QoS Guarantee and Power Distribution for Soft Handoff Connections in Cellular CDMA Downlinks

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***Abstract*— A two-phase power distribution scheme for supporting quality-of-service (QoS) and best effort traffic is proposed. We first formulate the power distribution for QoS traffic as an optimization problem so that the number of simultaneously transmitting connections is maximized. Optimum power distribution is difficult to implement in practice due to both the computational complexity and the requirement for global information about the mobile station (MS) locations, connection channel conditions, and traffic load in the system. We then propose a heuristic scheme of power distribution for soft handoff (SHO) connections. The full scheme includes an initial power distribution (IPD) and a power distribution adjustment (PDA). IPD allocates BS power resource based on the channel condition of each individual connection, while PDA further coordinates the power distribution between neighboring base stations (BSs) in order to accommodate more connections. The proposed power distribution scheme can achieve a capacity close to that of the optimum power distribution, while providing much higher transmission throughput for best effort data traffic. The proposed power distribution scheme can be applied to existing SHO schemes for efficient BS power resource usage. The scheme does not require global information, and its implementation can be further simplified by performing IPD only with slight performance degradation.**

***Index Terms*— Cellular CDMA, soft handoff, power distribution, quality of service, optimization.**

I. Introduction

As the wireless access to the Internet becomes increasingly popular, the downlink may have to transport a lot more traffic than ever before. In a CDMA system where the available radio spectrum is shared by all active users, appropriate power distribution is critical in order to provide satisfactory quality-of-service (QoS) for more mobile users. In the downlink transmissions, each connection needs a sufficient amount of power to overcome the interference from the transmissions of the base stations (BSs) for all other connections sharing the same system. A higher level transmission power is required for a connection having higher transmission rate and signal-to-interference ratio (SIR) requirements. A connection in deep fading may also consume more power resources. Given the instant packet transmission rate for all the active connections, appropriately distributing the transmission power for each connection from the BS may simultaneously guarantee the required SIR for all the connections, if the traffic load is smaller than the system capacity. Because all the connections share the limited BS transmission power, it is important to distribute only a minimum amount of power for each connection, so that more simultaneous connections can coexist in the system.

Soft handoff (SHO) is an inherent property of CDMA. We define an active set of a mobile station (MS) as a set of BSs with which the MS keeps active communication. In the downlink, an MS in SHO receives signals from multiple BSs in its active set and combines the received signals. There has been a lot of efforts in selecting the BSs involved in the SHO process of a connection. Generally, a BS is added to or removed from an active set of an MS according to the received pilot signal strength from the BS and the current active set size.

Soft handoff makes a connection smoother when the MS crosses cell boundaries or experiences channel fading by allowing the MS to simultaneously communicate with more than one BS. The gain in macroscopic diversity obtained by combining the received signals from multiple BSs may compensate for some effect of random channel fading and improve communication quality or save BS power resource. On the other hand, in the downlink transmissions, a connection in SHO requires transmission power from multiple BSs, which may reduce system capacity since otherwise there is only one BS transmits to the connection. There is a limitation on the maximum number of BSs in an active set.

IS-95A [2] is the first CDMA technology for cellular systems. The SHO base station selection scheme in IS-95A, referred to as the IS95A-SHO scheme in this paper, is based on static thresholds. When the received pilot signal strength from a BS at an MS is above a threshold (T_ADD) and the active set of the MS is not full (number of the BSs in the active set is less than the maximum value), the BS is added to the active set of the MS, while the BS is removed from the active set if the received pilot signal strength from it at the MS falls below another threshold (T_DROP), where T_DROP<T_ADD. This pilot-strength based handoff scheme is simple, and ensures that all BSs with reasonable pilot signal strength are added to the active set without delay.

The SHO BS selection scheme in IS-95B/CDMA 2000 [3], referred to as the IS95B-SHO scheme, is also based on thresholds, but has more parameters in order to incorporate QoS and avoid unnecessary legs[1]. The thresholds for adding

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[1]The term “leg” is used here to denote a communications link between the MS and a BS.

a BS to and dropping a BS from an active set are calculated dynamically based on aggregate SIR of all active-set legs. In the IS95B-SHO scheme, T_ADD and T_DROP are defined as follows:

$$\text{T\_ADD} = \max\left\{\frac{\text{Soft\_Slope}}{8} \times 10\log\sum_{j=1}^{N_a}\text{SIR}_j + \frac{\text{Add\_Intercept}}{2}, T_1\right\} \quad (1)$$

and

$$\text{T\_DROP} = \max\left\{\frac{\text{Soft\_Slope}}{8} \times 10\log\sum_{j=1}^{N_a}\text{SIR}_j + \frac{\text{Drop\_Intercept}}{2}, T_2\right\} \quad (2)$$

where Soft_Slope, Add_Intercept, and Drop_Intercept are all design parameters, T_1 and T_2 are bounds for adding or dropping a BS, SIR_j is the received SIR from BS j, N_a is the total number of BSs in the active set. A BS is added to the active set if the received pilot signal strength is above T_ADD, while it is removed from the active set if the pilot signal strength from the BS at the MS is below T_DROP for a certain time period.

The UMTS [4] systems have dynamic thresholds for selecting BSs in an active set based on the best pilot signal strength. BS b is added into the active set of a connection if

$$\text{Pilot}_b > \max_{\text{All } c \text{ in active set}}\{\text{Pilot}_c\} - \text{As\_Th} + \text{As\_Th\_Hys}, \quad (3)$$

for a period of time, and BS b in the active set will be removed from the active set if

$$\text{Pilot}_b < \max_{\text{All } c \text{ in active set}}\{\text{Pilot}_c\} - \text{As\_Th} - \text{As\_Th\_Hys} \quad (4)$$

for a period of time, where Pilot_b is the received pilot signal strength at the MS from BS b, both As_Th and As_Th_Hys are design parameters. We refer the SHO BS selection scheme in the UMTS systems as the UMTS-SHO scheme.

In the UMTS-SHO scheme, a BS currently not in the active set may replace a BS in the active set if a certain condition is satisfied. Because of the dynamic property in selecting BSs in the active set, both the IS95B-SHO and UMTS-SHO schemes may result in frequent BS updates in the active set. Both the IS95B-SHO and UMTS-SHO handoff schemes involve timers to make the membership changes in the active set less frequent.

There has been extensive research on the effect of the active set size, threshold values and other parameters in SHO on the system performance. In [18], SHO thresholds are dynamically changed to control the power resource usage and communication quality. In [20] both T_ADD and T_DROP vary dynamically based on the traffic density. These thresholds, together with the maximum size limitation on an active set, control the number of BSs in the active set. The active set size, or the number of BSs involved in SHO of a connection, may affect the system performance. Intuitively, having more BSs in the active set of a connection improves the macro-diversity of the connection and can improve the communication quality, whereas this may reduce the system capacity since a connection in SHO may require transmission power from multiple BSs. In [19], effect of the active BS set size and some other parameters in selecting BSs for the active set on the system performance is studied. In [17] a locally optimal handoff algorithm is derived to approximate the optimal tradeoff between the rate of handoffs, active set size and link quality. In site selection diversity transmission (SSDT) [21] a connection is always served by the BS with the minimum path loss in the active set in order to reduce interference from transmissions of multiple BSs and improve the system capacity. In [12], [13] [14] and [16], soft handoff can only be performed when an MS enters a geographical soft handoff area, which is a distance based one.

Conventionally, transmission power control commands are transmitted from the MS to the BSs in the active set and the same power correction is applied on all links without taking into account the different link conditions to each of the BSs. Based on this, most of the current work on SHO assumes that multiple BSs in an active set of an MS transmit simultaneously with the same power to the MS. This simple power distribution scheme is referred to as equal power distribution (EPD), which may result in some contradictory effects on the system capacity, and there may be a significant capacity reduction as shown in [12]-[14] [16]. The reason is that the transmission power for a connection in soft handoff from each BS is not appropriately distributed, and a connection in soft handoff may require much more total power resource than that in the hard handoff. Blaise *et al.* in [1] propose to separately control the transmission power from multiple BSs to a SHO connection. Communication quality (e.g., outage probability) and system capacity can be improved if transmission powers for a SHO connection can be appropriately distributed among the BSs in the active set of the connection. Our previous research [15] has shown that by an appropriate power distribution, performing soft handoff can greatly improve the connection reliability and system capacity. An appropriate power distribution should provide users with satisfactory QoS, while efficiently utilizing the available BS power resources. Although power distribution in the downlink transmissions of cellular CDMA has been studied extensively based on hard handoff [6]-[11], effective and efficient power distribution for SHO connections is still a challenging issue due to the coordinations among neighboring BSs.

In this paper, we are concerned with QoS provisioning and power distribution for SHO connections in cellular CDMA downlinks. Both QoS traffic and best effort traffic are considered. Power resources after serving the QoS traffic are used for best effort data transmissions. We first formulate the power distribution for QoS traffic as an optimization problem so that with an optimum power distribution of the BSs, the number of simultaneously transmitting connections with guaranteed QoS is maximized. The computational complexity to solve the optimization problem increases significantly as the number of BSs and MSs increases. Optimum power distribution is difficult to implement in practice because of the computational complexity and the requirement of global information about the MS locations, connection channel conditions, and traffic load in the system. We then propose a less complex heuristic power distribution scheme. The full scheme includes an initial power distribution (IPD) and a power distribution adjustment (PDA). The IPD allocates BS power resource based on the channel condition of each individual connection, while the PDA further coordinates the power distribution between neighboring BSs in order to accommodate more connections. The proposed power distribution scheme can be applied to existing SHO schemes for more efficient BS transmission power distribution. Compared with the optimum power distribution, the proposed scheme simplifies the implementation of power distribution without significant performance degradation.

The remainder of the paper is organized as follows. Section II defines the system model. In Section III the power distribution for soft handoff connections in the cellular CDMA downlink is formulated as an optimization problem and solved approximately. Section IV describes the proposed power distribution scheme. Transmission scheduling for best effort data traffic is presented in Section V. Numerical results are shown in Section VI to demonstrate the performance of communication outage of the QoS traffic and transmission throughput of the best effort data traffic. Section VII concludes the paper.

II. System Model

We consider a cellular CDMA system configuration with a hexagonal layout. The coverage area of the system is divided into small cells. There is one BS located at the center of each cell. All BSs are connected to a mobile switching center (MSC) which monitors the traffic to and from the BSs and provides control for the BSs. We consider a frequency-division-duplexing (FDD) based system, where different frequency bands are used for uplink and downlink transmissions. Therefore, there is no interference between the uplink and downlink transmissions.

In the downlink transmissions, each MS receives desired signals from its serving BS, and interference power from other BSs as well as that from its own BS. Orthogonal codes used in the downlink can reduce interference between signals intended for different mobiles in the same cell. However, orthogonality may not be perfectly maintained because channel impairments tend to perturb the orthogonal condition. Let η be the orthogonality factor used to characterize this interference effect among the users within a cell. $\eta = 0$ signifies perfect orthogonality, and $\eta = 1$ signifies that power from all other users in the cell contributes to the interference on the tagged user.

The propagation channel is characterized by path loss and independent log-normal shadowing. The link gain, a_{ib}, between the ith MS and BS b is given by

$$a_{ib} = \left(\frac{d_{ib}}{d_0}\right)^{-\alpha} e^{-\beta X_{ib}}, \tag{5}$$

where d_{ib} is the distance between the MS and the BS, $\beta = \ln 10/10$ is a constant, d_0 is the close-in reference distance which is determined from measurements close to the BS transmitter [25], and α is the path loss exponent. Typical values of α, usually obtained through measurement, are between 2 and 5 for cellular communications. X_{ib} is a Gaussian distributed random variable representing the channel fading of connection i due to shadowing in cell b. X_{ib} has a zero mean and variance σ_X^2. We assume that the shadowing effects in different cells are independent and identically distributed.

Channel time is divided into equal length slots, each long enough to transmit one packet. Packet transmission takes place at the beginning of each slot. Each connection has a QoS requirement, which includes a minimum transmission rate, R^*, and an SIR threshold, γ^*. The minimum SIR requirement corresponds to the maximum tolerable transmission bit-error-rate (BER) for given modulation and coding schemes. Our proposed power distribution scheme is also applicable for connections with different QoS requirements. The assumption of homogeneous QoS requirement is for emphasizing the effect of the power distribution on the system capacity. An MS may carry both QoS and best effort traffic. If there are power resources available at the BS after serving the QoS traffic, a higher rate for the best-effort traffic may be transmitted for the MSs. In order to achieve high packet transmission rate for the best-effort traffic, each BS always transmits at the maximum power. Dynamically adjusting the BS transmission power may also be possible, but may significantly increase the complexity of power distribution in order to both support QoS traffic and achieve high throughput for best effort data traffic. An iterative scheme for dynamically adjusting BS transmission power for supporting QoS traffic only is studied in [5].

Closed loop power control in the downlink can track and compensate for the effect of slow channel fading by adjusting the transmission power for each connection. We assume that the channel condition changes relatively slowly, so that it can be approximated as stationary during one packet transmission slot. We assume that a suitable closed-loop power control scheme is available. Fast fading is not explicitly considered in this work, and we assume that the effect of fast fading can be ideally overcome by a well-designed receiver. Each BS has a maximum transmission power limit, P_b^m, where b is the BS index. In the downlink, every BS transmits a cell specific pilot signal at a constant power, P^p. Let $p = P^p/P_b^m$. An amount of the power, $(1-p)P_b^m$, is shared by all active users associated with the BS for data packet transmissions, including both QoS traffic and best effort traffic. When the total amount of transmission power for the QoS raffic is less than $(1-p)P_b^m$, power resource at BS b is still available for best effort data transmission.

An MS listens to the pilot channels of the neighboring BSs to facilitate the making of handoff decisions. BSs are added to or removed from the active set of a connection according to specific SHO schemes, such as IS95A-SHO, IS95B-SHO or UMTS-SHO. In this paper, we assume that only two BSs can provide transmissions for a connection in soft handoff, i.e., the maximum size of the active set is 2. We define a SHO association matrix $\mathbf{S} = (S_{ib})$, for $i = 1, 2, \ldots, M$ and $b = 0, 1, \ldots, B$, where M and $B+1$, respectively, are the number of MSs and BSs in the system. When BS b is in the active set of MS i based on a specific SHO scheme, $S_{ib} = 1$; otherwise, $S_{ib} = 0$.

The MS tunes two fingers of its Rake receiver to receive signals from the two BSs in the active set. The Rake receiver in the MS processes the received signals from different BSs by using maximum ratio combining [23]. Our proposed power distribution scheme is not restricted to a particular SHO scheme, but focuses on an effective and efficient power distribution of the BSs for SHO connections. Transmission powers from the BSs to the MSs in SHO should be allocated to best impact on the system capacity. Guaranteed QoS should be provided for more QoS connections, while leaving more power for best effort data packet transmissions.

In the remaining part of the paper, we assume that the active set for each MS to perform SHO BS selection already exists, and focus on calculating the transmission power from each BS in the active set to the MS. An existing SHO scheme, such as IS95A-SHO, IS95B-SHO or UMTS-SHO, may use a different strategy for distribution of the BS transmission power.

III. Optimum Power Distribution for QoS Provisioning

Consider connection i carried by MS i, and let b be a BS in the active set of MS i, i.e., $S_{ib} = 1$. Let P_{ib} be the transmission power from BS b for the connection. We then normalize the transmission power for the connection with respect to the maximum transmission power of the BS as $f_{ib} = \frac{P_{ib}}{P_b^m}$.

Consider the signal transmission from BS b to MS i. The interference experienced by a packet for the connection at the MS receiver input is

$$\eta(P_b^m - f_{ib}P_b^m)a_{ib} + \textstyle\sum_{b' \neq b} P_{b'}^m a_{ib'}. \qquad (6)$$

The actual SIR at the receiver despread output of MS i is given by

$$\begin{aligned}\gamma_{ib} &= \frac{f_{ib}P_b^m a_{ib} G_i}{\eta(P_b^m - f_{ib}P_b^m)a_{ib} + \sum_{b' \neq b} P_{b'}^m a_{ib'}} \\ &= \frac{f_{ib}G_i}{\eta(1 - f_{ib}) + Z_{ib}},\end{aligned} \qquad (7)$$

where $G_i = W/R_i$ is the spread spectrum processing gain, W is the spread spectrum bandwidth, R_i is the transmission rate of the connection, and Z_{ib} is given by

$$Z_{ib} = \textstyle\sum_{b' \neq b} \frac{P_{b'}^m a_{ib'}}{P_b^m a_{ib}}. \qquad (8)$$

The values of Z_{ib} can be calculated at the MS based on the measurement of the link gains to different BSs. The link gains are obtained by measuring the received pilot signal strength from different BSs at the MS.

When a connection receives power from the two BSs in the active set simultaneously, the Rake receiver at the MS combines the received signals using maximum ratio combining. Therefore, the actual SIR at the MS receiver output is a sum of the output SIR values for each of the received signals [23] and is given by

$$\gamma_i = \sum_{b, S_{ib}=1} \gamma_{ib}, \qquad (9)$$

where γ_{ib} is the SIR for the signal branch received from BS b. We consider that with power control $\gamma_i = \gamma^*$ can be ideally achieved for the connection in order to guarantee its required QoS. The solution for f_{ib} in order to achieve $\gamma_i = \gamma^*$ may not be unique, and we assume that there is at least one feasible solution, or communication outage occurs to the connection. Let $\gamma_{ib} = \xi_{ib}\gamma^*$, where $\xi_{ib} \in [0, 1]$ is a parameter used to adjust the power distribution for the connection between the two BSs involved in the SHO of the connection. Then $\gamma_i = \sum_{b, S_{ib}=1} \gamma_{ib} = \gamma^*$ is equivalent to

$$\textstyle\sum_{b, S_{ib}=1} \xi_{ib} = 1 \qquad (10)$$

in order to support the connection with guaranteed SIR. We refer to $\xi = [\xi_{ib}]$ as the power distribution association matrix, where $i = 1, \ldots, M$ and $b = 0, 1, \ldots, B$. When $\xi_{ib} = 1$, the MS receives from BS b only and no power is transmitted to the connection from other BSs; when $0 < \xi_{ib} < 1$, both the BSs involved in the soft handoff process of the connection should transmit to the MS and jointly support the QoS of the connection. $\xi_{ib'} = 0$ for BS b' not in the active set of connection i. Then (7) can be rewritten as

$$\frac{f_{ib}W/R_i}{\eta(1 - f_{ib}) + Z_{ib}} = \xi_{ib}\gamma^*, \qquad (11)$$

for BS b in the active set of connection i.

We then consider the power distribution for the QoS traffic and let $R_i = R^*$. Power distribution for supporting a higher rate than R^* is discussed later. Consider connection i and BS b in the active set of i and let $f_{ib}^* P_b^m$ denote the required transmission power from BS b for connection i in order to support the QoS of the connection. Then f_{ib}^* can be found from (11) as

$$f_{ib}^* = f_{ib}|_{R_i = R^*} = \frac{\eta + Z_{ib}}{W/(\xi_{ib}\gamma^* R^*) + \eta}, \qquad (12)$$

for $0 < \xi_{ib} \leq 1$, $b = 0, 1, \ldots, B$, and $i = 1, 2, \ldots, M$. Note that $f_{ib}^* = 0$ if $\xi_{ib} = 0$.

Rewriting (12) as follows

$$f_{ib}^* = \frac{(\eta + Z_{ib})\xi_{ib}}{W/(\gamma^* R^*) + \eta\xi_{ib}}. \qquad (13)$$

The value of $W/(\gamma^* R^*)$ represents the capacity of a CDMA system with homogeneous traffic (each connection requiring a transmission rate R^* and an SIR requirement γ^*) in a single cell without co-channel interference, and both η and ξ_{ib} are between 0 and 1. Therefore, for a system with reasonable capacity, $W/(R^*\gamma^*) \gg 1 > \eta\xi_{ib}$. For example, for a system with $W = 5$ MHz and a connection with transmission rate $R^* = 64$kbps and a minimum SIR requirement $\gamma^* = 7$dB, $W/(R^*\gamma^*) = 15.6$. Therefore, f_{ib}^* can be well approximated as

$$f_{ib}^* \approx \frac{(\eta + Z_{ib})\xi_{ib}}{W/(\gamma^* R^*)} = \frac{(\eta + Z_{ib})\gamma^* R^*}{W}\xi_{ib}. \qquad (14)$$

Assume there exists a power distribution scheme (or matrix ξ is given) and let $f_b^t P_b^m$ be the total amount of required power resources from BS b with the scheme in order to support all the QoS traffic. Then

$$f_b^t = \textstyle\sum_{i, S_{ib}=1} f_{ib}^*, \qquad (15)$$

for $b = 0, 1, \ldots, B$. If $f_b^t > 1 - p$, BS b does not have sufficient power resource to support all the connections with guaranteed QoS. In this case, a certain number of connections has to be removed temporarily in the current packet transmission slot so that all the remaining connections can receive guaranteed QoS. The connections that are removed experience temporary communication outage. Define χ_i as a two value variable, with $\chi_i = 1$ if a packet transmitted for connection i can be served with guaranteed QoS at a particular packet transmission slot and $\chi_i = 0$ otherwise. Then the probability of communication outage is defined as the probability that $\chi_i = 0$. We assume that communication outage is uniformly distributed among all connections, so that the long term time average of $1 - \sum_{i=1}^{M} \chi_i / M$ is equal to the average outage probability for each connection. For a given number of connections, the objective of the power distribution in each packet transmission slot is to find the optimum power distribution association matrix ξ, so that guaranteed QoS can be provided to the QoS traffic, while the transmission outage probability can be minimized. The power distribution in each packet transmission slot is to minimize the number of connections with $\chi_i = 0$. This can be formulated as the following optimization problem:

$$\min_{\xi} \left(1 - \frac{\sum_{i=1}^{M} \chi_i}{M}\right) \quad (16)$$

$$s.t. \quad f_b^t = \sum_{i,S_{ib}=1} f_{ib}^* \leq 1 - p, \quad b = 0, 1, \ldots, B \quad (17)$$

$$0 \leq \xi_{ib} \leq 1, \quad i = 1, 2, \ldots, M, \quad b = 0, 1, \ldots, B \quad (18)$$

$$\sum_{b,S_{ib}=1} \xi_{ib} - \chi_i = 0, \quad i = 1, 2, \ldots, M \quad (19)$$

$$\chi_i = 0 \text{ or } 1, \quad i = 1, 2, \ldots, M \quad (20)$$

where $\chi = [\chi_i]$, $i = 1, 2, \ldots, M$ is a vector, and f_{ib}^* is given by (12). In the above optimization problem, (19) and (20) together indicate that if a connection can receive a guaranteed QoS, then all BSs involved in the SHO process of the connection provide the required SIR, i.e., $\sum_{b,S_{ib}=1} \xi_{ib} = \chi_i = 1$; otherwise, $\sum_{b,S_{ib}=1} \xi_{ib} = \chi_i = 0$, and no BS allocates power for the connection. The above problem is a mixed integer (χ_i) and nonlinear optimization problem (condition (17) is nonlinear) which is difficult to solve. Substituting f_{ib}^* in (17) with the approximate expression in (14), we can approximate condition (17) by the following condition

$$\sum_i \frac{(\eta + Z_{ib})\gamma^* R^*}{W} S_{ib} \xi_{ib} \leq 1 - p, \quad b = 0, 1, \ldots, B. \quad (21)$$

Then the mixed integer and non-linear optimization problem is approximated as a mixed integer and linear optimization problem and can be solved using software packages such as MOSEK [26] or CPLEX [27]. To simplify the presentation, power distribution for SHO connections based on approximately solving the optimization problem (16) is referred to as OPD.

The above OPD can be implemented at the MSC, which generally has high computation power and is responsible for a relatively large number of BSs, with the assistance from the MSs through the BSs. Specifically, each MS i measures the received signal strength, calculates the Z_{ib} values (for all BS b in the active set of MS i) and reports them to the MSC through its currently serving BS(s). The MSC performs the optimization and finds ξ_{ib} for all i and b and informs each BS in the active set of the ξ_{ib} values. The BSs then adjust their power distributions accordingly. As the number of BSs and active connections increases, the computational complexity to implement the optimum power distribution increases significantly, and the time for collecting the global information from the MSs through the BSs to the MSC also increases. We then propose a heuristic scheme for power distribution which does not require global information but provides system performance (communication outage and system capacity) very close to the optimum solution.

IV. Proposed Power Distribution Scheme

In this section, we propose a heuristic power distribution scheme for implementation in the BSs. The scheme includes an initial power distribution (IPD), which allocates a minimum amount of power for each individual connection and can be performed at each BS independently. Then a power distribution adjustment (PDA) scheme is performed in order to coordinate the power distribution between neighboring BSs so that more simultaneous transmissions can be supported. IPD can be done at each BS distributively with an assistance from the MSs, and is independent of the power distribution at other BSs. PDA requires information exchanges between neighboring BSs.

A. Initial power distribution (IPD)

Consider connection i, and b is the BS involved in the SHO process of the connection, i.e., $S_{ib} = 1$. Let $\xi_{ib}\gamma^*$ be the SIR for the received signal branch from BS b, and $\sum_{b,S_{ib}=1} \xi_{ib} = 1$ if the connection can be supported with guaranteed QoS. The total amount of power resources required by the connection is $\sum_{b,S_{ib}=1} f_{ib}^* P_b^m$. If this value can be minimized, every connection requires a minimum amount of power resources, and the number of simultaneously supported connections can be maximized for given values of S_{ib}. Based on this discussion, we first minimize the total amount of required power resources for each individual connection:

$$\min_{\xi_i} \sum_{b,S_{ib}=1} f_{ib}^* = \min_{\xi_i} \sum_{b,S_{ib}=1} (\eta + Z_{ib}) \xi_{ib} \gamma^* R^* / W, \quad (22)$$

where $\xi_i = [\xi_{ib}]$ is a vector for all b with $S_{ib} = 1$. Since f_{ib}^* is a monotonically increasing function of Z_{ib}, (22) can be easily written as

$$\min_{\xi_i} \sum_{b,S_{ib}=1} f_{ib}^* = (\eta + Z_{ib_i^*}) \gamma^* R^* / W, \quad (23)$$

when $\xi_{ib_i^*} = 1$ and $\xi_{ib'} = 0$ for all $b' \neq b_i^*$, where b_i^* is referred to as the primary BS of MS i and is given by

$$b_i^* = \text{argmin}_{b,S_{ib}=1} \{Z_{ib}\}. \quad (24)$$

The above result indicates that Z_{ib} can be considered as an indication of the channel condition between MS i and BS b, and the primary BS is the BS that the MS has the best channel condition. In order to minimize the total amount of required power resources for each individual connection, the system should always assign the primary BS to the connection.

Based on the above minimum-power distribution for each individual connection, an initial power distribution (IPD) scheme can be developed as follows.

(1) MS i calculates the values of Z_{ib} for all b in its active set, where $i = 1, 2, \ldots, M$.

(2) MS i finds its primary BS, b_i^*, according to (24) and notifies BS b_i^* that the BS is its primary BS. MS i also notifies each BS in its active set of the corresponding Z_{ib} values.

(3) BS b_i^* sets $\xi_{ib_i^*} = 1$ and calculates the amount of required transmission power $f_{ib_i^*}^* P_{b_i^*}^m$ for connection i.

(4) Each BS calculates the total amount of required transmission power for the QoS traffic as

$$f_b^t = \sum_{i,S_{ib}=1,\xi_{ib}=1} f_{ib}^*. \quad (25)$$

Note that $f_{ib}^* = 0$ in (25) if $b \neq b_i^*$.

The above power distribution based on the minimum power distribution for individual connections cannot guarantee that the amount of the required power resource is always available at the BS for all connections. Because of the random channel fading and MS movement, channel conditions and the amount of the required power resources for each connection may change from time to time. The number of the connections associated to each BS may also change with time. Therefore, f_b^t is a random variable. After performing Steps (1)-(4) of IPD, if $f_b^t > 1-p$, the total amount of required power resources from BS b is more than the total available power resources. In this case, one solution is to temporarily remove a certain number of connections in the current scheduled time slot, so that all the remaining connections can transmit packets with guaranteed QoS. Generally, an optimum connection removal process that can both maximize the power resource utilization and accommodate more connections is NP-complete. We will propose one with relatively low complexity. In order to minimize the number of removed connections, a connection that requires the highest amount of transmission power from BS b is first removed from service. The following procedures follow Step (4) in IPD and are performed independently at each BS.

(5) If $f_b^t > 1-p$, BS b finds connection k, so that $k = \mathrm{argmax}_{i,S_{ib}=1,\xi_{ib}=1}\{f_{ib}^*\}$, and removes connection k from service, i.e., $\xi_{kb}=0$, and $f_{kb}^*=0$.

(6) BS b recalculates f_b^t as $f_b^t = \sum_{i,S_{ib}=1,\xi_{ib}=1} f_{ib}^*$. If $f_b^t \leq 1-p$, IPD for QoS traffic is done at BS b; otherwise, the process is repeated until $f_b^t \leq 1-p$.

B. Power distribution adjustment (PDA)

The following procedures are optional depending upon the BS processing capability and QoS requirement. Note that it is possible that the values of f_b^t are different for neighboring BSs because of unbalanced traffic loads. Besides, even for a system with uniformly distributed traffic load on average, the traffic loads in different cells may not be exactly the same at any packet transmission slot due to the random channel conditions and user movement patterns. In this case, neighboring BSs can exchange information about the power resource availability and coordinate the power distributions, i.e., perform power distribution adjustment (PDA), so that a removed connection in IPD from one BS may be supported through a neighboring BS or multiple neighboring BSs in the active set of the connection can jointly support the connection.

After connection k is removed in Step (5) when performing IPD, neighboring BSs may coordinate and adjust their power distribution as follows. If $f_b^t < 1-p$, an amount of power $[(1-p) - f_b^t]P_b^m$ is still available to partially serve the QoS traffic of connection k. Let $f_{kb}^* = (1-p) - f_b^t$. The SIR that this remaining power can provide for connection k is calculated from (11) as

$$\gamma_{kb} = \frac{f_{kb}^* W}{R^*\left[\eta(1-f_{kb}^*) + Z_{kb}\right]}. \tag{26}$$

Let BS b_1 be the other BS in the active set of the connection, i.e., $S_{kb_1}=1$ and $b_1 \neq b$. Then in order for BSs b and b_1 to jointly support the QoS of connection k, the SIR that BS b_1 should provide for the connection is

$$\gamma_{kb_1} = \gamma^* - \gamma_{kb}. \tag{27}$$

The amount of power resource required from BS b_1 in order to achieve this SIR is $f_{kb_1}^* P_{b_1}^m$, where $f_{kb_1}^*$ can be calculated as

$$f_{kb_1}^* = \frac{\eta + Z_{kb_1}}{W/(R^*\gamma_{kb_1}) + \eta}. \tag{28}$$

If $f_b^t < 1-p$ after performing Step (5), PDA is performed as follows:

5.1 BS b notifies BS b_1 of γ_{kb_1}, which is calculated using (26) and (27).

5.2 BS b_1 calculates $f_{kb_1}^*$ using (28).

5.3 If $f_{b_1}^t + f_{kb_1}^* \leq 1-p$, then connection k can be supported by the system, BS b_1 updates $f_{b_1}^t = f_{b_1}^t + f_{kb_1}^*$ and notifies BS b which updates $f_b^t = 1-p$; Otherwise, BS b_1 updates $\xi_{kb_1}=0$ and $f_{ib_1}^*=0$, and notifies BS b which updates $\xi_{ib}=0$ and $f_{kb}^*=0$.

The PDA process requires information exchanges between immediate neighboring BSs. Whether or not to perform these procedures for each removed connection in IPD may depend on the practical BS processing capability and QoS/capacity requirements of the system. According to the IPD and PDA processes, $\chi_i = 1$ for all connections that can be served with guaranteed QoS, and $\chi_i = 0$ otherwise, where χ_i is defined in (19).

After performing IPD and PDA, the associations between connection i with $\chi_i = 1$ and BS b in the active set of the connection may fall in one of the following categories:

(a) $\xi_{ib}=1$, and $b=b_i^*$. In this case, the connection is served by its primary BS.

(b) $\xi_{ib}=1$, and $b \neq b_i^*$.

(c) $0 < \xi_{ib} < 1$.

This PDA scheme for power distribution does not necessarily save the total required power resources. However, it provides possibilities that connections can make use of the instantaneous unbalanced traffic loads in neighboring cells and receive their required QoS. The effects of this adjustment on the system capacity and the power resource distribution will be demonstrated in Section VI.

V. Power Distribution for Best Effort Traffic

After performing IPD and PDA (if necessary), the power distribution association relationships between the connections and the BSs have been determined, i.e., matrix ξ has been determined. After serving the guaranteed QoS traffic, the amount of the remaining power available at BS b for best effort traffic is $(1-p-f_b^t)P_b^m$. The objective of the power distribution for best effort traffic is to maximize the total packet transmission rate, subject to the QoS guarantee and the BS transmission power limit. This can be formulated as the following optimization problem:

$$\begin{cases} & \max\limits_{\mathbf{R}} \sum_{i=1}^{M} R_i\chi_i, \\ \text{s.t.} & R_i \geq R^* \ \text{ for } \chi_i = 1, \quad i=1,2,\ldots,M, \\ \text{and} & \sum_{i,S_{ib}=1} f_{ib} = 1-p, \quad b=0,1,\ldots,B, \end{cases} \tag{29}$$

where $\mathbf{R} = [R_i]$ is a vector, R_i is the actual packet transmission rate for MS i, f_{ib} is the required transmission power from

BS b in order to support R_i for MS i with ξ_{ib} calculated from the IPD or PDA (if it is performed). Then $R_i - R^*$ (≥ 0) is the best effort transmission rate for MS i with $\chi_i = 1$. It can be easily seen that maximizing the total packet transmission rate for the entire system is equivalent to maximizing the total transmission rate for MSs associated with each BS.

Consider connection i with $0 < \xi_{ib} < 1$. The connection is jointly supported by the two BSs in the active set of the connection. According to the PDA process, at least one of the two BSs has no power remaining after serving all the guaranteed QoS traffic. In this case, the MS cannot transmit at any rate higher than R^*. Therefore, maximizing the total transmission rate for all connections associated with BS b is equivalent to maximizing the total transmission rate for the connections with $\xi_{ib} = 1$. Then the above optimization problem can be rewritten as

$$\begin{cases} & \max\limits_{\mathbf{R}} \sum_{i,\xi_{ib}=1}(R_i - R^*), \qquad b = 0,1,\ldots,B, \\ \text{s.t.} & R_i - R^* \geq 0 \ \text{ for } \ \xi_{ib} = 1, \quad i = 1,2,\ldots,M, \\ \text{and} & \sum_{i,S_{ib}=1} f_{ib} = 1 - p, \qquad b = 0,1,\ldots,B. \end{cases} \tag{30}$$

It can be seen from (11) that with the same amount of power available, a connection with a smaller value of Z_{ib} can transmit at a higher rate. The BS should transmit in the connection with the smallest Z_{ib} in order to achieve a high packet transmission rate. Based on this observation, BS b chooses connection k, so that

$$k = \mathrm{argmin}_{i,\xi_{ib}=1}\{Z_{ib}\}, \tag{31}$$

and allocates an amount of power resource, $f_{kb}P_b^m = [(1-p) - f_b^t + f_{kb}^*]P_b^m$, to connection k, where $f_{kb}^* = \frac{\eta + Z_{kb}}{W/(\gamma^* R^*)+\eta}$, and $f_{kb}^* P_b^m$ is the amount of power for supporting rate R^* for connection k. The total transmission rate for connection k is then calculated from (11) as

$$R_k = \frac{W f_{kb}}{\gamma^*[Z_{kb} + (1-f_{kb})\eta]} = \frac{W[(1-p) - f_b^t + f_{kb}^*]}{\gamma^*[Z_{kb} + (1-f_{kb})\eta]}. \tag{32}$$

VI. Numerical Results

We consider a cellular system as described in Section II. The system has 19 cells with cell 0 at the center, 6 first-tier and 12 second-tier cells surrounding cell 0. The cell size, which is the distance from the BS to one of the corners of the cell, is normalized to 1. We consider that all BSs have the same maximum transmission power which is normalized to 1. For each connection, we consider the interference from all the first-tier BSs surrounding the BS which the connection is communicating with. The simulation is based on snapshots, and MS positions at any given moment are uniformly distributed in the service area. Unless otherwise stated, the parameters used in the numerical results are as follows. The system has a total of 5 MHz bandwidth, reused in every cell. The path loss exponent, α, is 4 and the standard deviation, σ_X, for log-normal fading is 8 dB. The channel transmission orthogonality factor, η, is 0.4. For each connection, the minimum required transmission rate, R^*, is 64 kbps, and the required SIR, γ^*, for each connection is 7 dB.

Communication outage probability is collected as a long-term time average of $(1 - \sum_{i=1}^{M} \chi_i / M)$ which is calculated

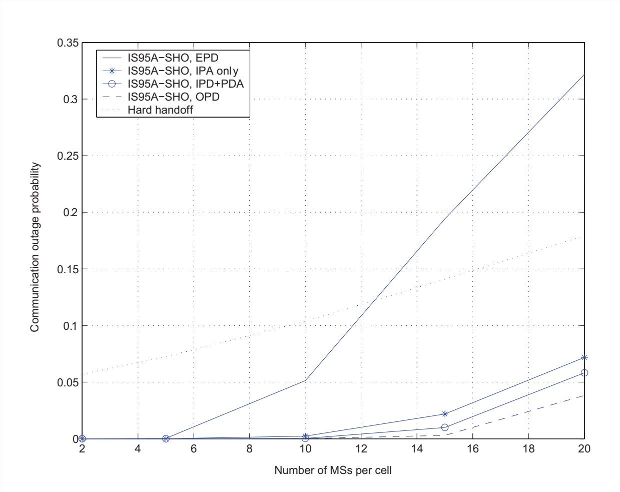

Fig. 1. Outage probability using the IS95A-SHO scheme

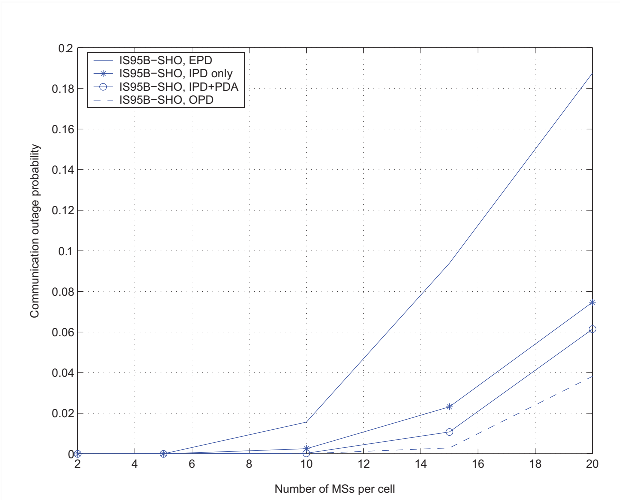

Fig. 2. Outage probability using the IS95B-SHO scheme

in each packet transmission slot, where M is the total number of connections in the system, $\chi_i = 1$ if the connection can be served with guaranteed QoS and $\chi_i = 0$ if the connection is in outage. We compare the proposed power distribution scheme with the EPD and OPD schemes when each is applied to different SHO BS selection schemes, including the IS95A-SHO, IS95B-SHO and UMTS-SHO schemes. The maximum size of an active BS set for performing SHO is 2. In the IS95A-SHO scheme, T_ADD=-13 dB and T_DROP=-15dB. In the IS95B-SHO scheme, Soft_Slope=8, Add_Intercept=Drop_Intercept=2 dB, $T_1 = T_2 = 0$ dB. In the UMTS-SHO scheme, As_Th=As_Th_Hys=2 dB. All the timers in both the IS95B-SHO and UMTS-SHO schemes are set to zero for simplicity.

We first compare the outage probability of the three SHO schemes using the EPD and that using the proposed power distribution. Figs. 1-3 show a comparison of outage probability for IS95A-SHO, IS95B-SHO and UMTS-SHO, respectively, as the number of connections changes. All the three figures show that, compared to the EPD, the proposed power distribution (IPD and PDA together) can significantly reduce outage

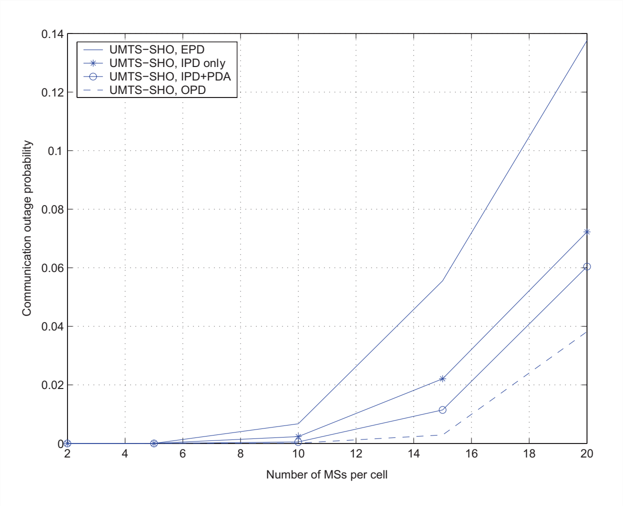

Fig. 3. Outage probability using the UMTS-SHO scheme

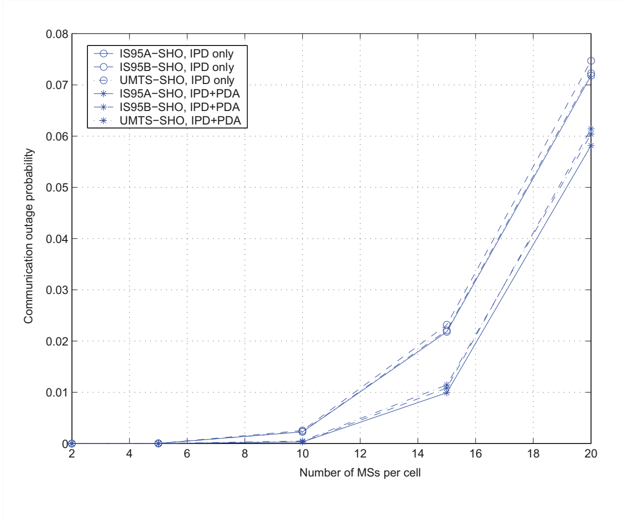

Fig. 4. Outage probability using the proposed power distribution scheme

probability. For given outage probability requirement, this improvement can be translated into higher system capacity. It can also be seen that the outage probability using the proposed power distribution scheme is very close to that using OPD for all three different SHO schemes. The outage probability of the proposed power distribution scheme is slightly higher than that using OPD, since the proposed power distribution scheme does not use global information about traffic load and channel conditions and simplifies the implementation. The figures also show that the outage performance using IPD only is slightly increased, compared with the full power distribution scheme which includes both IPD and PDA. For example, Fig. 1 shows that if the required outage probability threshold is 5%, then using IS95A-SHO with EPD can support about 10 QoS connections per cell, while about 19 QoS connections can be supported using the same SHO scheme but with the proposed power distribution scheme, and 18 using the IPD only. The performance gain of the proposed power distribution scheme comes from making use of the random channel conditions of connections and the coordination between neighboring BSs. Without PDA, using IPD only can simplify the power distribution process, since IPD does not require information exchanges between neighboring BSs and can be performed at each BS independent of the power distribution at other BSs.

Comparing the results using EPD in Figs. 1-3 we can see that the improvement of the outage probability performance using the proposed power distribution scheme is relatively less significant in the UMTS-SHO and IS95B-SHO schemes, compared to that using IS95A-SHO, since both IS95B-SHO and UMTS-SHO schemes incorporate QoS when selecting the BSs in the active set of a connection. Comparing Figs. 1-3 we can see that the outage performance is strongly dependent on different SHO schemes if EPD is used. That is, with EPD the UMTS-SHO scheme achieves the best outage performance for given traffic load, or highest capacity given the required outage probability threshold, while the IS95A-SHO scheme results in the highest outage probability among the three. When using the proposed power distribution scheme, however, all three SHO schemes achieve approximately the same outage performance as shown in Fig. 4. This indicates that, unlike the EPD scheme, the proposed power distribution scheme is not very sensitive to the selected BSs in the active set. Therefore, a relatively simple SHO BS selection scheme can be used when using the proposed power distribution scheme for capacity/outage performance improvement. The computational complexity of the proposed power distribution scheme can be further reduced without significantly sacrificing the outage/capacity performance by removing PDA process. Fig. 4 shows that the outage performance using IPD only is also approximately the same for all three SHO schemes.

Figs. 5-7 show the total transmission throughput for best effort traffic in each cell after serving the QoS traffic when different SHO schemes are used. As the number of QoS connections increases, more power resources are used by the QoS traffic, leaving less power resources available for best effort data traffic. Therefore, transmission throughput for best effort traffic decreases as the number of QoS connections increases. It is seen that the system using the OPD achieves very low transmission throughput for best effort data traffic, compared with that using the proposed power distribution scheme. With OPD for the QoS traffic, more connections can be supported simultaneously. The extra connections that may not be supported using the proposed power distribution scheme but can be supported using OPD may consume very high power resources since they may be redirected to a BS with poor link quality.

Figs. 5-7 also show that all three different SHO schemes, when using the proposed power distribution scheme, achieve approximately the same throughput for best effort traffic. This is consistent with the outage probability performance shown in Fig. 4. Both of these show that the power distribution efficiency is approximately the same when using the proposed power distribution scheme in the three different SHO schemes. The figures also show that best effort transmission throughput performance is also approximately the same for all the three SHO schemes when using IPD only, and there is a very minor reduction in the best effort traffic throughput when removing PDA in the proposed scheme.

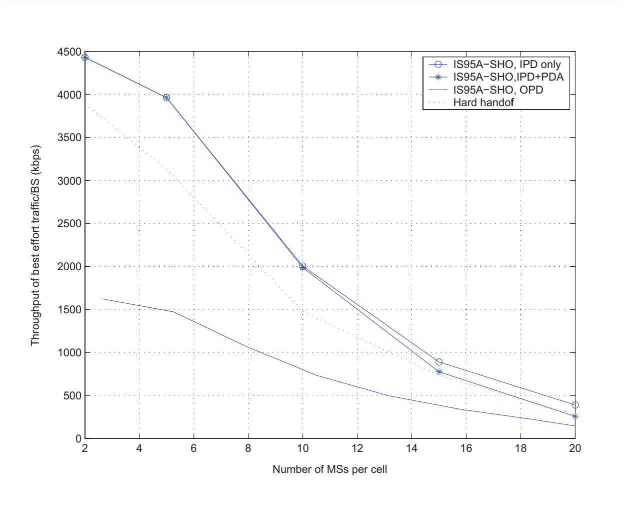

Fig. 5. Throughput of best effort traffic using the IS95A-SHO scheme

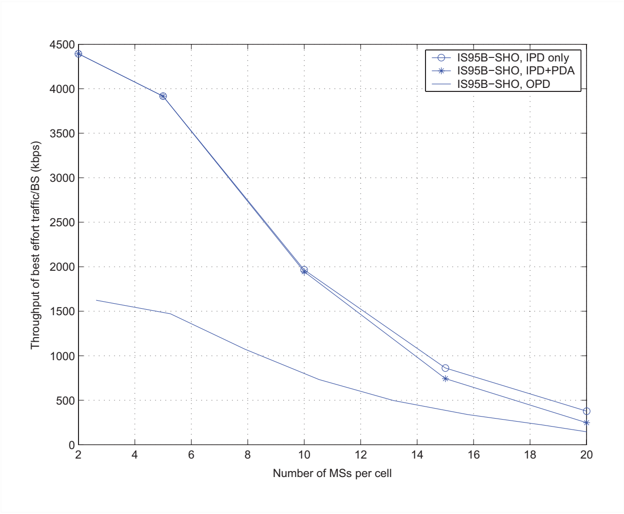

Fig. 6. Throughput of best effort traffic using the IS95B-SHO scheme

The performance of the system using the hard handoff only is shown in both Figs. 1 and 5. In the hard handoff case each connection is always served by the nearest BS, and the transmission power is calculated using (11) with $\gamma_{ib} = \gamma^*$. It is seen that using SHO with the proposed power distribution scheme can significantly reduce the communication outage probability, compared to that using the hard handoff. The throughput for best effort traffic in the system using the hard handoff is lower than that using SHO with the proposed power distribution scheme. This further shows that the proposed power distribution scheme for SHO connections is more efficient than the power distribution in the hard handoff. Fig. 5 also shows that the throughput for best effort traffic in the system using the hard handoff is higher than that using OPD, since OPD achieves lower outage probability for QoS traffic at the price of high BS transmission power.

VII. Conclusions

We have formulated an optimum power distribution scheme for soft handoff connections in cellular CDMA downlinks and

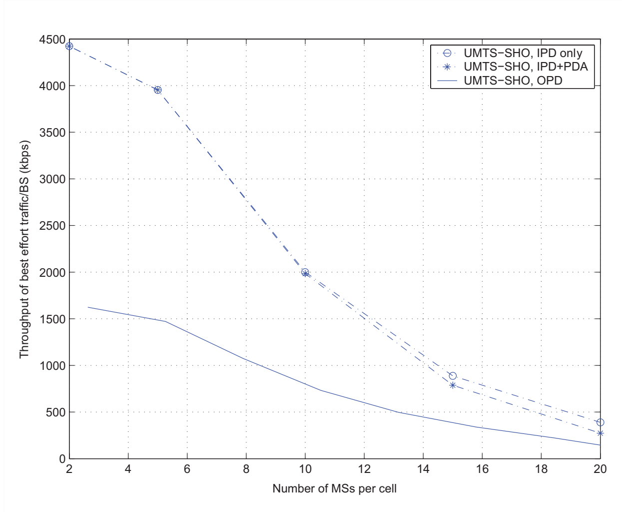

Fig. 7. Throughput of best effort traffic using the UMTS-SHO scheme

solved it approximately. With the optimum power distribution, the capacity for connections with QoS requirements can be maximized for a given transmission outage requirement. We have also proposed a heuristic power distribution scheme which can be implemented at the BSs and work distributively. Our results show that the proposed power distribution scheme can achieve low outage probability and high capacity for QoS traffic, while providing high transmission throughput for best effort data traffic. All the qualitative results should also be applicable to a more general case when more than two BSs are involved in the SHO process of a connection.

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References

[1] F. Blaise, L. Elicegui, F. Goeusse, and G. Vivier, "Power control algorithms for soft handoff users in UMTS," in *Proc. IEEE VTC 2002*, vol. 2, pp. 1110-1114, Sep. 2002.

[2] "Mobile station-base station compatibility standard for dual-mode wideband spread spectrum cellular system," Telecommunications Industry Association, TIA/EIA/IS-95, 1993.

[3] "Wideband CDMA one radio transmisison technology proposal," International Telecommunication Union, Radio Communication Study Groups, TIA CDMA 2000, 1998.

[4] "3rd Generation Partnership Project," Technical Specification TS 25.214, 2000.

[5] D. Kim, "A simple algorithm for adjusting cell-site transmitter power in CDMA cellular systems," *IEEE Trans. Veh. Technol.*, vol. 48, no. 4, pp. 1092-1098, July 1999.

[6] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, and C. E. Wheatley, " On the capacity of a cellular CDMA system," *IEEE Trans. Veh. Technol.*, vol. 40, no. 2, pp. 303-312, May 1991.

[7] W. C. Y. Lee, "Overview of cellular CDMA," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 291-302, May 1991.

[8] M. Zorzi, "Simplified forward-link power control law in cellular CDMA systems," *IEEE Trans. Veh. Technol.*, vol. 43, pp. 1088-1093, Nov. 1994.

[9] R. R. Gejji, "Forward-link-power Control in CDMA cellular systems," *IEEE Trans. Veh. Technol.*, vol. 41, pp. 532-536, Nov. 1992.

[10] R. Vannithamby and E. S. Sousa, "An optimum rate/power allocation scheme for downlink in hybrid CDMA/TDMA cellular systems," in *Proc. IEEE VTC 2000*, vol. 4, pp. 1734-1738, Sep. 2000.

[11] A. Bedekar, S. Borst, K. Ramanan, P. Whiting, and E. Yeh, “Downlink scheduling in CDMA data networks,” in *Proc. IEEE GLOBECOM 1999*, vol.5, pp. 2653-2657, Dec. 1999.

[12] J. Y. Kim and G. L. Stüber, “CDMA soft handoff analysis in the presence of power control error and shadowing correlation,” *IEEE Trans. Wireless Commun.*, vol. 1, pp. 245-255, Apr. 2002.

[13] Y. Chen and L. Cuthbert, “Optimum size of soft handover zone in power-controlled UMTS downlink systems,” *IEEE Electron. Lett.*, vol. 38, pp. 89-90, Jan. 2002.

[14] Y. H. Kwon, D. C. Lee, and W. Park, “Capacity analysis of forward link with deterministic power model in CDMA Systems with adaptive antenna array and soft handoff,” in *Proc. IEEE VTC 2002*, vol.1, pp. 335-339, May 2002.

[15] D. Zhao, X. Shen, and J. W. Mark, “Power distribution and soft handoff for cellular CDMA downlinks,” in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, vol. 3, pp. 1901-1906, Mar. 2003.

[16] C.-C. Lee and R. Steele, “Effect of soft and softer handoffs on CDMA system capacity,” *IEEE Trans. Veh. Technol.*, vol. 47, no. 3, Aug. 1998, pp. 830-841.

[17] R. Prakash and V. V. Veeravalli, “Locally optimal soft handoff algorithms,” *IEEE Trans. Veh. Technol.*, vol. 52, no. 2, Mar. 2003, pp. 347-356.

[18] B. Homnan and W. Benjapolakul, “QoS-controlling soft handoff based on simple step control and a fuzzy inference system with the gradient descent method,” *IEEE Trans. Veh. Technol.*, vol. 53, no. 3, May 2004, pp. 820-834.

[19] D. Avidor, N. Hegde, and S. Mukherjee, “On the impact of the soft handoff tereshold and the maximum size of the active group on resource allocation and outage probability in the UMTS system,” *IEEE Trans. Wireless Commun.*, vol. 3, no. 2, Mar. 2004, pp. 565-577.

[20] S.-H. Hwang, S.-L. Kim, H.-S.Oh, C.-E. Kang, and J.-Y. Son, “Soft handoff algorighm with variable thresholds in CDMA cellular systems,” *IEEE Electron. Lett.*, vol. 33, no. 19, Sep. 1997, pp. 1602-1603.

[21] H. Furukawa, K. Hambe, and A. Ushirokawa, “SSDT–site selection diversity transmission power control for CDMA forwarad link,” *IEEE J. Select. Areas Commun.*, vol. 18, no. 8, pp. 1546-1554, Aug. 2000.

[22] D. Wong and T. J. Lim, “Soft handoffs in CDMA mobile systems,” *IEEE Pers. Commun.*, vol. 4, pp. 6-17, Dec. 1997.

[23] G. L. Stüber, *Principles of Mobile Communication*, Boston: Kluwer Academic Publishers, 2002.

[24] J. W. Mark and W. Zhuang, *Wireless Communications and Networking*, Upper Saddle River, NJ: Prentice Hall, 2003.

[25] T. S. Rappaport, *Wireless Communications: Principles and Practice,* Englewood Cliffs, NJ: Prentice-Hall, 1996.

[26] MOSEK. Available: http://www.mosek.com.

[27] CPLEX.
Available: http://www.informatica.us.es/ calvo/ampl/amplcasacplex.html.

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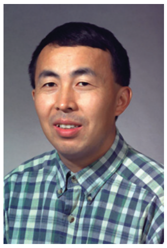

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