Power Multiplexing Based Call Admission Control Scheme for Bursty Multimedia Traffic in Imperfect-Power-Controlled Cellular CDMA Networks

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Abstract: A CAC algorithms (PM-CAC) is proposed and analyzed for multimedia cellular CDMA networks with imperfect power control and statistical power multiplexing among bursty traffics. Based on ON-OFF traffic model and lognormal interference model, we derive the traffic’s comprehensive outage probability, which is served as the metric of admission control. Two power allocation scheme, LOPA [1] and QOPA[2], are considered to study the performance of this CAC algorithms. By numerical examples, we verify the great capacity gains achieved by statistical power multiplexing and show that PM-CAC+QOPA provides superior system resource utilization to PM-CAC+LOPA in terms of lower call blocking probability and higher system throughput.

Key Words: CAC, multimedia CDMA, imperfect power control

1 Introduction

CDMA systems are characterized as the interference limited system and power control has been one of the most important techniques to reduce interference and enhance system capacity. In an ideal CDMA system, powers received at the base station are assumed to be kept at some desired levels to maximize system capacity. This is referred to as the perfect power control. However, in a practical CDMA system, the received signal is usually hard to be maintained at some fixed level because of the fading resulted by the movements of mobile users. This is generally called as imperfect power control.

Extensive studies have been conducted on the capacity issue of both the perfectly and imperfectly power controlled CDMA system. 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 [2] that it is optimal only under perfect power control environment. Under imperfect power control, in [2], we reconsidered the capacity optimization problem and derived the conditions that an optimal power allocation should satisfy. By using conservative bounds approximation, a closed form quasi-optimal solution is proposed to enhance the system capacity. We call it the quasi-optimal power allocation (QOPA) scheme. However, in the analysis of [2] all users are assumed to be active and the burst nature of traffic is ignored. In fact, in a CDMA system, when a traffic is inactive, no power should be assigned to its transmitter whether for the sake of power saving or reducing the multiple access interference (MAI). We refer it to as the power multiplexing in this paper.

The CAC problem were considered in [3] for voice users and in [4] for voice and data integrated CDMA systems. In [5], the authors proposed a framework of CAC for multimedia traffic in CDMA networks. However, perfect power control environment is assumed. In this paper, we consider the bursty nature of traffic in our capacity analysis and propose a power multiplexing CAC (PM-CAC) algorithm for bursty multimedia traffic in the imperfect-power-controlled CDMA networks. Based on the LOPA scheme and QOPA scheme, respectively, we further study the capacity gains of PM-CAC scheme by considering the power multiplexing feature of multimedia CDMA networks. We also compared the CAC performance between LOPA and QOPA scheme by numerical examples and demonstrate that, by combining with the QOPA scheme, PM-CAC algorithms is able to admit as many users as possible under imperfect power control environment while satisfying users’ diverse outage requirements.

The rest of this paper is organized as follows. We describe the system model in section 2. In section 3, we analyze the bursty traffic’s comprehensive outage probability. In section 4, we present the PM-CAC algorithms. In section 5, we study the capacity gains brought by power multiplexing and the performance
of PM-CAC+LOPA and PM-CAC+QOPA by numerical examples. We conclude our works in section 6.

2 Model Description

A. System Model and Traffic Model

We consider a single-cell multimedia DS-CDMA system. We only consider the uplink (from mobile to base) situation. The spread spectrum bandwidth is WHz, and we ignore the impact of background Additive White Gaussian Noise (AWGN) in our analysis.

There are $K$ classes of users in the system. The number of user class $i$ ($i = 1, \ldots, K$) traffic is $N_i$ and we define $(N_1, \ldots, N_K)$ as the network user configuration vector. We model the bursty nature of the traffic by ON-OFF sources. For class $i$ traffic, its ON and OFF periods follow exponential distributions with mean $\frac{1}{\alpha_i}$ and $\frac{1}{\beta_i}$, respectively. We define the active factor of class $i$ traffic as $\delta_i = \frac{b_i}{a_i + b_i}$. At an arbitrary time, denote the number of active users of class $i$ ($i = 1, \ldots, K$) traffic by random variables $n_i$. In addition, we define $(n_1, \ldots, n_k)$ as the network active user vector. The BS allocates powers to the mobile stations in a multiplexing manner: at each power control point, the BS only allocates transmission powers to those active mobile users (i.e., the users who are at ON period), no powers are allocated to the mobile users who are at OFF period. The QoS requirement of class $i$ user is represented by a triple $(R_i, \alpha_i, \delta_i)$, where $R_i$ is the user’s bit rate requirement at its ON period, and $\Pr\{E_b/I_0 < \alpha_i\} \leq \delta_i$, in which $E_b/I_0$ is the bit-energy-to-interference density ratio. We define the state that user’s $E_b/I_0$ goes below $\alpha_i$ as outage, at which the transmission may be shut down temporarily to save transmission powers. Thus $\delta_i$ is the largest outage probability that class $i$ user can tolerate. In general, different class of traffic requires different outage probability.

B. Signal and Interference Model

Let $S_{ij}$ be the received signal power of the $j$th ($j = 1, \ldots, N_i$) user in class $i$ ($i = 1, \ldots, K$) at the BS in cell 0 when it is active. According to the study in [6], under imperfect power control $S_{ij}$ is well approximated as a lognormal random variable with mean $u_{ij}$ and variance $\gamma_{ij}$. Let $X_{ij}$ be the decibel representation of $S_{ij}$, i.e. $X_{ij} = 10 \log_{10} S_{ij}$. Then $X_{ij}$ is a Gaussian random variable, whose mean $n_i$ and variance $\sigma_{ij}^2$ have the following relation with $u_{ij}$ and $\gamma_{ij}$:

$$u_{ij} = e^{3m_{ij} + \frac{1}{2} \beta^2 \sigma_{ij}^2},$$

$$\gamma_{ij} = e^{2m_{ij} + \beta^2 \sigma_{ij}^2}(e^{\beta^2 \sigma_{ij}^2} - 1),$$

where $\beta = \frac{\ln 10}{10}$. The parameter $\sigma_{ij}^2$ reflects the imperfection degree of the power control and is determined by the fading rate and the receiver structure[6]. For the purpose of tractability, we assume all users in cell 0 have similar mobility and the same receiver structure so that $\sigma_{ij}^2$ equals to $\sigma^2$ for all possible $i$ and $j$. This assumption justifies for the reason that the cell size of a multimedia CDMA system is small and the users’ mobility within a cell can be deemed to be homogeneous. By this assumption, the users in the same class have the same values of $u_{ij}$, $\gamma_{ij}$, $m_{ij}$, and $\sigma_{ij}^2$, and we denote them as $u_i$, $\gamma_i$, $m_i$, and $\sigma_i^2$. For a particular $i$, $S_{ij}$ ($j = 1, \ldots, N_i$) are modeled as independently and identically distributed (i.i.d.) lognormal random variables with mean $u_i$ and variance $\gamma_i$, as described above.

3 Outage Probability Analysis

A. Analysis of Active Network User Vector Distribution

We assume that whether a user is at its ON or OFF period is independent from the users belonging to different traffic classes, 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

$$\Pr\{n_1 n_2 \ldots n_K\} = \Pr\{n_1\} \Pr\{n_2\} \ldots \Pr\{n_K\}. \quad (3)$$

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 probability that at an arbitrary time there are $k$ active users of traffic class $i$ is given by

$$\Pr\{n_i = k\} = \frac{C_k^{n_i} \left( \frac{a_i}{b_i} \right)^k}{1 + \frac{a_i}{b_i}^{n_i}}, \quad (k = 0, 1, \ldots, N_i) \quad (4)$$

Thus the distribution of network active user vector is given by

$$\Pr\{n_1 \ldots n_K\} = \prod_{i=1}^{K} \frac{C_k^{n_i} \left( \frac{a_i}{b_i} \right)^{n_i}}{1 + \frac{a_i}{b_i}^{n_i}}. \quad (5)$$

B. Analysis of Comprehensive Outage Probability

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

$$P_i = \sum_{n_1=0}^{N_1} \ldots \sum_{n_K=0}^{N_K} \Pr\left\{ \left( \frac{E_b}{I_0} \right)_i < \alpha_i \right\} \Pr\{n_1 \ldots n_K\}. \quad (6)$$
At each power control point, the BS0 allocates powers to those active mobile users according to certain power allocation scheme. By “power allocation scheme”, we mean to the determination of the average received signal power vector \((u_1, \ldots, u_K)\) or equivalently its decibel representation \((m_1, \ldots, m_K)\) for the given active user vector \((n_1, \ldots, n_K)\). Generally speaking, this is a dynamic algorithms for the bursty traffics, which will be performed at each power control point. Two examples of such scheme are LOPA scheme proposed in [1], and QOPA scheme proposed in [2], both of which we will employ in our CAC scheme in this paper as the performance reference.

Given active user vector \((n_1, \ldots, n_K)\), denote by \(I\) the conditional total interference (we only account for the MAI and ignore the AWGN) received at BS0, i.e.,

\[
I = \sum_{j=1}^{n_1} S_{1j} + \ldots + \sum_{j=1}^{n_K} S_{Kj}.
\]  

(7)

Since \(I\) is a sum of independent lognormal random variables, it can also be approximated as a lognormal random variable[7], whose mean and variance are given respectively by

\[
E[I] = \sum_{i=1}^{K} n_i \beta_i, \quad \sigma^2 = \sum_{i=1}^{K} n_i \gamma_i.
\]  

(8)

(9)

Let \(Y = 10 \log I\). \(Y\) is also a Gaussian random variable. By Wilkinson’s method[7], its mean \(p\) and variance \(\eta^2\) are given respectively by

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

(10)

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

(11)

Under the condition of active user vector \((n_1, \ldots, n_K)\), for any active class \(i\) user in cell 0 with received power \(S_i\), its received \(E_b/I_0\) is given by

\[
\frac{E_b}{I_0} = \frac{3W}{2R_i} S_i(I - S_i),
\]

(12)

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

\[
\Pr \left\{ \left( \frac{E_b}{I_0} \right) \frac{n_1}{n} < \alpha_i \right\} = \Pr \left\{ \frac{3W}{2R_i} S_i < \alpha_i \right\},
\]

(13)

\[
= \Pr \left\{ S_i < \frac{I}{1 + \frac{3W}{2R_i}} \right\}.
\]

Let \(g_i = \frac{1}{1 + \frac{3W}{2R_i}}\) and \(A_i = 10 \log g_i\). By using the decibel representations of \(S_i\) and \(I\), the conditional probability of (13) is further rewritten as

\[
\Pr \left\{ \left( \frac{E_b}{I_0} \right) \frac{n_1}{n} < \alpha_i \right\} = \Pr \left\{ X_i < Y + A_i \right\}.
\]

(14)

Since \(X_i\) and \(Y\) are independent Gaussian random variables with mean \(m_i\) and \(p\), and variance \(\sigma^2\) and \(\eta^2\), respectively, the conditional outage probability is then given by

\[
\Pr \left\{ \left( \frac{E_b}{I_0} \right) \frac{n_1}{n} < \alpha_i \right\} = Q \left( \frac{m_i - A_i - p}{\sqrt{\sigma^2 + \eta^2}} \right),
\]

(15)

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

By (6)(5) and (15), the comprehensive outage probability of traffic class \(i\) is given by

\[
P_i = \sum_{n_{i_1} = 0}^{N_i} \ldots \sum_{n_{i_K} = 0}^{N_K} \left[ Q \left( \frac{m_i - A_i - p}{\sqrt{\sigma^2 + \eta^2}} \right) \prod_{j=1}^K C_{N_{i_j}}^n \left( \frac{g_{i_j}}{g_i} \right)^{n_{i_j}} \right].
\]

(16)

\section{4 Power Multiplexing Call Admission Control}

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 bandwidth, \(E_b/I_0\) requirement, outage requirement, and active factor \(\theta_i\). The parameters are derived from its traffic characteristics and QoS requirements. Then the following steps are performed to make an admission decision:

\subsection*{Step1} Update the network user configuration to \((N_1, \ldots, N_i + 1, \ldots, N_K)\).

\subsection*{Step2} Depending on the new network user configuration, for all the possible state of \((n_1, \ldots, n_K)\), compute the active network user distribution according to (5).

\subsection*{Step3} Depending on the new network user configuration, for all the possible state of \((n_1, \ldots, n_K)\), compute the conditional outage probability of each traffic class according to (15).

\subsection*{Step4} Compute the comprehensive outage probability of each traffic class according to (16). The admission controller checks whether the outage requirements of all traffic classes can be satisfied at the same time. If so, the incoming user is admitted; if not, the incoming user is refused.
An important feature of this CAC algorithms lies in that the comprehensive outage probability is power-allocation-scheme-dependent according to (16), thus the admission decision is also power-allocation-scheme-dependent. By (16), the particular power allocation scheme is easily embedded into the CAC procedure. In this paper, the LOPA scheme and the QOPA scheme are considered for the performance evaluation of the CAC algorithms. We should also note that according to (16), the ratios among allocated powers (or relative values in other words) sufficiently determine the comprehensive outage probabilities, thus the absolute values of allocated powers are unnecessary in outage probability computation. This is due to the ignorance of background AWGN. For the purpose of integrity, we outline the basic ideas of these two power allocation schemes below, where we ignore the effect of background AWGN:

**LOPA scheme[1]:** 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

$$g_i = \frac{1}{1 + \frac{3W}{2K_i^2}}. \quad (17)$$

**QOPA scheme[2]:** 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

$$g'_i = g_i \frac{\sqrt{\sum_i n_i^2}}{\eta_{min}} Q^{-1}(\delta_i), \quad (18)$$

where

$$\eta_{min} = \frac{1}{\beta^2} \ln \left[ 1 + \frac{C}{\sum_{i=1}^K n_i} \right], \quad (19)$$

and

$$C = e^{\beta^2}\sigma^2 - 1, \quad (20)$$

is a measure of control errors.

## 5 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 are $\theta_1 = 0.4$ 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 maximum number of admissible class 2 users under different active factors are plotted in Fig.2 for slow fading (user mobility is 5km/h). The results are computed according to (16) and the X-axis is the inverse of the active factor of type 2 user. The results of PM-CAC+LOPA and PM-CAC+QOPA are plotted in the same figure for comparison. The dash lines and the dot lines represent the $\frac{1}{3}$ times of the capacity when active factor is 1. It shows that great capacity gains are derived by the PM-CAC algorithms. However, different from the case of perfect power control, where a user active factor of $\theta_1$ will contribute $\frac{1}{\theta_1}$ times of capacity increase on this type of users [8], the slope of capacity gain does not reach $\frac{1}{\theta_1}$ 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 closed-form relation exists between the active factor and the capacity gains.

**B. Call Blocking Probability and System Throughput**

In this numerical example, we verify the system resource utilization resulted by PM-CAC+LOPA and PM-CAC+QOPA in terms of the call blocking probability and the system throughput.

In our simulation, we consider a multi-cell multimedia CDMA system with three classes of users, whose parameters 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 call blocking probability is defined as the ratio of total rejected call numbers to the total incoming call numbers. The system throughput is defined as the average total data volumes transmitted in one second by those active users. The assumed system spread spectrum bandwidth is 5MHz.

<table>
<thead>
<tr>
<th>Table 1: Parameters used in the simulation</th>
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<tr>
<td>class 1</td>
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<tr>
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<tr>
<td>$R_i(\text{kb/s})$</td>
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<tr>
<td>$\alpha_i$</td>
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<td>$\delta_i$</td>
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<tr>
<td>$\theta_i$</td>
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<tr>
<td>$\frac{1}{\mu_i}(s)$</td>
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The call blocking probabilities under PM-CAC+LOPA and PM-CAC+QOPA schemes are plotted as a function of the erlang load of class 1 traffic for slow fading in Fig.3. It shows that lower call blocking probability is derived by PM-CAC+QOPA scheme than that of PM-CAC+LOPA scheme.

The system throughput under PM-CAC+LOPA and PM-CAC+QOPA schemes are plotted as a func-
tion of the erlang load of class 1 traffic for slow fading in Fig.4. With the increase of traffic load, the system throughpout increases. It shows that the system throughput under PM-CAC+QOPA scheme is always higher than that of PM-CAC+LOPA scheme.

Figs.3-4 are consistent and indicate such a fact that under PM-CAC+QOPA scheme, fewer incoming calls are blocked thus more data volumes are transmitted, which means a higher utilization of system resource.

6 Conclusions

We have analyzed the comprehensive outage probability for bursty multimedia traffic in imperfect-power-controlled cellular CDMA networks employing power multiplexing technique. Based on the analysis, we have proposed a Power Multiplexing Call Admission Control (PM-CAC) algorithms for bursty multimedia traffics under imperfect power control. By numerical example, its validity and efficiency are verified.

References


