Soft Handoff and Connection Reliability in Cellular CDMA Downlinks

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***Abstract*— A two-phase soft handoff scheme, which includes an initial power allocation phase followed by a power re-distribution phase, is proposed. The initial power allocation phase makes a handoff decision for each connection by assigning a connection to the BS with the best link quality and allocating a minimum amount of power from the BS for the connection. The initial handoff decisions are made for individual connections independent of other connections or the BS power availability. Therefore, there might be heavily loaded and lightly loaded BSs because (i) traffic load may not be equally distributed in all cells, and (ii) the channel condition of the connections is random. The power re-distribution phase is to smooth out the loading on the system by coordinating the power allocations among neighboring BSs so that more connections can receive reliable transmissions. We then develop an analytical model for studying the connection reliability with the proposed soft handoff scheme. Our results show that the proposed two-phase soft handoff scheme can significantly improve connection reliability and increase system capacity in downlink transmissions.**

***Index Terms*— Soft handoff, power distribution, cellular CDMA, quality-of-service.**

I. Introduction

In a CDMA system where the available radio spectrum is shared by all active users, appropriate resource allocation is critical in order to provide satisfactory quality-of-service (QoS) for more connections. Transmission power is one of the basic system resources for CDMA-based systems. In the cellular CDMA downlink, each connection requires a sufficient amount of power to overcome intra-cell and inter-cell interference. Distance-based power control [1]-[4] is an easy way to distribute the power resources for homogeneous traffic. The basic rationale behind this is that a connection close to its serving BS experiences less path loss and lower inter-cell interference, and requires less transmission power from the BS, while a connection near the cell boundary requires higher transmission power. When heterogeneous traffic is considered, power distribution is not only related to the location of a mobile station (MS), but also the traffic parameters and QoS requirements, such as transmission rate and bit error rate (BER) requirement. A higher power level is required for a connection requesting a higher transmission rate and lower BER. An optimum power allocation scheme is developed in [7] which minimizes the SIR difference among different cells. The optimal power distribution in [8] is to minimize the average BER of users. Given the instantaneous packet transmission rates for all the active connections, an appropriate transmission power distribution for each connection from the BS may simultaneously guarantee the required QoS for all the connections [5]. Since all the MSs share the limited BS power resources, insufficient power in the BS may affect the communication quality of all the connections. There may be temporary communication outage for one or more connections. Although a small communication outage probability (e.g., $1-2\%$) is usually tolerable, a higher communication outage probability makes a connection unreliable. Therefore, appropriate power allocation is critical in order to guarantee the packet transmission QoS while supporting more users with reliable connections.

CDMA is interference limited. Soft handoff in which a connection is simultaneously connected to more than one BS before handoff completion is required to enhance information delivery reliability. However, much research work on CDMA downlinks has been based on hard handoff [1]-[6], mainly because QoS provisioning with soft handoff requires coordinations of resource allocation among neighboring cells, and is much more complicated. Reference [9] provides an overview of soft handoffs in CDMA systems. In soft handoff, an MS in downlink receives signals from multiple BSs. The diversity gain obtained by combining the signals received from multiple BSs may compensate for some effect of random channel fading, and improve the communication quality or conserve the BS power. On the other hand, a connection in soft handoff may require transmission power from multiple BSs involved in the soft handoff process. Therefore, it is important to study the effect of soft handoff on the connection reliability and system capacity. In [17] the power distribution is studied by focusing on one specific soft handoff connection, which shows that a BS with a better link to the MS should transmit a higher transmission power so that the total amount of transmission power for the MS is minimized.

Some recent research on soft handoff has been based on circuit-switched systems, such as [10]-[12], where soft handoff is performed once an MS enters a distance-based soft handoff area. In [11] and [12], an equal amount of power is distributed to a connection from all the BSs involved in the soft handoff

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process. The downlink soft handoff in [10]-[12] results in some contradictory effect on the system capacity, and there is a significant capacity reduction when the geographical soft handoff area is not appropriately chosen. The reason is that a connection in soft handoff may require much more power resources than that in the hard handoff. In site selection diversity transmission (SSDT) [13] a connection is always served by the BS with the best link quality. A similar approach is used in [14] for soft handoff, although it emphasizes on the power control algorithm. The SSDT saves power resources and improves the CDMA downlink capacity. The scheme, however, does not consider the coordination of resource allocations among neighboring cells. There have been some efforts in the literature to coordinate the transmissions in neighboring cells. In [15] reduced inter-cell interference is achieved by temporarily stopping transmissions in neighboring cells. The approach used in [16] is to schedule the BS transmission time to alternately serving users in its own cell and neighboring cells. These types of inter-cell coordinations are more suitable for improving transmission throughput of time-insensitive data traffic.

In this paper, we study soft handoff and its effect on connection reliability in cellular CDMA downlink transmissions, where a connection is said to be unreliable if its experienced communication outage probability is larger than a predefined value. We propose an efficient and effective power distribution/soft handoff scheme that guarantees the QoS requirements of the users, while allowing more simultaneous connections in the system with high reliability. The motivation of the proposed scheme is based on the two-fold effect of soft handoff on the connection reliability in the downlink transmissions. First, whenever power resources are available, the MS can be assigned to the BS with which the MS has the best link quality. In this way, each connection is allocated a minimum amount of power in order to satisfy its QoS, and more power resources can be used for other connections. Thus, the connection reliability in the entire system can be improved. Second, for a given connection, by simultaneously communicating with more than one BS, the connection can make use of the power resources from multiple BSs, and have a higher probability to achieve its required QoS. By making use of these properties, the proposed soft handoff scheme consists of two phases: an initial power allocation phase followed by a power re-distribution phase. The initial power allocation phase makes an independent soft handoff decision for each connection by assigning a connection to the BS with the best link quality. Compared with SSDT, our initial power allocation uses a different criterion for selecting the cell site, and considers not only the path loss of the links between the MS to the BSs, but also the interferece conditions of the links. The initial power allocation also takes the link quality measurement errors into consideration when allocating the BS power resources for each connection. The power re-distribution phase allows more connections with reliable transmissions by coordinating the power allocations among neighboring BSs and moving traffic from heavily loaded cells to lightly loaded ones. We then develop an analytical model for studying the connection reliability with the proposed soft handoff scheme. Our results show that compared with the hard handoff and several known soft handoff schemes in the literature, the proposed two-phase soft handoff scheme can provide more connections with reliable transmissions.

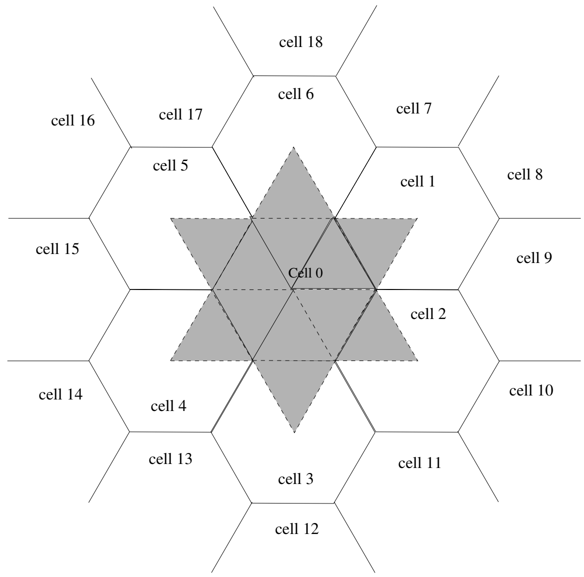

Fig. 1. Service areas.

The remainder of the paper is organized as follows. Section II defines the system model. Section III describes the proposed soft handoff scheme. An analytical model of the connection reliability with the soft handoff scheme is developed in Section IV. Numerical results are shown in Section V to demonstrate the performance of the soft handoff scheme. Section VI concludes the paper.

II. System Model

We consider a cellular CDMA system populated with hexagonal cells as shown in Fig. 1. The coverage area of the system is divided into small cells, each with a BS located at the center. An MS is located in the footprint of BS b, or cell b, if BS b is the nearest BS to the MS. This BS footprint is also referred to as a hard cell. A cluster of BSs is connected to a mobile switching center (MSC) which concentrates the traffic of multiple BSs in the cluster and provides control for these BSs. The MSC also serves as the attachment point to a wireline backbone network. Communications in the wireless domain is transmitted by frequency-division-duplexing (FDD), so that the uplink and downlink transmissions are isolated.

In the downlink transmissions, each MS receives desired signals from its serving BS, and receives interference power from other BSs as well as that from its own BS. We consider a situation in which intra-cell and inter-cell interferences dominate, so that background noise can be ignored. Although orthogonal codes used for transmission to different users can be free of intra-cell interference, the orthogonality property may be corrupted by the propagation channel so that the received signals are no longer orthogonal. In what follows, we let η denote the interference factor arising from imperfect orthogonality in the received signals. That is, $\eta = 0$ signifies perfect orthogonality at the receiver, and $\eta = 1$ signifies that powers from all other users in the same cell contribute to the interference on the tagged user's desired signal.

Each BS has a maximum transmission power limit, P^m. In the downlink, every BS transmits a cell specific pilot signal at a constant power, P^p. Let $p = P^p/P^m$. The amount of the power, $(1-p)P^m$, is shared by all active users for data packet transmissions. The MSs listen to the pilot channels of the neighboring BSs to facilitate making handoff decisions [20]. In this paper, we assume that only two BSs can provide transmissions for a connection in soft handoff. The MSs monitor the pilot signal levels received from neighboring BSs and report to the network (from its current serving BS to the MSC) those pilot signals that exceed the prescribed thresholds. When there are two or more BSs whose pilot signal levels are above the threshold, the MSC chooses the two BSs with the strongest pilot signal levels and instructs the MS to tune two fingers of its Rake receiver to the two BSs. In order to avoid frequently changing the two BSs due to random channel fading, the measurements of the received pilot signals are averaged over a period of time at the MS. Assuming the averaging time period is long enough to counter the fading effect, the two BSs involved in the soft handoff process for an MS are the two nearest BSs to the MS. The transmission power and soft handoff decisions for each connection are made at the MSC. The Rake receiver in the MS combines the received signals from different BSs using maximum ratio combining.

Channel time is divided into slots with equal length. Packet transmissions take place at the beginning of each packet transmission slot. Different connections can transmit simultaneously during one packet transmission slot, as long as their required QoS can be guaranteed. Each connection may have ON and OFF periods. Let the required packet transmission rate for connection i during its ON period be R_i, and the required signal-to-interference ratio (SIR) for the connection be γ_i^*. The SIR value corresponds to the required BER performance for given modulation and coding schemes. No packet is transmitted for a connection during its OFF periods. Since the packets first arrive at the MSC before they are transmitted to the BS, the MSC has the information about the ON and OFF states of a connection. We assume that there is also best effort traffic in addition to QoS traffic. Extra power available at the BS after serving all the guaranteed QoS traffic is used to transmit best effort traffic, and the BS always transmits at the maximum power.

Closed loop power control in the downlink can track and compensate for the effect of channel fading by adjusting the transmission power for each connection. The power control is based on measurement of channel conditions, i.e., the link gain between the MS and its serving BS(s), and that between the MS and the interfering BSs. The link gain, a_{ib}, between the ith MS, which is the MS carrying the ith connection, and BS b is given by

$$a_{ib} = \left(\frac{d_{ib}}{d_0}\right)^{-\alpha} e^{-\beta X_b}, \tag{1}$$

where d_{ib} is the distance between the MS and the BS, $\beta = \ln 10/10$ is a constant, d_0 is a close-in reference distance which is determined from measurements close to the BS transmitter [21], and α is the path loss exponent. Typical values of α, usually obtained through measurement, are between 2 and 5 for cellular communications. The effect of channel slow fading in cell b is represented by the Gaussian distributed random variable X_b with zero mean and standard deviation σ_X (in dB). We assume that the slow fading in different cells is independent and identically distributed. Fast fading is not explicitly considered. It is assumed that the effect of fast fading can be ideally overcome by a well-designed receiver.

III. Proposed Soft Handoff Scheme

Without loss of generality, we consider connection i. Let BSs 0 and 1 be the two nearest BSs to MS i. When connection i is in soft handoff, the MSC adjusts the transmission power of the two BSs for the connection. Let P_{i0} and P_{i1}, respectively, be the transmission power from BSs 0 and 1 for the connection. Depending on the current link quality and the power allocations in neighboring cells, the MSC may have the following three possible ways to allocate the power for the connection:

(i) $P_{i0} > 0$ and $P_{i1} = 0$, i.e., the MS receives transmission power from BS 0 only. Define $f_{i0} = \frac{P_{i0}}{P^m}$ as the allocated power ratio from BS 0 for connection i in this case.

(ii) $P_{i0} = 0$ and $P_{i1} > 0$, i.e., the MS receives transmission power from BS 1 only. Define $f_{i1} = \frac{P_{i1}}{P^m}$ as the allocated power ratio from BS 1 for connection i in this case.

(iii) $P_{i0} = P_{i1} > 0$ using the straightforward power allocation strategy in [22], i.e., both BSs simultaneously transmit the same amount of power to the MS. Define $f_{is} = \frac{P_{i0}}{P^m}$ as the allocated power ratio from each BS for connection i in this case.

There are other options for allocating the transmission power from the two BSs in order to satisfy the SIR requirement of the connection. However, there is always a tradeoff between performance and computational complexity. In the remaining part of the section, we first derive the minimum required transmission power from the serving BS or BSs to the MS given the association relationship between the MS and the BSs. Based on this, soft handoff decisions are described which specify the serving BS(s) for the connections so that more connections can be simultaneously supported with high reliability.

A. Power allocation

We first consider the case when MS i receives power from BS 0 only, i.e., $P_{i1} = 0$, and derive the minimum required power from BS 0 in order to satisfy the SIR requirement of the connection. The amount of required power, P_{i1}, when the MS receives power from BS 1 only (i.e., when $P_{i0} = 0$) can be derived in the same way.

When $P_{i0} \geq 0$ and $P_{i1} = 0$, the interference experienced by a packet for the connection at the MS receiver input is $\eta(P^m - P_{i0})a_{i0} + \sum_{b=1}^{B} P^m a_{ib}$, where B is the total number of interfering BSs. The actual SIR at the receiver despread output of MS i is given by

$$\gamma_i = \frac{P_{i0} a_{i0} G_i}{\eta(P^m - P_{i0})a_{i0} + \sum_{b=1}^{B} P^m a_{ib}} = \frac{f_{i0} G_i}{\eta(1 - f_{i0}) + z_{i0}}, \tag{2}$$

where $G_i = W/R_i$ is the spread spectrum processing gain, W is the spread spectrum bandwidth, z_{i0} is given by

$$z_{i0} = \sum_{b=1}^{B} \frac{a_{ib}}{a_{i0}} = \sum_{b=1}^{B} \left(\frac{d_{i0}}{d_{ib}}\right)^{\alpha} e^{\beta(X_0 - X_b)}. \tag{3}$$

The value of z_{i0} is considered as a link quality indication of MS i to BS 0. Smaller values of z_{i0} represent better link quality and less transmission power is required in order to support the same transmission rate and SIR requirement. We consider that the power resources can be distributed accurately if the exact values of z_{i0} are available. In practice, the values of z_{i0} can be obtained by measuring the received pilot signals at the MS from different BSs, but these measurements may not be performed accurately due to the random channel fading and other measurement errors. We assume the measurement errors for each of the link gains to be log-normally distributed. The measurement of each z_{i0} consists of a sum of B relative link gains, $\frac{a_{ib}}{a_{i0}}$, $b = 1, 2, \ldots, B$, thus the errors in the sum can be approximated as log-normally distributed [25]-[26]. This is consistent with the log-normally distributed power control errors in [23]. Let Z_{i0} be the value of z_{i0} calculated based on the measured values of the link gains. We simply call Z_{i0} as the measured link quality of connection i to BS 0. Let $e^{\beta Y_{i0}}$ represent the measurement error in Z_{i0}, where Y_{i0} is a Gaussian distributed random variable having zero mean and standard derivation σ_Y (in dB). $\sigma_Y = 0$ dB represents no error in measuring z_{i0}. The relationship between Z_{i0} and z_{i0} is given by

$$z_{i0} = Z_{i0} e^{\beta Y_{i0}}. \tag{4}$$

Substituting z_{i0} in (2) by the right-hand side of (4), we have

$$\gamma_i = \frac{f_{i0} G_i}{\eta(1 - f_{i0}) + e^{\beta Y_{i0}} Z_{i0}}. \tag{5}$$

In order to achieve successful communications, $\gamma_i \geq \gamma_i^*$ must hold. Communication outage occurs when $\gamma_i < \gamma_i^*$. In order to guarantee that the transmission outage probability is less than a predefined outage probability, ξ, the following condition must hold:

$$\Pr\{\gamma_i < \gamma_i^*\} \leq \xi. \tag{6}$$

Substituting γ_i in (6) by the right-hand side of (5) and manipulating, we have

$$\Pr\left\{e^{\beta Y_{i0}} > \frac{f_{i0}\left(\eta + G_i/\gamma_i^*\right) - \eta}{Z_{i0}}\right\} \leq \xi. \tag{7}$$

When equality in (7) holds, each connection is allocated the minimum amount of power resource, and more simultaneous transmissions can be supported. The minimum power ratio from BS 0 for the ith connection is found from (7) as

$$f_{i0} = \frac{\eta + e^{\beta\sigma_Y \mathrm{Q}^{-1}(\xi)} Z_{i0}}{\eta + G_i/\gamma_i^*}, \tag{8}$$

where $\mathrm{Q}^{-1}(x)$ is the inverse function of $\mathrm{Q}(x)$, and $\mathrm{Q}(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{t^2}{2}} dt$ for $x \geq 0$.

When a connection receives power from both BSs 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 [24] and is given by

$$\gamma_i = \frac{f_{is} G_i}{\eta(1 - f_{is}) + z_{i0}} + \frac{f_{is} G_i}{\eta(1 - f_{is}) + z_{i1}}. \tag{9}$$

It is seen that when $z_{i0} \ll z_{i1}$, the second ratio on the right-hand side of (9) is much less than the first one, which indicates that transmission power from BS 1 contributes much less to the MS output SIR than that from BS 0 does, although both BSs transmit the same power for the connection. Therefore, assigning BS 0 only to transmit (i.e., BS 0 transmits at $f_{i0} P^m$ and BS 1 does not transmit) to the connection is preferred in this case. For the same reason, when $z_{i0} \gg z_{i1}$, assigning BS 1 only to transmit to the connection is preferred. When $z_{i1} \approx z_{i0}$, both BSs 0 and 1 have approximately the same contribution to the MS output SIR. Therefore, we only consider (9) when $z_{i1} \approx z_{i0}$ and make the following approximation

$$z_{i0} \approx z_{i1} \approx \frac{1}{2}(z_{i0} + z_{i1}) = \frac{1}{2}\left(e^{\beta Y_{i0}} Z_{i0} + e^{\beta Y_{i1}} Z_{i1}\right). \tag{10}$$

Then the SIR in (9) can be approximated as

$$\gamma_i \approx \frac{4 f_{is} G_i}{2\eta(1 - f_{is}) + e^{\beta Y_{i0}} Z_{i0} + e^{\beta Y_{i1}} Z_{i1}}. \tag{11}$$

In order to meet the requirement of communication outage, the following condition must be satisfied:

$$\begin{aligned} &\Pr\{\gamma_i < \gamma_i^*\} \\ &= \Pr\left\{\frac{4 f_{is} G_i}{2\eta(1 - f_{is}) + e^{\beta Y_{i0}} Z_{i0} + e^{\beta Y_{i1}} Z_{i1}} < \gamma_i^*\right\} \leq \xi, \end{aligned} \tag{12}$$

which after some algebraic manipulation becomes

$$\Pr\left\{e^{\beta Y_{i0}} Z_{i0} + e^{\beta Y_{i1}} Z_{i1} > \frac{4 f_{is} G_i}{\gamma_i^*} - 2\eta(1 - f_{is})\right\} \leq \xi. \tag{13}$$

The left-hand side of the inequality between the braces in (13) is a sum of two log-normally distributed random variables for given measurements Z_{i0} and Z_{i1}. Computation of the distribution of a sum of log-normal random variables has been studied extensively in the literature, e.g., [25]-[27]. Nevertheless, no exact closed form solution is available. In [27], it is shown that Fenton's approach [26] gives a good approximation for the probability distribution function of a sum of multiple log-normally distributed random variables, and the outage probability calculated based on this approach is very close to the simulation results. Therefore, we follow the procedure in [26] and approximate the sum as a log-normally distributed random variable. Let H_i be a Gaussian random variable with mean μ_{H_i} and variance $\sigma_{H_i}^2$. Define

$$e^{H_i} = e^{\beta Y_{i0}} Z_{i0} + e^{\beta Y_{i1}} Z_{i1}. \tag{14}$$

Then (13) can be equivalently written as

$$\Pr\left\{e^{H_i} > \frac{4 f_{is} G_i}{\gamma_i^*} - 2\eta(1 - f_{is})\right\} \leq \xi. \tag{15}$$

When equality holds in (15), the minimum value of f_{is} can be found as

$$f_{is} = \frac{2\eta + e^{\sigma_{H_i} \mathrm{Q}^{-1}(\xi) + \mu_{H_i}}}{2\eta + 4 G_i/\gamma_i^*}. \tag{16}$$

Expressions for μ_{H_i} and $\sigma_{H_i}^2$ are derived in Appendix 1.

B. Soft handoff decisions

The MS in soft handoff tunes two fingers of its Rake receiver to receive signals from the two nearest BSs. The transmission power of each BS is determined by the MSC. Since the MSC can check the resource availability in all the cells, transmissions to the MS can be maintained if any one of the BSs, or both the BSs together, can provide the required SIR. The proposed soft handoff scheme is a two-phase procedure: an initial power allocation phase followed by a power re-distribution phase.

Consider MS i and BSs 0 and 1 are the two nearest BSs to it. The initial power allocation for the connection works as follows:

- If $Z_{i0} < Z_{i1}$, the connection is assigned to BS 0 only, and BS 0 should transmit to the connection with power $f_{i0}P^m$.
- If $Z_{i0} \geq Z_{i1}$, the connection is assigned to BS 1 only, and BS 1 should transmit to the connection with power $f_{i1}P^m$.

Note that the above decisions are based on the measured values of the link quality, since the exact values of the link quality z_{i0} and z_{i1} are unknown. Our results will show that soft handoff decisions based on the measured link quality can still achieve good performance. The basic idea of the initial power allocation is to assign an MS to the BS with the best link quality. In this way, the tagged connection is assigned the minimum amount of power resource, and more power resources can be left for other connections.

In the initial power allocation phase the decision of assigning a serving BS or BSs for each connection is made independent of that for any other connections or the BS power resource availability. Thus, for a given BS b, after the initial power allocation phase the total amount of required power from the BS may be larger than the total amount of available power resources at the BS. In this case, BS b is overloaded. Note that when this is true, it is possible that a neighboring BS of BS b is still underloaded after performing the initial power allocation. This may happen when the traffic load is not uniformly distributed in the system coverage area. 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 a particular moment due to the random channel fading and random connection ON and OFF activities. In this case, the MSC can check the resource availability in the neighboring cells, adjust the power distribution/soft handoff decisions for the connections by moving some connections from heavily loaded BSs to lightly loaded BSs, so that more connections can be supported simultaneously.

Let $f_b^t P^m$ represent the total required power from BS b for all the connections. Suppose BSs 0 and 1 are the two nearest BSs to connection i, and the connection has been assigned to BS 0 after the initial power allocation phase. When $f_0^t > 1-p$ after the initial power allocation phase, a flow chart for the power re-distribution phase is shown in Fig. 2. If BS 1 is lightly loaded, then it is possible that the connection can be moved to be jointly served by both BSs 0 and 1 or by BS 1 only, so that the total power requirement from BS 0 is reduced. If BS 1 also has no extra power resource available,

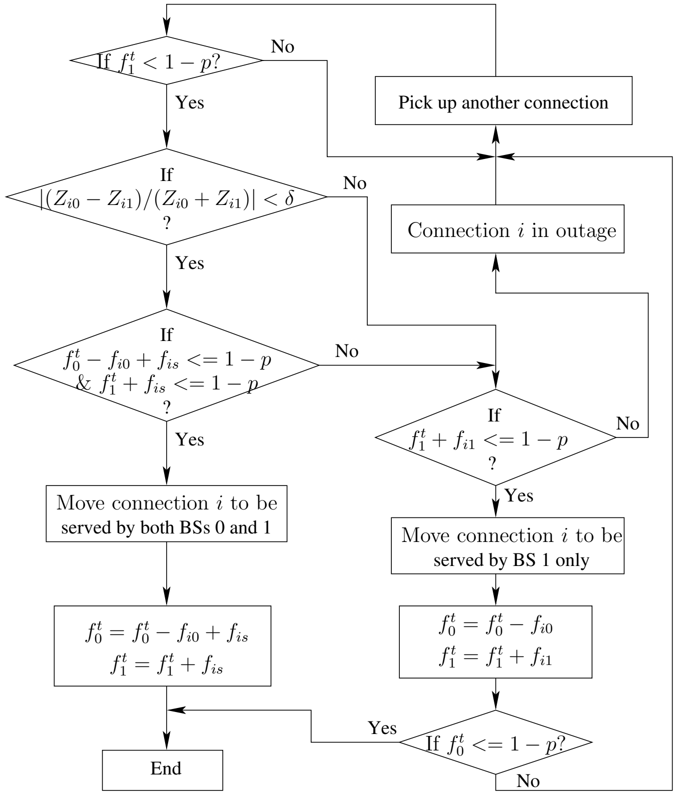

Fig. 2. Power re-distribution flow chart.

then another connection is selected to be moved from BS 0. In order to reduce the number of iterations, the connection which requests the highest power from BS 0 is first chosen to be moved.

- When BS 1 has extra power available and $|\frac{Z_{i0}-Z_{i1}}{Z_{i0}+Z_{i1}}| < \delta$ is true, the scheme first tries to move the connection to be jointly served by BSs 0 and 1. In this case, if $f_0^t - f_{i0} + f_{is} \leq 1-p$ and $f_1^t + f_{is} \leq 1-p$, then the connection can be jointly served by the two BSs.
- When $|\frac{Z_{i0}-Z_{i1}}{Z_{i0}+Z_{i1}}| < \delta$ does not hold, or the connection cannot be jointly served by BSs 0 and 1, the scheme tries to move the connection to be fully served by BS 1. If $f_1^t + f_{i1} \leq 1-p$, then the connection is moved from BS 0 to BS 1; otherwise, the connection is temporarily removed from service.

In this process δ is a small value so that the measured link quality values of the connection to both the BSs are approximately the same. As δ increases, it leaves more chances for re-distributing connections to be jointly served by both the BSs, while the difference of link quality of the connection to the two BSs increases which leads to unnecessary transmission power from the BS having poorer link condition to the connection as discussed in Section III-A. In Section V we will show the effect of different values of δ on the performance of the soft handoff scheme. If none of the power re-distribution operations can be done with connection i, then another connection is selected and the above process is repeated until either all the connections have been provided with satisfactory SIRs, or the power resources of all the neighboring BSs of BS 0 have been used up. Whether or not it is necessary to run additional rounds of the power re-distribution process depends on the performance requirements and the computational capability of the MSC. Note that this process of power re-distribution/soft handoff decision adjustment does not necessarily save the total required power resources. However, it provides possibilities that the connections can make use of the instantaneous unbalanced traffic loads in neighboring cells and are able to receive their required QoS. Connection reliability is expected to improve significantly using this procedure. In the next Section, we develop an analytical bound for the connection reliability with the proposed soft handoff scheme.

IV. Connection Reliability Analysis

A connection is said to be unreliable if its required SIR cannot be guaranteed due to insufficient power resources. The unreliability of a connection is defined as the probability that the experienced outage probability for the connection is larger than a predefined maximum tolerable value. The connection reliability is related to the traffic parameters, SIR requirements, connection activities, MS location distribution and connection link quality. We consider a cellular system with homogeneous traffic. Although the proposed handoff scheme is also applicable to the case when each of the BSs has a different maximum transmission power and pilot transmission power, in the following analysis we consider the case in which all the BSs have the same maximum transmission power and pilot transmission power. Without loss of generality, BS 0 is considered as the reference BS. When only the two nearest BSs can provide the soft handoff service for a connection, the MSs that may require transmission power from BS 0 must be located in the shaded area shown in Fig. 1. Let M be the total number of connections in the soft handoff area of cell 0, each indexed by $i = 1, 2, \ldots, M$. Let $f_0^t P^m$ be the amount of the total required power resources from BS 0 for all the connections. Then the value of f_0^t after performing the initial power allocation can be found as

$$f_0^t = \sum_{i=1}^{M} \nu_i f_i, \tag{17}$$

where ν_i represents the ON and OFF activities for connection i with 1 for the ON periods and 0 for the OFF periods, and $f_i P^m$ is the amount of transmission power for the connection from BS 0.

A. Connection unreliability after initial power allocation

After performing the initial power allocation, we have

$$f_i = \begin{cases} f_{i0}, & \text{if } Z_{i0} < Z_{i1} \\ 0, & \text{otherwise.} \end{cases} \tag{18}$$

Thus, the conditional probability that $f_i = f_{i0}$ for a given MS position is

$$\Pr\{f_i = f_{i0} \mid (x_i, y_i)\} = \Pr\{Z_{i0} < Z_{i1} \mid (x_i, y_i)\} \tag{19}$$

where (x_i, y_i) are the coordinates of the MS's current location in the two-dimensional service area. Let

$$e^{U_{i0}} = Z_{i0} = z_{i0} e^{-\beta Y_{i0}} = \sum_{b=1}^{B} \left(\frac{d_{i0}}{d_{ib}}\right)^{\alpha} e^{\beta(X_0 - X_b)} e^{-\beta Y_{i0}}, \tag{20}$$

$$e^{U_{i1}} = Z_{i1} = z_{i1} e^{-\beta Y_{i1}} = \sum_{b=b_1}^{b_B} \left(\frac{d_{i1}}{d_{ib}}\right)^{\alpha} e^{\beta(X_1 - X_b)} e^{-\beta Y_{i1}}. \tag{21}$$

Note that d_{i0}, d_{i1} and d_{ib} in (20) and (21) depend on the MS position. Therefore, U_{i0} and U_{i1} are MS location-dependent. It is seen that the right-hand side of (20) is a sum of multiple log-normally distributed random variables and can be approximated as a log-normally distributed random variable. Similarly, the sum on the right-hand side of (21) can also be approximated as another log-normally distributed random variable. Therefore, both U_{i0} and U_{i1} can be approximated as Gaussian distributed random variables. Let $\mu_{U_{i0}}$ and $\sigma^2_{U_{i0}}$ be the mean and variance of U_{i0}, respectively, $\mu_{U_{i1}}$ and $\sigma^2_{U_{i1}}$ be the mean and variance of U_{i1}, respectively, for given values of (x_i, y_i), and θ_U be the correlation coefficient between U_{i0} and U_{i1}. Appendix 2 derives $\mu_{U_{i0}}$, $\mu_{U_{i1}}$, $\sigma^2_{U_{i0}}$, $\sigma^2_{U_{i1}}$, and θ_U. Then (19) can be further derived as

$$\begin{aligned} \Pr\{f_i = f_{i0} \mid (x_i, y_i)\} &= \Pr\{e^{U_{i0}} < e^{U_{i1}} \mid (x_i, y_i)\} \\ &= \Pr\{U_{i0} - U_{i1} < 0 \mid (x_i, y_i)\} \\ &= \begin{cases} 1 - \mathrm{Q}(q_1), & \text{if } \mu_{U_{i0}} \le \mu_{U_{i1}}, \\ \mathrm{Q}(-q_1), & \text{otherwise,} \end{cases} \end{aligned} \tag{22}$$

where

$$q_1 = \frac{\mu_{U_{i1}} - \mu_{U_{i0}}}{\sqrt{\sigma^2_{U_{i0}} + \sigma^2_{U_{i1}} - 2\theta_U \sigma_{U_{i0}} \sigma_{U_{i1}}}}.$$

The mean value of f_i for given (x_i, y_i) is

$$\mathrm{E}[f_i \mid (x_i, y_i)] = \mathrm{E}[f_{i0} \mid (x_i, y_i)] \Pr\{f_i = f_{i0} \mid (x_i, y_i)\}. \tag{23}$$

As indicated by (8) f_{i0} is a function of Z_{i0} which is a function of U_{i0} as shown in (20), therefore, $\mathrm{E}[f_{i0} \mid (x_i, y_i)]$ can be found as

$$\begin{aligned} &\mathrm{E}[f_{i0} \mid (x_i, y_i)] \\ &= \mathrm{E}\left[\frac{\eta + e^{\beta\sigma_Y \mathrm{Q}^{-1}(\xi)} Z_{i0}}{\eta + G_i/\gamma_i^*} \mid (x_i, y_i)\right] \\ &= \frac{\eta + e^{\beta\sigma_Y \mathrm{Q}^{-1}(\xi)} \mathrm{E}\left[e^{U_{i0}} \mid (x_i, y_i)\right]}{\eta + G_i/\gamma_i^*}. \end{aligned}$$

The mean value of f_i^2 for given (x_i, y_i) is

$$\mathrm{E}\left[f_i^2 \mid (x_i, y_i)\right] = \mathrm{E}[f_{i0}^2 \mid (x_i, y_i)] \Pr\{f_i = f_{i0} \mid (x_i, y_i)\}, \tag{24}$$

where $\mathrm{E}[f_{i0}^2 | (x_i, y_i)]$ is given at the top of the next page.

The movement pattern for each MS can be obtained through measurements or other approaches such as those in [18] and [19], thus the probability density function of its locations, $f_{x_i, y_i}(x, y)$, can be assumed to be known. Then the mean values of f_i and f_i^2 can be found as

$$\begin{aligned} \mathrm{E}[f_i] &= \iint_A \mathrm{E}[f_i \mid (x_i, y_i)] f_{x_i, y_i}(x, y) dx dy, \\ \mathrm{E}[f_i^2] &= \iint_A \mathrm{E}[f_i^2 \mid (x_i, y_i)] f_{x_i, y_i}(x, y) dx dy, \end{aligned}$$

where A is the system coverage area.

For homogeneous traffic, when all the MSs have independent and identically distributed (i.i.d.) location distributions, all ν_i's and all f_i's are independent and identically distributed for $i = 1, 2, \ldots, M$, and ν_i and f_i are independent of each other. When the number of connections, M, is large, f_0^t in (17) can be approximated as a Gaussian distributed random variable

$$\begin{aligned}\mathrm{E}[f_{i0}^2 \mid (x_i, y_i)] &= \mathrm{E}\left\{\left[\frac{\eta + e^{\beta\sigma_Y \mathrm{Q}^{-1}(\xi)} Z_{i0}}{\eta + G_i/\gamma_i^*}\right]^2 \mid (x_i, y_i)\right\} \\ &= \frac{\eta^2 + 2\eta e^{\beta\sigma_Y \mathrm{Q}^{-1}(\xi)}\mathrm{E}[e^{U_{i0}} \mid (x_i, y_i)] + e^{2\beta\sigma_Y \mathrm{Q}^{-1}(\xi)}\mathrm{E}[e^{2U_{i0}} \mid (x_i, y_i)]}{(\eta + G_i/\gamma_i^*)^2}.\end{aligned}$$

according to the Central Limit Theorem. The mean of f_0^t can be found as

$$\begin{aligned}\mu_f = \mathrm{E}[f_0^t] &= \mathrm{E}\left[\sum_{i=1}^M \nu_i f_i\right] = M\mathrm{E}\left[\nu_i f_i\right] \\ &= M\mathrm{E}\left[\nu_i\right]\mathrm{E}\left[f_i\right] = MP_{on}\mathrm{E}[f_i], \quad (25)\end{aligned}$$

where $P_{on} = \Pr\{\nu_i = 1\}$ is the probability of connection being in the ON state. The mean of $(f_0^t)^2$ can be found as

$$\begin{aligned}\mathrm{E}\left[(f_0^t)^2\right] &= \mathrm{E}\left[\left(\sum_{i=1}^M \nu_i f_i\right)^2\right] \\ &= \mathrm{E}\left[\sum_{i=1}^M \nu_i^2 f_i^2\right] + 2\mathrm{E}\left[\sum_{i=1}^{M-1}\sum_{j=i+1}^M \nu_i\nu_j f_i f_j\right] \\ &= M\mathrm{E}\left[\nu_i^2\right]\mathrm{E}\left[f_i^2\right] + 2\sum_{i=1}^{M-1}\sum_{j=i+1}^M \mathrm{E}[\nu_i\nu_j]\mathrm{E}[f_i f_j] \\ &= MP_{on}\mathrm{E}\left[f_i^2\right] + M(M+1)P_{on}^2\mathrm{E}^2[f_i]. \quad (26)\end{aligned}$$

Thus the variance of f_0^t is

$$\sigma_f^2 = \mathrm{E}\left[(f_0^t)^2\right] - \mu_f^2. \quad (27)$$

When traffic is uniformly distributed among all cells, all f_b^t's have the same statistical characteristics.

After performing the initial power allocation, the probability that BS 0 does not have sufficient power to provide transmissions for all the connections assigned to it is

$$\Pr\{f_0^t > 1 - p\} = \int_{1-p}^{\infty} N_{f_0^t}(F, \mu_f, \sigma_f)dF, \quad (28)$$

where $N_{f_0^t}(F, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(F-\mu)^2}{2\pi\sigma^2}}$ is the probability density function (pdf) of normally distributed random variable f_0^t which has a mean value μ and variance σ^2. When a BS is overloaded after the initial power allocation, the worst case is that all connections are removed from service. Therefore, the probability in (28) represents an upper bound of the connection unreliability after the initial power allocation.

B. Connection unreliability after power re-distribution

If $f_0^t > 1 - p$ after the initial power allocation, a power re-distribution phase is performed. Given that connection i has been assigned to BS 0 after performing the initial power allocation, and BS 0 does not have sufficient power resources to serve it, we define the following two probabilities:

- P_1: the probability that the connection satisfies $|\frac{Z_{i0}-Z_{i1}}{Z_{i0}+Z_{i1}}| < \delta$, but cannot receive its required SIR by simultaneously assigned to both BSs 0 and 1 through the power re-distribution.
- P_2: the probability that BS 1 alone does not have sufficient power resource to accommodate the connection using the power re-distribution.

Then the probability P_1 can be calculated as (29), where the product of the second and third probabilities on the right-hand side of (29) represents the probability that both BSs 1 and 0 have sufficient power to support the connection if it is assigned to be jointly served by the two BSs. The probability P_2 is given by

$$P_2 = \Pr\{f_1^t + f_{i1} > 1 - p\} \quad (30)$$

where $(f_1^t + f_{i1})P^m$ is the total required transmission power from BS 1 after moving connection from being served by BS 0 alone to being served by BS 1 alone.

Next we look at how to find the probabilities on the right-hand side of (29) and (30). The first probability on the right-hand side of (29) can be calculated as (31) and (32) and where

$$q_2 = \frac{\mu_{U_{i0}} - \mu_{U_{i1}} - \ln\left(\frac{1+\delta}{1-\delta}\right)}{\sqrt{\sigma_{U_{i0}}^2 + \sigma_{U_{i1}}^2 - 2\theta_U\sigma_{U_{i0}}\sigma_{U_{i1}}}}.$$

Since f_{i1} and f_1^t are independent of each other, the probability on the right-hand side of (30) for given MS location can be calculated as

$$\begin{aligned}&\Pr\{f_1^t + f_{i1} > 1 - p|(x_i, y_i)\} \\ &= \int_{-\infty}^{\infty}\int_{y_1}^{\infty} N_{f_1^t}(F, \mu_f, \sigma_f)N_{U_{i1}}(u, \mu_{U_{i1}}, \sigma_{U_{i1}})dFdu, \quad (33)\end{aligned}$$

where f_{i1} is a function of Z_{i1} given by

$$f_{i1} = \frac{\eta + e^{\beta\sigma_Y \mathrm{Q}^{-1}(\xi)} Z_{i1}}{\eta + G_i/\gamma_i^*}, \quad (34)$$

Z_{i1} is further a function of U_{i1} given by

$$Z_{i1} = e^{U_{i1}} \quad (35)$$

and y_1 is the lower integration limit of U_{i1} and can be calculated from (34), (35) and $f_1^t + f_{i1} > 1 - p$. Note that f_{i1} depends on MS's location, so does U_{i1} as it is shown in Appendix 2. Therefore, we have

$$\begin{aligned}&\Pr\{f_1^t + f_{i1} > 1 - p\} \\ &= \iint_A \Pr\{f_1^t + f_{i1} > 1 - p|(x_i, y_i)\}f_{x_i,y_i}(x, y)dxdy \quad (36)\end{aligned}$$

Similarly, since f_{is} in (29) is independent of f_1^t, both f_{is} and f_{i0} are independent of f_0^t; each of the two probabilities, $\Pr\{f_1^t + f_{is} < 1 - p\}$ and $\Pr\{f_0^t + f_{is} - f_{i0} < 1 - p\}$, on the right-hand side of (29), can be calculated in a way similar to (33)-(36).

Then an upper bound, P_u, of the connection unreliability after performing the power re-distribution phase can be found as follows:

$$P_u = (P_1 + P_2)\cdot\Pr\{f_0^t > 1 - p\}, \quad (37)$$

$$P_1 = 1 - \Pr\left\{\left|\frac{Z_{i0}-Z_{i1}}{Z_{i0}+Z_{i1}}\right| < \delta\right\} \cdot \Pr\{f_1^t + f_{is} < 1-p\} \cdot \Pr\{f_0^t + f_{is} - f_{i0} < 1-p\} \tag{29}$$

$$\Pr\left\{\left|\frac{Z_{i0}-Z_{i1}}{Z_{i0}+Z_{i1}}\right| < \delta\right\} = \iint_A \Pr\left\{\left|\frac{Z_{i0}-Z_{i1}}{Z_{i0}+Z_{i1}}\right| < \delta|(x_i,y_i)\right\} f_{x_i,y_i}(x,y)dxdy \tag{31}$$

$$\begin{aligned}\Pr\left\{\left|\frac{Z_{i0}-Z_{i1}}{Z_{i0}+Z_{i1}}\right| < \delta \mid (x_i,y_i)\right\} &= \Pr\left\{\left|\frac{e^{U_{i0}}-e^{U_{i1}}}{e^{U_{i0}}+e^{U_{i1}}}\right| < \delta \mid (x_i,y_i)\right\}\\ &= \Pr\left\{\ln\left(\frac{1-\delta}{1+\delta}\right) < U_{i0}-U_{i1} < \ln\left(\frac{1+\delta}{1-\delta}\right) \mid (x_i,y_i)\right\}\\ &= \begin{cases} \mathrm{Q}(q_2)-\mathrm{Q}(-q_1), & \text{when } \mu_{U_{i0}}-\mu_{U_{i1}} \geq \ln\left(\frac{1+\delta}{1-\delta}\right),\\ 1-\mathrm{Q}(-q_1)-\mathrm{Q}(-q_2), & \text{when } \ln\left(\frac{1-\delta}{1+\delta}\right) < \mu_{U_{i0}}-\mu_{U_{i1}} < \ln\left(\frac{1+\delta}{1-\delta}\right),\\ \mathrm{Q}(q_1)-\mathrm{Q}(-q_2), & \text{when } \mu_{U_{i0}}-\mu_{U_{i1}} \leq \ln\left(\frac{1-\delta}{1+\delta}\right),\end{cases}\end{aligned} \tag{32}$$

which is the probability that the BSs do not have sufficient power to serve all the connections assigned to it after performing the initial power allocation and one round of power re-distribution.

V. Numerical Results

We consider a cellular system with 19 hexagonal cells as shown in Fig. 1. For each connection, we consider that the interference is from the serving BS (for transmitting to other connections) and from all the first-tier BSs surrounding the serving BS. The cell size, which is the distance from the BS to one of the corners of the cell, is normalized to 1. The maximum transmission power is assumed to be the same for all BSs and normalized to 1. Unless otherwise stated, the parameters used in the simulation and analysis are as follows. The system has 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 maximum outage probability, ξ, for each cell is 1%. The channel transmission orthogonality factor, η, is 0.5. The standard deviation of power control errors, σ_Y, is 2 dB. The required transmission rate, R_i, for each connection is 9.6 kbps. The required SIR, γ_i^*, for each connection is 6.8 dB. The value of δ is 5%. The traffic load and MSs are uniformly distributed in the system coverage area. We collect data from the center cell (cell 0 in Fig. 1) only in order to reduce the boundary effect.

Fig. 3 shows the simulation performance of the proposed soft handoff scheme together with the analytical performance bounds derived in Section IV. It can be seen that the derived bounds are very close to the simulation results when the traffic load is relatively low. As the number of the MSs increases, the difference between the derived bound and the simulation results increases. This is because not all possible power re-distribution operations are considered in the analysis when deriving the connection unreliability bound. For example, if both BSs 0 and 1 are overloaded while BS 2 still has power resources remaining after performing the initial power allocation, a connection located near the boundary between the two cells is considered as unreliable (i.e., temporarily removed from service) when deriving the unreliability bound. However, when performing the power re-distribution, connections

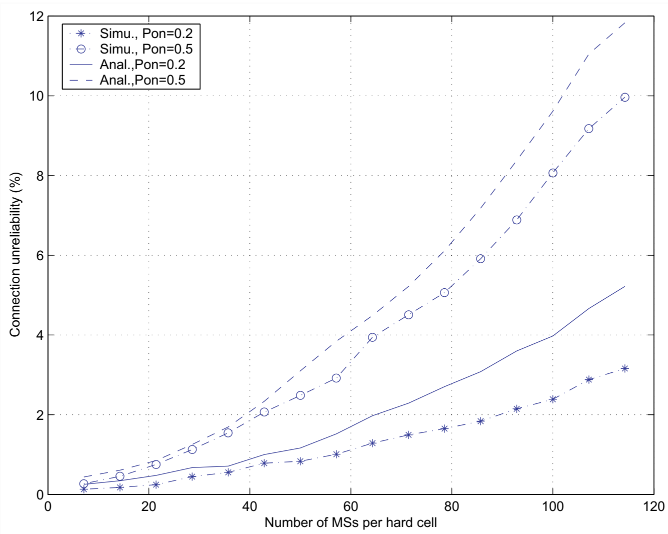

Fig. 3. Performance of the proposed SHO scheme.

located between BSs 0 and 1 may still be accommodated in the system by moving some connections in BSs 0 or/and 1 to BS 2. As the number of MSs in the system increases, the chance for power re-distribution increases, which is the main reason for the difference between the simulation results and the analytical bound.

Equation (28) is an upper bound of the connection unreliability using the initial power allocation only in the soft handoff. Fig. 4 shows that the analytical results are close to the simulation results when traffic load is relatively low. As the traffic load increases, the difference between the simulation results and the analytical bound increases due to the effect of statistical multiplexing the random channel conditions (and transmission powers).

Fig. 5 compares the connection unreliability performance of the proposed soft handoff scheme and the hard handoff scheme. It shows that the proposed soft handoff scheme improves the connection reliability significantly. This is achieved by first connecting to the BS with the best link quality, and then making use of the randomness of the traffic loads in neighboring cells and finding the currently available BS. For

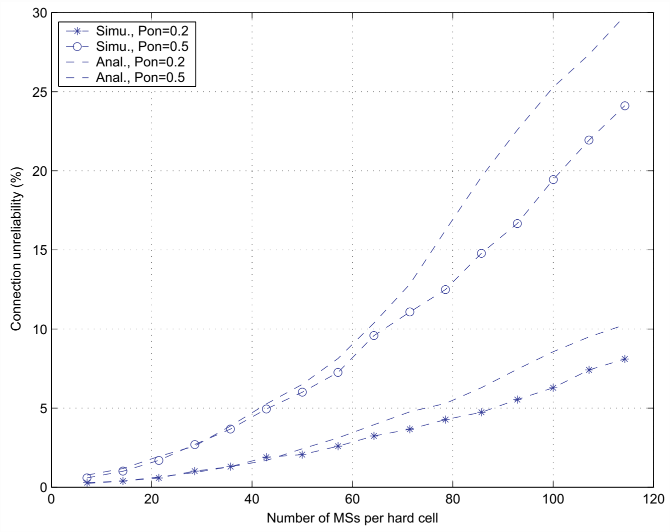

Fig. 4. Performance of the soft handoff with initial power allocation only.

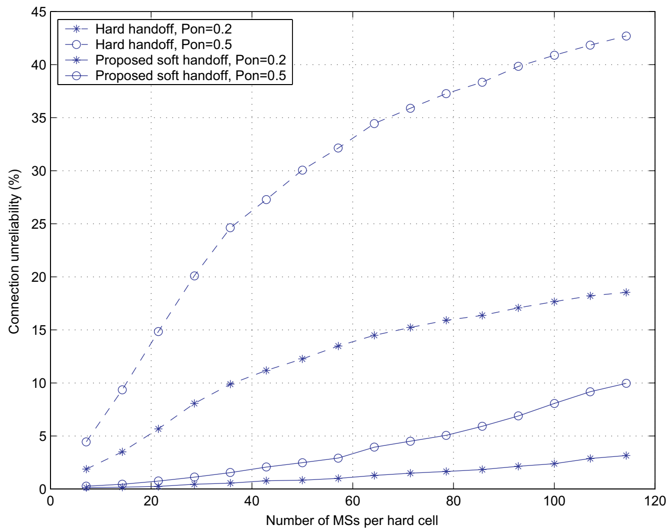

Fig. 5. Comparison between the proposed SHO scheme and the hard handoff.

given connection reliability requirement, this is equivalent to capacity improvement. The improvement is even more significant when traffic load is higher because of the statistical multiplexing of the channel conditions of different connections and the instantaneous traffic load among different cells.

Fig. 6 further compares the performance of the proposed two-phase soft handoff scheme (with both the initial power allocation and the power re-distribution) and a soft handoff scheme with the initial power allocation only. It can be seen that the proposed scheme achieves much better connection reliability than that with the initial power allocation only. The performance difference is achieved through power re-distribution between neighboring BSs. As the number of MSs increases, the improvement of using the power re-distribution increases. The results show that cellular CDMA system capacity can be significantly improved through coordinating resource allocations between neighboring BSs. This improvement comes from the coordination and sharing of power resources between neighboring BSs. Obvious, the complexity

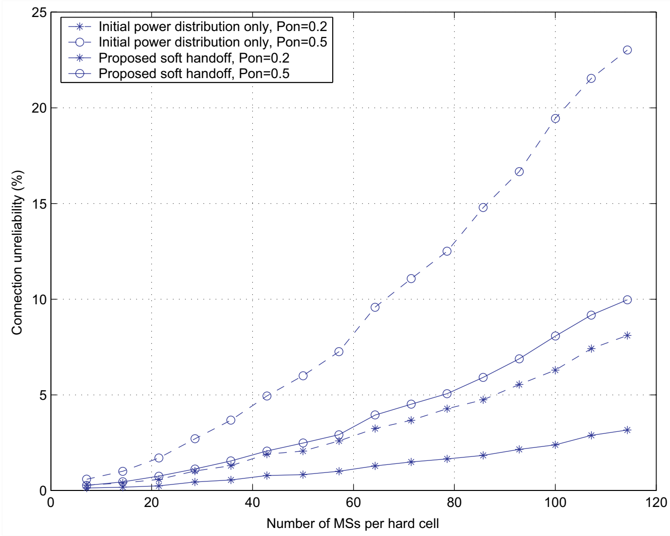

Fig. 6. Comparison between the proposed SHO scheme and the scheme with initial power allocation only.

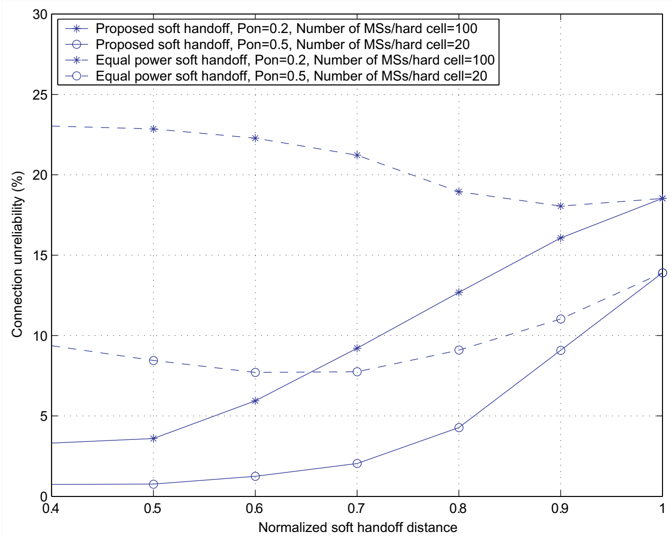

Fig. 7. Comparison between the proposed SHO scheme and the equal power soft handoff scheme.

is increased to implement the proposed two-phase scheme, compared to the scheme with initial power allocation only. However, since this operation is done in the MSC, which is usually powered with high computational capability and able to coordinate the resource allocations for all BSs and MSs connected to it. Furthermore, this power allocation coordination is not a global optimization. Instead, most of the operations are done between immediate neighboring cells. Therefore, it is still worth to implement the soft handoff scheme for high capacity and improved connection reliability.

Fig. 7 compares the connection reliability of the proposed soft handoff scheme with the "equal power scheme" in [11] and [12] as the soft handoff distance changes. The soft handoff distance is defined same as that in [11] and [12]: when the MS's distance from its nearest BS is less than the soft handoff distance, the MS can only be served by its nearest BS; otherwise, the MS enters a soft handoff area and can

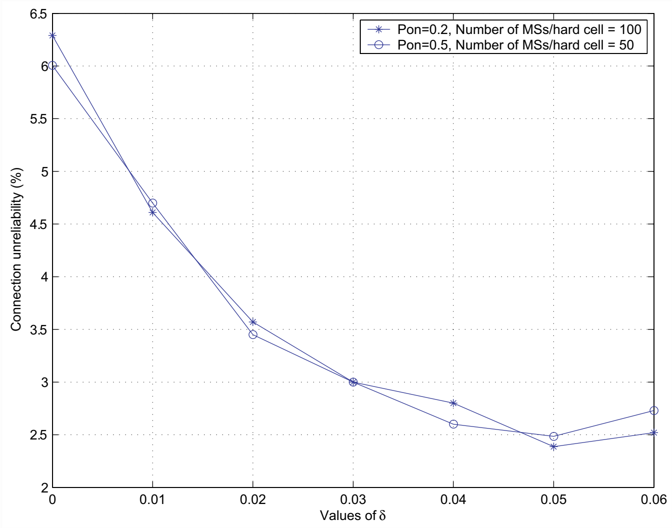

Fig. 8. Effect of values of δ on connection unreliability.

be served by the two nearest BSs. In this simulation, the soft handoff area is assumed to be a circular area within the hard cell and centered at the BS, although the hard cell is still hexagonal. When the soft handoff distance is 1, both schemes are equivalent to the hard handoff. The amount of the distributed power for a connection when the MS enters the soft handoff area depends on the specific schemes used. As the soft handoff distance decreases, i.e., the soft handoff area increases, the connections become more reliable using the proposed soft handoff algorithm, since connections using the proposed soft handoff algorithm have higher possibility to make use of the resource availability in neighboring cells. For the equal power scheme, the connections have the highest reliability when the soft handoff distance is around certain values, which is around 0.7 when the number of MSs per hard cell is 20 and the active probability is 0.5. As the soft handoff distance further decreases, the connection becomes more unreliable. This is due to some contradictory effect of the scheme on the power distribution. A larger soft handoff area (smaller soft handoff distance) allows more connections to use the resources in both BSs. However, when the link quality with the two BSs is significantly different, a connection using the equal power scheme requires much more total power resources than that in the hard handoff. Fig. 7 also shows that as the number of MSs increases, there is little improvement of connection reliability using the equal power scheme.

In Fig. 8 some selected results are shown to demonstrate the effect of different values of δ on the connection reliability. As δ increases, it allows more connections to have a choice to be served jointly by two BSs, which increases the chance that a connection can receive its required QoS and improves the connection reliability. However, as δ increases, the difference between the link quality of the connection to the two nearest BSs increases. In this case, the total amount of transmission power from the two BSs jointly serving the connection increases, which reduces the overall connection reliability. According to our simulation results, the value of δ should be around 5% in order to achieve good connection reliability.

VI. Conclusions and Further Research

A soft handoff/power distribution scheme has been proposed for cellular CDMA downlinks, and its effect on connection reliability has been studied. The proposed soft handoff scheme can significantly improve the connection reliability by efficiently distributing the power resources and coordinating power resource allocation among neighboring cells. The improved connection reliability for given traffic load can be translated to an increase in system capacity for given connection reliability requirement. Further research includes how the soft handoff scheme and power distribution law affect packet transmission scheduling and connection admission control in cellular CDMA systems.

Appendix 1: Derivation of μ_{H_i} and $\sigma^2_{H_i}$

Expressions for μ_{H_i} and $\sigma^2_{H_i}$ can be derived by taking the first two moments of e^{H_i} in (14). This yields

$$\mathrm{E}[e^{H_i}] = e^{\mu_{H_i}+\sigma^2_{H_i}/2} = (Z_{i0}+Z_{i1})e^{\beta^2\sigma^2_Y/2}. \qquad (38)$$

and

$$\begin{aligned}\mathrm{E}[e^{2H_i}] &= e^{2\mu_{H_i}+2\sigma^2_{H_i}}\\ &= (Z^2_{i0}+Z^2_{i1})e^{2\beta^2\sigma^2_Y} + 2Z_{i0}Z_{i1}e^{(1+\theta_Y)\beta^2\sigma^2_Y}, \qquad (39)\end{aligned}$$

where $\theta_Y = \frac{\mathrm{E}[Y_{i0}Y_{i1}]}{\sigma^2_Y}$ is the correlation coefficient between Y_{i0} and Y_{i1}. Since the measurements of Z_{i0} and Z_{i1} share some common link gains, $\theta_Y > 0$. Thus, μ_{H_i} and $\sigma^2_{H_i}$ can be found from (38) and (39) as

$$\mu_{H_i} = 2\ln(\mathrm{E}[e^{H_i}]) - \tfrac{1}{2}\ln(\mathrm{E}[e^{2H_i}]), \qquad (40)$$

$$\sigma^2_{H_i} = \ln(\mathrm{E}[e^{2H_i}]) - 2\ln(\mathrm{E}[e^{H_i}]). \qquad (41)$$

Appendix 2: Derivation of $\mu_{U_{i0}}$, $\mu_{U_{i1}}$, $\sigma^2_{U_{i0}}$, $\sigma^2_{U_{i1}}$, and θ_u

Taking the mean values of $e^{U_{i0}}$ and $e^{U_{i1}}$, respectively, we have

$$\begin{aligned}&\mathrm{E}\left[e^{U_{i0}} \mid (x_i,y_i)\right]\\ &= e^{\mu_{U_{i0}}+\sigma^2_{U_{i0}}/2} = \textstyle\sum_{b=1}^{B}\left(\frac{d_{i0}}{d_{ib}}\right)^{\alpha} e^{\beta^2\sigma^2_X}e^{\beta^2\sigma^2_Y/2}, \qquad (42)\end{aligned}$$

$$\begin{aligned}&\mathrm{E}\left[e^{U_{i1}} \mid (x_i,y_i)\right]\\ &= e^{\mu_{U_{i1}}+\sigma^2_{U_{i1}}/2} = \textstyle\sum_{b=b_1}^{b_B}\left(\frac{d_{i1}}{d_{ib}}\right)^{\alpha} e^{\beta^2\sigma^2_X}e^{\beta^2\sigma^2_Y/2}. \qquad (43)\end{aligned}$$

The mean values of $e^{2U_{i0}}$ and $e^{2U_{i1}}$ can be calculated as

$$\begin{aligned}&\mathrm{E}\left[e^{2U_{i0}} \mid (x_i,y_i)\right] = e^{2\mu_{U_{i0}}+2\sigma^2_{U_{i0}}}\\ &= \textstyle\sum_{b=1}^{B}\left(\frac{d_{i0}}{d_{ib}}\right)^{2\alpha} e^{4\beta^2\sigma^2_X}e^{2\beta^2\sigma^2_Y}\\ &+2\textstyle\sum_{b'=1}^{B-1}\sum_{b''=b'+1}^{B}\left(\frac{d_{i0}d_{i0}}{d_{ib'}d_{ib''}}\right)^{\alpha} e^{3\beta^2\sigma^2_X}e^{2\beta^2\sigma^2_Y}, \qquad (44)\end{aligned}$$

$$\begin{aligned}&\mathrm{E}\left[e^{2U_{i1}} \mid (x_i,y_i)\right] = e^{2\mu_{U_{i1}}+2\sigma^2_{U_{i1}}}\\ &= \textstyle\sum_{b=b_1}^{b_B}\left(\frac{d_{i1}}{d_{ib}}\right)^{2\alpha} e^{4\beta^2\sigma^2_X}e^{2\beta^2\sigma^2_Y}\\ &+2\textstyle\sum_{b'=b_1}^{b_B-1}\sum_{b''=b'+1}^{b_B}\left(\frac{d_{i1}d_{i1}}{d_{ib'}d_{ib''}}\right)^{\alpha} e^{3\beta^2\sigma^2_X}e^{2\beta^2\sigma^2_Y}. \qquad (45)\end{aligned}$$

With (42) and (44), $\mu_{U_{i0}}$ and $\sigma^2_{U_{i0}}$ can be found as

$$\mu_{U_{i0}} = 2\ln\left(\mathrm{E}\left[e^{U_{i0}} \mid (x_i, y_i)\right]\right) - \tfrac{1}{2}\ln\left(\mathrm{E}\left[e^{2U_{i0}} \mid (x_i, y_i)\right]\right),$$
$$\sigma^2_{U_{i0}} = \ln\left(\mathrm{E}\left[e^{2U_{i0}} \mid (x_i, y_i)\right]\right) - 2\ln\left(\mathrm{E}\left[e^{U_{i0}} \mid (x_i, y_i)\right]\right).$$

Similarly, with (43) and (45), $\mu_{U_{i1}}$ and $\sigma^2_{U_{i1}}$ can be found as

$$\mu_{U_{i1}} = 2\ln\left(\mathrm{E}\left[e^{U_{i1}} \mid (x_i, y_i)\right]\right) - \tfrac{1}{2}\ln\left(\mathrm{E}\left[e^{2U_{i1}} \mid (x_i, y_i)\right]\right),$$
$$\sigma^2_{U_{i1}} = \ln\left(\mathrm{E}\left[e^{2U_{i1}} \mid (x_i, y_i)\right]\right) - 2\ln\left(\mathrm{E}\left[e^{U_{i1}} \mid (x_i, y_i)\right]\right).$$

The mean value of $e^{U_{i0}+U_{i1}}$ can be calculated by

$$\begin{aligned}\mathrm{E}\left[e^{U_{i0}+U_{i1}} \mid (x_i, y_i)\right] &= e^{\mu_{U_{i0}}+\mu_{U_{i1}}+\frac{1}{2}\sigma^2_{U_{i0}}+\frac{1}{2}\sigma^2_{U_{i1}}+\theta_U\sigma_{U_{i0}}\sigma_{U_{i1}}} \\ &= \sum_{b=1}^{B}\sum_{\substack{b'=b_1\\ b'\neq b}}^{b_B}\left(\frac{d_{i0}d_{i1}}{d_{ib}d_{ib'}}\right)^{\alpha} e^{2\beta^2\sigma_X^2} e^{(1+\theta_Y)\beta^2\sigma_Y^2} \\ &\quad + \sum_{b\in\mathcal{B}_{0,1}}\left(\frac{d_{i0}d_{i1}}{d_{ib}d_{ib}}\right)^{\alpha} e^{3\beta^2\sigma_X^2} e^{(1+\theta_Y)\beta^2\sigma_Y^2}, \qquad (46)\end{aligned}$$

where $\mathcal{B}_{0,1}$ is the set of the BSs that interfere both cells 0 and 1, θ_U is the correlation coefficient between U_{i0} and U_{i1} and can be found from (46) as

$$\theta_U = \frac{\ln\left\{\mathrm{E}\left[e^{U_{i0}+U_{i1}} \mid (x_i, y_i)\right]\right\} - (\mu_{U_{i0}}+\mu_{U_{i1}}) - \frac{1}{2}(\sigma^2_{U_{i0}}+\sigma^2_{U_{i1}})}{\sigma_{U_{i0}}\sigma_{U_{i1}}}. \qquad (47)$$

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