α_j in (11) can be estimated by its mean value. Therefore, the accuracy of the approximate PCFC depends on the estimation error of parameters α_j. In the following, we give the evaluation results of the estimation errors for a two-antenna system. With 10 users in the system for each class, the error percentage, defined as the estimation error normalized by the actual value of α_j, is around 10%. When the user number is increased to 90, this error percentage can be reduced to 2%. Due to the non-zero estimation error, there exists an outage probability. In the next section, we discuss how to mitigate the outage.

B. ROP algorithm

In this paper, a simple ROP algorithm proposed in [7] is employed, which aims at reducing the outage by leaving some margin for the target SIR.

For a given transmission scheme and target BER, an equivalent SIR requirement for class j, where $j = 1, .., J$, can be calculated. The CAC and power control vector are then derived based on this target SIR. At the transmitter, instead of using the original transmission scheme with target SIR, the transmitter adjusts its modulation and coding scheme to reduce the target SIR by a factor α, denoted as the reduce-factor, where $\alpha < 1$. Without loss of generality, in the following we assume the same reduce-factor α for all users. As shown in [7], with an appropriate α, the outage probability can be reduced to a reasonably small level. This scheme achieves increased power efficiency at a necessary cost of spectral efficiency, due to the enhanced modulation and coding.

We remark that in the case of ROP, the network-layer performance remains the same for different reduce-factors. Therefore, outage probability can be reduced to a very small level without affecting network-layer performance.

IV. Cross-layer design of CAC

We aim to derive an optimal CAC algorithm, which is designed to minimize the blocking probability while simultaneously satisfying the QoS requirements in both the physical and network layers.

As shown in [1], the above constrained optimization problem can be achieved by formulating the CAC problem as a semi-Markov decision process (SMDP) which includes the following components: state space, action space, decision epoch, dynamic statistics, cost criterion and policy.

In the CAC problem we investigate, the formulation of a SMDP is very similar to the formulation employed in [1], except that the state space S has been modified to include the

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effects of beamforming, which can be obtained by using the PCFC derived in (16),

$$S = \left\{ s : n_q^j \leq B_j, j = 1, .., J; \sum_{j=1}^{J} \frac{k^j}{1 + \frac{B}{\gamma_j R_j \frac{E[\phi_{int}]}{E[\phi_{des}]}}} \leq 1 \right\}$$

where $s = [n_q^1, k^1, ..., n_q^J, k^J]^T$, in which n_q^j and k^j represent the number of users in the queue and the number of active users in class j, respectively.

The formulated SMDP can be solved by linear programming (LP) approach. The details on the formulation of a CAC problem by SMDP, as well as the solution to the SMDP, can be found in [1] [6] [10].

Throughout this paper, we assume an exponentially distributed duration, in which the SMDP formulation can be applied. For a system with generally distributed duration, it is very hard to obtain an optimal solution. However, the LP approach discussed in the above provides a sub-optimal solution.

V. Numerical examples

In this section, we evaluate the performance of the proposed CAC policies for beamforming systems in both physical and network layers. The overall system performance is also investigated.

A. System parameters

We consider a two-class system with circular antenna array at the BS with a uniformly distributed AoA.The target SIRs are given as $\gamma_1 = \gamma_2 = 10$, and the rate for each class is set to $R_1 = 8$ kbps and $R_2 = 32$ kbps. The total bandwidth is $B = 1.25MHz$, and the AWGN noise can be characterized by spectral density $\eta_0 = 10^{-6}$. The arrival and departure rates for class 1 and class 2 users are denoted by $\lambda_1 = 1$, $\lambda_2 = 0.5$, $\mu_1 = 0.25$ and $\mu_2 = 0.1375$, respectively.

It is obvious that compared with beamforming systems, single antenna systems encounter an infeasibility problem more easily, i.e., the QoS requirements may not be satisfied by any CAC policy. Since we aim to compare the performance between single and multiple antenna systems in a quantitative way, this infeasibility situation should be avoided. Therefore, in this paper, we employ a relatively relaxed blocking probability constraints, which are set to 0.1 and 0.3 for class 1 and 2, respectively. The constraints on connection delay, which are represented by the average queue length, are set to 1.5030 and 1.2250, respectively. The conclusions derived in this paper can be generalized to any QoS constraint.

B. Network layer performance

We consider a beamforming environment in which the effects of mutual coupling and scattering are both taken into account. The angle spread is set to $\Delta = 5°$. The numerical values of $E[\phi_{int}]$ and $E[\phi_{des}]$, derived in [5], are presented in Table I. The analytical network layer performance from linear programming (LP) is depicted in Tables II and III for single-antenna and two-antenna systems, respectively, where Pb_j and nq_j denote the blocking probability and average queue length in class j, respectively. It is observed that employing beamforming with only two antennas at the BS can dramatically reduce the blocking probability and connection delay. For example, the blocking probability for class 2 users is 0.2875 when a single antenna is employed, while this value is decreased to 0.0953 for the case of two antennas. At the same time, the connection delay is reduced from 0.37 to 0, i.e., even the case of no buffering can achieve a much better blocking probability for a two-antenna beamforming system.

TABLE I

Numerical values of $E[\phi_{des}]$ and $E[\phi_{int}]$ for a beamforming system with mutual coupling and scattering with an angle spread of $\Delta = 5°$.

M	1	2	3	4	5	6
$E[\phi_{des}]$	1.0	0.9958	0.9409	0.8156	0.8867	0.8378
$E[\phi_{int}]$	1.0	0.5908	0.4610	0.3782	0.2952	0.2363

TABLE II

Single antenna system: analytical blocking probabilities and connection delays when SMDP-based CAC is employed.

$[B_1, B_2]$	Pb_1	Pb_2	nq_1	nq_2
[1,1]	0.0631	0.2875	0.0872	0.3700
[2,1]	0.0436	0.2786	0.2229	0.3294
[2,2]	0.0519	0.2307	0.2623	0.7645
[3,1]	0.0310	0.2723	0.4065	0.3176

We note that there exists some infeasible buffer configurations for single antenna systems. Extra computation and time are needed to search for a feasible buffer configuration, while in beamforming systems, a buffer of very small size, or even no buffering at all, leads to the satisfaction of all QoS requirements. Therefore, the search procedure for beamforming systems can be greatly simplified.

C. Physical layer performance

Here we consider an environment without mutual coupling and scattering for simplicity. However, our results can be extended to a general case with mutual coupling and scattering straightforwardly. Numerical values of parameters $E[\phi_{des}]$ and $E[\phi_{int}]$, derived in [5], are shown in Table IV.

Figure 1 shows the outage probability, denoted by P_{out}^j for class j users, where $j = 1, 2$, in which no buffer is

TABLE III

Two-antenna beamforming system: analytical blocking probabilities and connection delays when SMDP-based CAC is employed.

$[B_1, B_2]$	Pb_1	Pb_2	nq_1	nq_2
[0,0]	0.0237	0.0953	0	0
[0,1]	0.0181	0.0597	0	0.1115
[1,0]	0.0161	0.0898	0.0730	0
[1,1]	0.0121	0.0547	0.0367	0.0901

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TABLE IV

NUMERICAL VALUES OF $E[\phi_{des}]$ AND $E[\phi_{int}]$ FOR A BEAMFORMING SYSTEM WITHOUT MUTUAL COUPLING AND SCATTERING.

M	1	2	3	4	5	6
$E[\phi_{des}]$	1.0	1.0	1.0	1.0	1.0	1.0
$E[\phi_{int}]$	1.0	0.5463	0.3950	0.3241	0.2460	0.2058

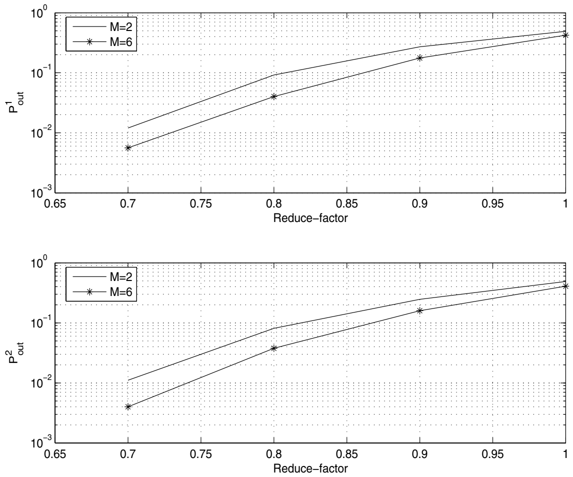

Fig. 1. SMDP-based CAC: Outage probability as a function of reduced-factor.

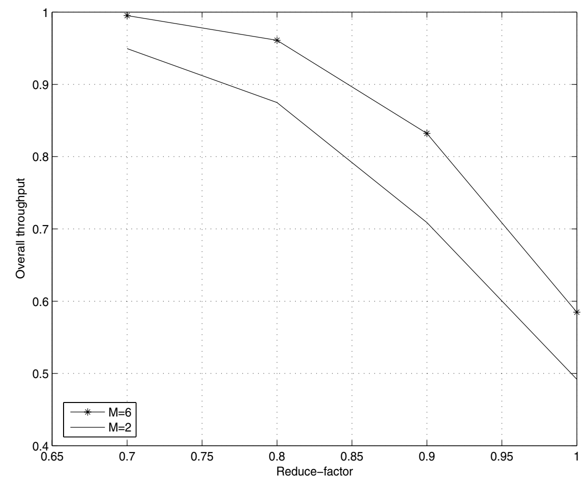

Fig. 2. SMDP-based CAC: throughput as a function of reduced-factor.

employed. It is observed that outage probability can be reduced dramatically by decreasing the reduce-factor. In the case of $M = 6$, when the reduce-factor is decreased from 0.9 to 0.7 by an enhanced modulation and coding scheme, the outage probability for class 1 users can be decreased from 0.176 to 0.0056, i.e., decreased by 97%.

We note that the above performance gain in terms of reduced outage probability is achieved without affecting network layer performance. However, the target SIR should be reduced by employing an enhanced modulation and coding scheme. Therefore, there exists a necessary loss in spectral efficiency.

D. Overall system performance

The overall system throughput is defined as

$$\text{Throughput} = \sum_j w_j(1 - P^j_{out})(1 - Pb_j)$$

where w_j is the weighting factor. Here we use $w_1 = w_2 = 0.5$.

For a system without buffering, Figure 2 shows the throughput as a function of reduce-factor. As observed, the throughput can be improved by either increasing number of antennas, or decreasing reduce-factor.

VI. CONCLUSIONS AND FUTURE WORK

A cross-layer CAC policy is proposed for a general CDMA beamforming system. This CAC policy, combined with a reduced-outage-probability algorithm, is capable of guaranteeing the QoS requirements in both physical and network layers. The proposed CAC policy can achieve a significant performance gain in terms of blocking probability, connection delay and system throughput, and as a result provides a solution to the capacity limitation problem for future wireless networks. Currently, we are optimizing the CAC algorithm to incorporate outage directly into the SMDP and therefore improve performance over the simpler solution proposed here that involves a separate ROP algorithm.

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