Call Admission Control Using Differentiated Outage Probabilities in Multimedia DS-CDMA Networks with Imperfect Power Control

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Abstract—A key problem under imperfect power control in multimedia DS-CDMA networks is how to guarantee the differentiated outage probabilities of different traffic classes resulted by the uncertainty of received powers. In addition, in order to utilize the scarce wireless resource efficiently, as many users as possible should be admitted into the network while providing guaranteed quality-of-service support for them. In this work, a call admission control scheme, Differentiated Outage Probabilities CAC or DOP-CAC, is proposed to achieve the above goals for imperfectly power controlled multimedia CDMA networks. Two important features of CDMA system are considered in our scheme: one is the power multiplexing among bursty traffics and the other is the power allocation scheme employed at the physical layer. The validation and efficiency of DOP-CAC are verified by numerical examples.

I. INTRODUCTION

The next generation wireless networks are supposed to provide quality-of-service (QoS) support for multimedia traffic based on the Code Division Multiple Access (CDMA) air interface. For the scarcity of wireless resource, two important techniques have been the focuses of many studies on CDMA networks in recent years: one is the power control (or power allocation) [1]-[3] at the physical layer and the other is the call admission control (CAC) [4]-[6] at the link layer.

CDMA systems are characterized as being interference limited so that power control has been one of the most important techniques to reduce interference therefore enhance system capacity. In an ideal CDMA system, powers received at the base station are assumed to be kept at desired levels to maximize system capacity [1]. This is generally referred to as the perfect power control. However, in practical CDMA systems, the received powers are usually hard to be maintained at fixed levels because of the fading resulted by the movements of mobile users. Specifically, when the user is in high-speed movement, the fading rate may be much larger than the power control rate so that the closed loop power control can not trace the signal fluctuation and large control errors happen. This is generally referred to as imperfect power control.

A direct result of imperfect power control is the randomness of received powers, which makes the received signal-to-interference ratio (SIR) of each user a random variable. The state that user’s SIR goes below some predefined threshold is defined as outage, during which the user’s bit error rate (BER) is too big to decode received signals successfully so that the transmission may be interrupted temporarily. In general, different classes of traffic require different outage probabilities. Therefore, in addition to the traditional parameters such as rate requirement, SIR threshold, etc., outage probability constraint should also be included in the QoS characteristics of individual traffic class.

As one of the most important QoS guaranteeing techniques at the link layer, CAC in CDMA networks has attracted extensive studies in recent years. The CAC problem was considered for voice only CDMA systems in [4] and for voice and data integrated systems in [5]. And in [6], the authors proposed a framework of CAC for multimedia traffics in CDMA networks with perfect power control. However, all these works only guaranteed the total interference constraints at the base station either by off-line determination of maximum admissible user numbers [4] or by on-line measurements of the total interference. None of them accounted for the differentiated outage probability requirements of multimedia traffic under imperfect power control environment.

In this paper, we develop a framework of call admission control to guarantee users’ differentiated outage probabilities (DOP-CAC) while sufficiently utilizing system resource in multimedia DS-CDMA networks with imperfect power control. Two important features of CDMA networks are considered in our analysis: the first one is the so called power multiplexing among traffic. Due to the bursty nature of multimedia traffic, not all users are on their active periods at the same time. When a traffic is inactive, no power should be assigned to it whether for the sake of battery power saving or for the multiple access interference (MAI) reducing. Thus at any instance, the total received powers (or the interference) at the base station depends on the number of active users, which is a random variable. This is called power multiplexing in this paper. This statistical feature brings capacity gains for the system and benefits the efficiency of resource utilization. The second feature is the power allocation scheme employed at the physical layer. This enables our CAC algorithm adaptable to the particular power allocation scheme employed so that enable us to select the best performed one without much changing the CAC algorithm. Two power
allocation schemes are considered respectively and compared in the performance evaluation of DOP-CAC: one is the Limited Optimal Power Allocation (LOPA) scheme proposed in [1], which is capacity optimal under perfect power control, and the other is the Quasi-Optimal Power Allocation (QOPA) scheme we proposed in [3], which is capacity quasi-optimal under imperfect power control. By numerical examples, the validation and efficiency of DOP-CAC are verified. The results also show that DOP-CAC achieves much better resource utilization under QOPA than it does under LOPA.

The rest of this paper is organized as follows. We describe the system model in Section 2. In Section 3, we perform outage probability analysis. In Section 4, we present the DOP-CAC algorithm and outline LOPA and QOPA schemes which will be employed in our performance evaluation via computer simulation in Section 5. And we conclude our works in Section 6.

II. MODEL DESCRIPTION

A. System Model

We consider a single cell DS-CDMA system with multimedia traffic, in which all traffic classes with different data rates are spread over the whole bandwidth with different spreading factors. We only consider the uplink (from mobile to base) situation because it is believed that in the cellular systems, the uplink has more crucial influence on the system capacity than the downlink does.

Suppose there are $K$ classes of users in the system. The user number of class $i$ ($i = 1, \ldots, K$) is denoted by $N_i$ and therefore $(N_1, \ldots, N_K)$ is called the network user configuration vector. Taking bursty nature of the traffic into account, we characterize the class $i$ traffic by ON-OFF model: its ON and OFF periods follow exponential distributions with mean $\frac{1}{R_i}$ and $\frac{1}{\delta_i}$, respectively. Then the active factor of class $i$ traffic is given by $\theta_i = \frac{\beta_i}{\alpha_i+\beta_i}$. At arbitrary time, denote the number of active users of class $i$ by random variables $n_i$ and the network active user configuration vector by $(n_1, \ldots, n_K)$. The QoS requirement of class $i$ user is represented by a triple $(R_i, \alpha_i, \delta_i)$, where $R_i$ is user’s bit rate requirement during its ON period, $\alpha_i$ and $\delta_i$ must satisfy $Pr\{E_b/I_0_i < \alpha_i\} \leq \delta_i$, in which $E_b/I_0$ is the bit-energy-to-interference density ratio. Thus $\alpha_i$ is the pre-defined SIR threshold of class $i$ and $\delta_i$ is the maximum outage probability that class $i$ user can tolerate.

B. Signal Model under Imperfect Power Control

Let $S_i$ be the received signal power of any active user in class $i$ ($i = 1, \ldots, K$) at the base station (BS) and $X_i$ be the decibel representation of $S_i$, i.e., $X_i = 10 \log S_i$. According to the study in [7], under imperfect power control $S_i$ is well approximated as a lognormal random variable with mean $u_i$ and variance $\gamma_i$. Then $X_i$ is a Gaussian random variable, whose mean $m_i$ and variance $\sigma_i^2$ have the following relations with $u_i$ and $\gamma_i$:

$$u_i = e^\beta m_i + \frac{1}{2} \beta^2 \sigma_i^2,$$

(1)

$$\gamma_i = e^{2 \beta m_i + \beta^2 \sigma_i^2} - 1,$$

(2)

where $\beta = \frac{\ln 10}{10}$. The parameter $\sigma_i^2$ reflects the imperfection degree of the power control and is determined by $\gamma_i$ and the receiver structure [7].

For tractability, we assume all users in the cell have similar movements and the same receiver structure so that the users’ movements within a cell can be deemed to be homogeneous. One example is the case in the downtown area, where nearly all mobile users are having similarly low-speed movements and experiencing slow fading. At each power control point, a new set of desired received power levels $(u_1, \ldots, u_K)$ are determined by the power allocation scheme employed at BS according to the current active traffic situation $(n_1, \ldots, n_K)$ and their QoS parameters. No powers are allocated to the mobile users who are during their OFF period.

III. OUTAGE PROBABILITY ANALYSIS

A. Analysis of Active User Configuration Vector Distribution

Suppose the state (ON or OFF) of a user is independent of the state of other class users, i.e. $n_i$ ($i = 1, \ldots, K$) are independent random variables. For a given network user configuration $(N_1, \ldots, N_K)$, the network active user vector distribution is given by

$$Pr\{n_1, n_2, \ldots, n_K | N_1, N_2, \ldots, N_K\} = Pr\{n_1 | N_1\} Pr\{n_2 | N_2\} \ldots Pr\{n_K | N_K\}.$$  

(3)

In order to capture the active user number distribution of individual traffic class, a one-dimensional continuous time Markov chain is necessary for traffic class $i$, as shown in Fig.1, where the state represents the number of active users in traffic class $i$. The infinitesimal generator matrix of this Markov process is given by

$$Q = \begin{pmatrix}
-N_i \alpha_i & N_i \alpha_i & 0 & 0 \\
-b_i & -b_i - (N_i - 1) \alpha_i & 0 & 0 \\
0 & 2b_i & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & N_i b_i - N_i b_i
\end{pmatrix}$$

(4)

Fig. 1. One-dimensional continuous time Markov model for active user number analysis

By solving the forward-recurrent equation set, the probability that at arbitrary time there are $k$ active users of traffic class $i$ is
given by

$$\Pr\{n_i = k | N_i\} = \frac{C_{N_i}^k \left(\frac{a_i}{b_i}\right)^k}{\left(1 + \frac{a_i}{b_i}\right)^{N_i}}. \quad (k = 0, 1, \ldots, N_i) \quad (5)$$

Thus the distribution of network active user vector is given by

$$\Pr\{n_1, \ldots, n_K | N_1, \ldots, N_K\} = \prod_{i=1}^K \frac{C_{N_i}^{n_i} \left(\frac{a_i}{b_i}\right)^{n_i}}{\left(1 + \frac{a_i}{b_i}\right)^{N_i}}. \quad (6)$$

In the following, all probabilities are derived under the condition \((N_1, \ldots, N_K)\), thus we neglect this notation in equations for the purpose of simplicity.

B. Analysis of Conditional Outage Probabilities

For a given network user configuration \((N_1, \ldots, N_K)\), the outage probability for traffic class \(i\) is derived by

$$P_i = \Pr\left\{ \left(\frac{E_b}{I_0}\right)_i < \alpha_i \right\} = \sum_{n_1=0}^{N_1} \cdots \sum_{n_K=0}^{N_K} \Pr\left\{ \left(\frac{E_b}{I_0}\right)_i < \alpha_i | n_1 \ldots n_K \right\} \times \Pr\{n_1 \ldots n_K\}. \quad (7)$$

where \(\Pr\left\{ \left(\frac{E_b}{I_0}\right)_i < \alpha_i | n_1 \ldots n_K \right\}\) is the outage probability of traffic class \(i\) under the condition of active user configuration \((n_1, \ldots, n_K)\).

Given active user vector \((n_1, \ldots, n_K)\), denote by \(S_{ij}\) the received power of the \(j\)th active user in traffic class \(i\) and denote by \(I\) the conditional total interference (we only account for the MAI and ignore the AWGN) received at BS, i.e.,

$$I = \sum_{j=1}^{n_i} S_{1j} + \cdots + \sum_{j=1}^{n_K} S_{Kj}. \quad (8)$$

Since \(I\) is the sum of independent lognormal random variables, it can also be approximated as a lognormal random variable[8], whose mean and variance are given respectively by

$$E[I] = \sum_{i=1}^K n_i u_i, \quad (9)$$

$$D[I] = \sum_{i=1}^K n_i \gamma_i. \quad (10)$$

The accuracy of this approximation is compared to that of Gaussian approximation in [2]. It was shown that much better effect is achieved by lognormal approximation than Gaussian approximation, especially when the users’ number is not large enough.

Let \(Y = 10 \log I\). \(Y\) is also a Gaussian random variable. By Wilkinson’s method[8], its mean \(p\) and variance \(\eta^2\) are given respectively by

$$p = \frac{1}{\beta} \ln E[I] - \frac{1}{2\beta} \ln \left[1 + \frac{D[I]}{(E[I])^2}\right], \quad (11)$$

$$\eta^2 = \frac{1}{\beta^2} \ln \left[1 + \frac{D[I]}{(E[I])^2}\right]. \quad (12)$$

Under the condition of active user vector \((n_1, \ldots, n_K)\), for any active class \(i\) user, its received \(E_b/I_0\) at BS is given by

$$\left(\frac{E_b}{I_0}\right)_i = \frac{3W S_i}{2R_i (I - S_i)}, \quad (13)$$

where \(3/2\) is the inverse of the orthogonal factor of the chip with a rectangular shape and \(W\) is the spread spectrum bandwidth. Then the outage probability of traffic class \(i\) conditioned on \((n_1, \ldots, n_K)\) is given by

$$\Pr\left\{ \left(\frac{E_b}{I_0}\right)_i < \alpha_i | n_1 \ldots n_K \right\} = \Pr\left\{ X_i < Y + A_i \right\}. \quad (14)$$

Let \(A_i = 10 \log \frac{1}{1 + \frac{2\sqrt{m_i}}{3\sigma_i}}\). By using the decibel representations of \(S_i\) and \(I\), the conditional probability of (14) is further rewritten as

$$\Pr\left\{ \left(\frac{E_b}{I_0}\right)_i < \alpha_i | n_1 \ldots n_K \right\} = \Pr\{X_i < Y + A_i\}. \quad (15)$$

Since \(X_i\) and \(Y\) are independent Gaussian random variables with mean \(m_i\) and \(p\), and variance \(\sigma^2\) and \(\eta^2\), respectively, \(X_i - Y\) is also a Gaussian random variable with mean \(m_i - p\) and variance \(\sigma^2 + \eta^2\). Then the conditional outage probability is given by

$$\Pr\left\{ \left(\frac{E_b}{I_0}\right)_i < \alpha_i | n_1 \ldots n_K \right\} = Q\left(\frac{m_i - A_i - p}{\sqrt{\sigma^2 + \eta^2}}\right), \quad (16)$$

where \(Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{t^2}{2}} dt\).

By (7)(6) and (16), the comprehensive outage probability of traffic class \(i\) is given by

$$P_i = \sum_{n_1=0}^{N_1} \cdots \sum_{n_K=0}^{N_K} \left[ Q\left(\frac{m_i - A_i - p}{\sqrt{\sigma^2 + \eta^2}}\right) \prod_{j=1}^K \frac{C_{N_j}^{n_j} \left(\frac{a_j}{b_j}\right)^{n_j}}{\left(1 + \frac{a_j}{b_j}\right)^{N_j}} \right]. \quad (17)$$
IV. CALL ADMISSION CONTROL ALGORITHM AND POWER ALLOCATION SCHEMES

Based on the analysis of the outage probability of traffic class, we present the Differentiated Outage Probabilities CAC (DOP-CAC) algorithm as follows:

Assume the current network user configuration is \((N_1, \ldots, N_K)\). An incoming user of traffic class \(i\) sends an admission request to the BS, together with its desired rate, \(E_b/I_0\) requirement, outage requirement, and active factor \(\theta_i\).

Then the following steps are performed to make an admission decision:

Step 1: Update the network user configuration to \((N_1, \ldots, N_1 + 1, \ldots, N_K)\).

Step 2: Depending on the new network user configuration, for all the possible state of \((n_1, \ldots, n_K)\) with \(n_j = 0, 1, \ldots, N_j, j = 1, \ldots, K\), compute the active network user distribution according to (6).

Step 3: Depending on the new network user configuration, for all the possible state of \((n_1, \ldots, n_K)\) with \(n_j = 0, 1, \ldots, N_j, j = 1, \ldots, K\), compute the conditional outage probability of each traffic class according to (16).

Step 4: Compute the comprehensive outage probability of each traffic class according to (17). Using these information, the admission controller checks whether the outage requirements of all traffic classes can be satisfied at the same time with this new network user configuration. If so, the incoming user is admitted and the new network user configuration is maintained; if not, the incoming user is refused and the previous network user configuration is maintained.

An important feature of this CAC algorithm lies in that the outage probability is power-allocation-dependent according to (17), thus the admission decision is also power-allocation-dependent. In other words, for the same network user configuration \((N_1, \ldots, N_K)\), the admission decision varies for different power allocation schemes. By (17), the particular power allocation scheme is easily embedded into the CAC procedure.

In [1], under the assumption of perfect power control the authors derived the optimal power allocation scheme for multimedia traffics that maximize system capacity. We call it the limited optimal power allocation (LOPA) scheme in this paper because we proved in [3] that it is optimal only under perfect power control environment. In [3], we reconsidered the capacity optimization problem in the imperfect power control framework and derived the conditions that an optimal power allocation should satisfy. By using conservative bounds approximation, a closed form quasi-optimal solution is proposed and great capacity gain is achieved by this scheme. We call it the quasi-optimal power allocation (QOPA) scheme. In this paper the LOPA scheme and the QOPA scheme are considered for the performance evaluation of the DOP-CAC algorithm. We assume the background AWGN is neglectable compared to the MAI, thus according to (17) the ratios among allocated powers (or the relative values in other words) sufficiently determine the outage probabilities of each traffic class. The ratios among allocated powers under LOPA scheme and QOPA scheme are outlined as follows respectively:

- **LOPA**
  - For each active user, the average received power allocated to it (i.e., \(u_i\)) should be proportional to its power index \(g_i\), which is given by
    \[
    g_i = \frac{1}{1 + \frac{3W}{2R_i\alpha_i}}.
    \]  
    \[\text{(18)}\]

- **QOPA**
  - For each active user in the active user vector \((n_1, \ldots, n_K)\), the average received power allocated to it (i.e., \(u_i\)) should be proportional to its generalized power index \(g'_i\), which is given by
    \[
    g'_i = g_i \frac{\sqrt{\sigma^2 n_{\text{min}}^2}}{\eta_{\text{min}}} Q^{-1}(\delta_i),
    \]  
    \[\text{(19)}\]

    where
    \[
    \eta_{\text{min}} = \frac{1}{\beta^2} \ln \left[ 1 + \frac{C}{\sum_{j=1}^K n_j} \right],
    \]  
    \[\text{(20)}\]

    and
    \[
    C = e^{\beta^2 \sigma^2} - 1,
    \]  
    \[\text{(21)}\]

    is a measure of control errors.

V. NUMERICAL EXAMPLES

A. Capacity Gains Resulted by Power Multiplexing

Consider a CDMA system with only two classes of users, which have QoS representation of \((32\text{kb/s}, 4, 10^{-2})\) and \((64\text{kb/s}, 6, 10^{-1})\), respectively. The spread spectrum bandwidth is 5MHz. The active factor of class 1 traffic is \(\theta_1 = 0.4\) and we vary the active factor of class 2 to explore the capacity gains. We fixed the number of class 1 users to be 2 and increase the number of class 2 users to derive the capacity of class 2 users, i.e., the maximum number of admissible class 2 users. The values of \(\sigma^2\) used in this example come from [7].

The maximum number of admissible class 2 users under different active factors are plotted in Fig.2, where user speed of 5km/h is assumed. The results are derived by computation according to (17) and the X-axis is the inverse of \(\theta_2\). The results of DOP-CAC+LOPA and DOP-CAC+QOPA are plotted in the same figure for comparison. The dash lines and the dot lines represent the capacities under perfect power control, i.e., \(\frac{1}{\theta_i}\) times of the capacity when active factor is 1. It shows that with the decrease of \(\theta_2\) great capacity gains are derived by the DOP-CAC algorithms for both power allocation schemes. However, different from the case of perfect power control, where an active factor of \(\theta_i\) will contributes \(\frac{1}{\theta_i}\) times of capacity increase on this type of users [9], the slope of capacity gain does not reach \(\frac{1}{\theta_i}\) under imperfect power control environment. This is due to
the fact that the received signals under imperfect power control are random variables instead of constants as under perfect power control, and no explicit relation exists between the active factor and the capacity gains. In addition, Fig.2 also shows that DOP-CAC is able to admit more users under QOPA scheme than it does under LOPA scheme. This fact indicates that DOP-CAC+QOPA provides more efficient utilization of system resource than DOP-CAC+LOPA does. We will verify this view point in more details in the next example.

B. Performance Comparison of DOP-CAC under QOPA and LOPA Schemes

Consider a multimedia CDMA system with three classes of users, whose QoS requirements, average call time $\left( \frac{1}{\mu_i} \right)$ ($i = 1, 2, 3$) and active factors are listed in Tab.1. For each class, the arrivals of call follow the Poisson process with parameter $\lambda_i$ ($i = 1, 2, 3$) and the call time follows exponential distribution with parameter $\left( \frac{1}{\mu_i} \right)$. We maintain the ratio among $\lambda_i$ to be $\lambda_1 : \lambda_2 : \lambda_3 = 7 : 1 : 2$ while we increase the erlang load of each traffic class in our simulation. The assumed system spread spectrum bandwidth is 5MHz. We assume 2 Rayleigh paths receiver structure and 5km/h speed for all users, which is equivalent to $\sigma = 0.35$ according to [7]. We compare the system resource utilization of DOP-CAC under LOPA scheme and QOPA scheme. Two metrics of system resource utilization are used in the performance evaluation: one is the call blocking probability, which is defined as the ratio of total rejected call numbers to the total incoming call numbers. The other is the system throughput, which is defined as the average total data volumes transmitted in one second by those active users.

Fig.3 plots traffic outage probabilities as functions of offered load. The results of DOP-CAC+QOPA and DOP-CAC+LOPA are plotted in the same figure for comparison. The validation of DOP-CAC is clearly demonstrated in this figure: the outage probabilities of all classes of traffic are controlled below their respective outage upper bounds. However, the effect of CAC is different under different power allocation schemes: DOP-CAC+QOPA provides better outage differentiation among traffics than DOP-CAC+LOPA does. This also implies that DOP-CAC+QOPA takes more advantage of the diverse outage requirements of multimedia traffic than DOP-CAC+LOPA does thus higher resource utilization can be reached.

The call blocking probabilities are plotted as functions of offered load in Fig.4. It is clearly shown that lower call blocking probability is derived by DOP-CAC+QOPA scheme than that of DOP-CAC+LOPA scheme. The system throughputs are plotted as functions of offered load in Fig.5. With the increase of traffic load, the system throughput increases. It is clearly shown that higher system throughput are always achieved under DOP-CAC+QOPA scheme than that of DOP-CAC+LOPA scheme.

Figs.4-5 are consistent and verify the indication of Fig.3, i.e., by taking more advantage of the diverse outage requirements
of multimedia traffic, DOP-CAC+QOPA is able to block fewer incoming calls and transmit more data volumes, which means a higher utilization of system resource. By employing QOPA at the physical layer and DOP-CAC at the link layer, our work suggests a high efficiency solution for QoS support of multimedia traffic under imperfect power control environment.

VI. CONCLUSIONS

We have developed a framework of call admission control to guarantee differentiated users’ outage requirements while sufficiently utilize system resource in multimedia DS-CDMA networks with imperfect power control. Two important features of CDMA networks were considered in our analysis: one is the power multiplexing among bursty traffic and the other is the power allocation scheme employed at the physical layer. The validation and efficiency of DOP-CAC were verified by numerical examples. Two power allocation schemes, QOPA and LOPA, were considered respectively and compared in the performance evaluation of DOP-CAC. The results showed that DOP-CAC achieves much better resource utilization in terms of lower call blocking probability and higher system throughput under QOPA than it does under LOPA. By employing QOPA at the physical layer and DOP-CAC at the link layer, our work suggested a high efficiency solution for QoS support of multimedia traffic under imperfect power control environment.

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