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Comparison of Downlink Power Allocation Mechanisms in Soft Handoff for the WCDMA System with Heterogeneous Cell Structures*

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Abstract. Handoff in heterogeneous cellular networks is one of the hot topics for wireless networks beyond the third generation. We observe that a *power exhausting* issue may occur in a code division multiple access (CDMA) system with mixed-sized cells. During soft handoff in the downlink transmission, a number of base stations transmit signals to a user simultaneously. Usually, a microcell has a more stringent limitation on the total available power than a macrocell. Thus, ignoring the impact of various cell sizes, the traditional downlink power allocation techniques for soft handoff may easily consume excessive power to serve soft handoff users, while leaving insufficient power for serving other regular users.

To resolve such an power exhausting issue in CDMA systems, we investigate different downlink power allocation techniques used in soft handoff subject to the impact of mixed-sized cells. For the single-site power allocation technique we consider the site selection diversity transmission (SSDT) technique, while for the multi-site power allocation we study the link proportional power allocation (LPPA), the quality balancing power allocation (QBPA), and the equal power allocation (EPA) techniques. We find that the multi-site LPPA technique can more efficiently allocate power to both handoff and non-handoff users than others. In an example with the ratio of the micrcocell radius/macrocell radius equal to 1/3, it is demonstrated that LPPA can improve the capacity over EPA, QBPA, and SSDT by 125, 30, and 5%, respectively. By taking account of measurement errors in the same case, the capacity improvements of LPPA over EPA, QBPA, and SSDT become 180, 41, and 23%, respectively.

Keywords: soft handoff, CDMA, power allocations, heterogeneous cellular structures

1. Introduction

Soft handoff is an important technique for the code division multiple access (CDMA) cellular system. Traditional soft handoff algorithms are mainly developed for the homogeneous cellular system. In practice, however, in order to extend the coverage area or increase system capacity, a cluster of microcells may be employed at the boundaries of surrounding macrocells. Thus, a heterogeneous cellular network will occur naturally as shown in figure 1. Although soft handoff has been extensively investigated in the literature, fewer works have concentrated on evaluating the soft handoff performance in heterogeneous cellular environments.

The major goal of this paper is to evaluate the impact of various cell sizes on CDMA systems from the downlink soft handoff performance perspective. We focus on the downlink soft handoff because for the future wireless Internet services the traffic volume in the downlink will be much higher than that in the uplink. We observe a "power exhausting" issue that may occur in the handoff process of a heterogeneous cellular network. The power exhausting issue results from the fact that the total transmission power of a base station is constrained by a maximum value and a microcell usually has a more stringent limitation on the total available power than a macrocell. Thus, ignoring the impact of various cell sizes, the traditional downlink power allocation techniques for soft handoff may easily consume excessive power to serve soft handoff users, while leaving insufficient power for serving other regular users.

The previous works about downlink power allocation for soft handoff in CDMA systems can be summarized as follows. In [20], the authors examined the impact of soft handoff on downlink capacity of the CDMA system in a homogeneous cellular structure. It was mentioned that soft handoff can maximize the diversity gain when the involved serving base stations allocate the same amount of power to a user. In this paper, if the serving base stations allocate the same amount of power to the handoff user, we call it the equal power allocation (EPA) method. In [11], a simple quality balancing algorithm was proposed to adjust cell-site transmitter power for non-handoff and handoff users in the downlink. We call the power allocation method of [11] as the quality balancing power allocation (QBPA) method in this paper. In [4], it was shown that EPA-based downlink soft handoff may decrease system capacity due to unequal path gains from a handoff user to the two serving base stations. Furukawa [6] proposed a site selection diversity transmission (SSDT) technique for CDMA downlink transmissions to select a serving base station with the best link quality among the active set. In [19], the author proposed an enhanced SSDT technique to allow more than one base station to transmit signals to the handoff user. Blaise

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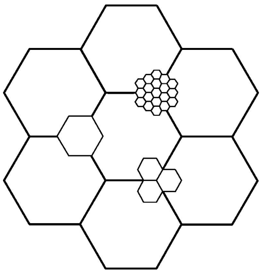

Figure 1. The heterogeneous cellular model.

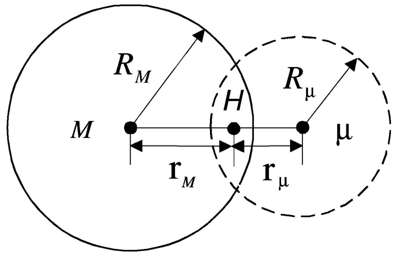

Figure 2. A simplified heterogeneous cellular model.

et al. [3] presented a a cost-function based differentiated power control technique to determine different power levels of each radio link from two base stations to the handoff user. Staehle et al. [18] proposed two proportional power allocation methods, in terms of transmission power and target signal quality. In our previously proposed *link proportional power allocation* (LPPA) technique [21], the base station with better link quality will be responsible for allocating more power to the handoff user. It was shown that LPPA can alleviate the power exhausting issue for the microcellular CDMA system. None of the aforementioned downlink power allocation for soft handoff have been evaluated in a cellular system with mixed-sized cells.

With respect to the performance of heterogeneous CDMA cellular systems, some works have been reported in the literature [10,12,16,22]. In [22], it was concluded that the capacity of a hierarchical cellular system can be improved by integrating downlink power control of microcells and uplink power control of a macrocell. In [10] it was found that for a CDMA system with mixed-sized cells, the interference from adjacent macrocell may decrease the uplink capacity improvements resulting from cell splitting. In [16] the authors suggested tier selection algorithms to improve the uplink capacity of a microcell/macrocell overlaying system. In [12], a macrodiversity scheme was proposed to enable a hierarchical CDMA system to share the same spectrum between the macrocell and the microcell by adopting the SSDT technique in the downlink and the maximal ratio combining technique in the uplink. To our knowledge, in an environment with a cluster of microcells surrounded by macrocells, the downlink capacity of such a CDMA system considering both handoff and power control has not been fully addressed in the literature.

Aiming to resolve the power exhausting issue for a CDMA system with mixed-sized cells, this paper investigates different downlink power allocation techniques used in soft handoff. To this end, we consider the single-site SSDT power allocation technique, while for the multi-site power allocation technique, we investigate LPPA, QBPA, and EPA. To obtain an overall evaluation, in addition to power allocation and soft handoff, through a process of distinguishing handoff users from regular power-controlled users, we further consider the distributed constrained power control [1] and temporary removal algorithms [2]. Through simulations, it will be demonstrated that the LPPA technique can deliver higher system capacity in a CDMA system with mixed-sided cells than other considered downlink power allocation techniques.

The rest of this paper is organized as follows. Section 2 describes the system model. Section 3 discusses the related downlink handoff power allocation algorithms. Section 4 illustrates the power exhausting problem for downlink soft handoff in a heterogeneous cellular network. Section 5 analyzes system capacity. Section 6 details the operation of a CDMA system integrating soft handoff, power control, and removal procedures. Simulation model and numerical results are shown in Section 7. We give our concluding remarks in Section 8. We also prove the convergent characteristics of the LPPA algorithm in Appendix.

2. System model

2.1. Signal model

Consider a simplified heterogeneous cellular model with a single microcell adjacent to a macrocell as shown in figure 2. Denote R_M and R_μ as the radii of the macrocell M and the microcell μ. In the figure, a user is located at H with the distance of r_M and r_μ to the macrocell M and the microcell μ, respectively.

Denote $q_{i,j}$ as the transmission power from base station i to user j. Let $\Gamma(q_{i,j})$ be the downlink received bit energy-to-noise density ratio (i.e., E_b/N_o). Then $\Gamma(q_{i,j})$ can be written by

$$\Gamma(q_{i,j}) = \frac{q_{i,j} \cdot L_{i,j} \cdot G}{(P_i - q_{i,j}) \cdot L_{i,j} + \sum_{k,k\neq i}^{N} P_k \cdot L_{k,j} + \eta_o} \geq \gamma_{req}, \tag{1}$$

where $L_{i,j}$ is the radio link attenuation from cell i to user j; G is the processing gain; $P_i = \sum_{j=1}^{N} q_{i,j}$ is the total downlink transmission power of base station i; N is the number of active users in cell i; η_o is the background noise; and γ_{req} is the required E_b/N_o. By including the effects of both path loss and shadowing, $L_{i,j}$ can be expressed by

$$L_{i,j} = \frac{A}{d_{i,j}^{\alpha}\left(1 + \left(\frac{d_{i,j}}{z_i}\right)^{\beta}\right)} \times 10^{\xi_i/10}, \tag{2}$$

where α and β are the path loss exponents, $d_{i,j}$ is the distance from user j to the base station i, z_i is the break point in cell i, and A is a constant. In (2), the standard deviation of the shadowing ξ_i is described by a distance dependent variable [13], i.e.,

$$\sigma_i(d_{i,j}) = \begin{cases} \sigma_1, & d_{i,j} \le z_i \\ \sigma_2, & d_{i,j} > z_i. \end{cases} \quad (3)$$

The breakpoint z_i is given by

$$z_i = \frac{4\, h_i\, h_{ms}}{\lambda}, \quad (4)$$

where h_i is the antenna height of base station i, h_{ms} the antenna height at the user side, and λ the wavelength. We define the cell boundary as the point at which user j receives the same power from both adjacent cells M and μ first [17]. Then at the cell boundary, we have

$$\tilde{P}_M \times L_{M,j} = \tilde{P}_\mu \times L_{\mu,j}, \quad (5)$$

where $\tilde{P}_M$ and $\tilde{P}_\mu$ represent the base station pilot power of a macrocell and microcell, respectively. For simplicity, we only consider the effect of path loss in (5) first. Then, combining (2) and (5), we have

$$\frac{\tilde{P}_M}{\tilde{P}_\mu} = \frac{L_{\mu,j}}{L_{M,j}} = \frac{R_M^\alpha\left(1 + \left(\frac{R_M}{z_M}\right)^\beta\right)}{R_\mu^\alpha\left(1 + \left(\frac{R_\mu}{z_\mu}\right)^\beta\right)} \propto \left(\frac{R_M}{R_\mu}\right)^{\alpha+\beta} \times \left(\frac{h_\mu}{h_M}\right)^\beta. \quad (6)$$

Note that (6) is valid only when the microcell radius is larger than the break point distance. When considering only the microcell interference in (1), we have

$$\begin{aligned} q_{i,j} &\ge \frac{\gamma_{\text{req}} \cdot (P_M \cdot L_{M,j} + P_\mu L_{\mu,j})}{(G + \gamma_{\text{req}}) \cdot L_{M,j}}, \\ &= \frac{\gamma_{\text{req}}}{(G + \gamma_{\text{req}})} \cdot \left(P_M + P_\mu \frac{L_{\mu,j}}{L_{M,j}}\right), \\ &= \frac{\gamma_{\text{req}}}{(G + \gamma_{\text{req}})} \cdot \left\{P_M + P_\mu\, D_j\, 10^{(\xi_\mu - \xi_M)/10}\right\}, \end{aligned} \quad (7)$$

where

$$D_j = \frac{\left(d_\mu^{-\alpha_\mu}\left(1 + \frac{d_\mu}{z_\mu}\right)^{-\beta_\mu}\right)}{\left(d_M^{-\alpha_M}\left(1 + \frac{d_M}{z_M}\right)^{-\beta_M}\right)}. \quad (8)$$

To make macrocell users have the required E_b/N_o, the maximum allocating transmission power $\hat{q}_M$ can be obtained by substituting the maximum total base station transmission power $\hat{P}_M$ and $\hat{P}_\mu$ in (7). Then, we have

$$\hat{q}_M = \frac{\gamma_{\text{req}}}{(G + \gamma_{\text{req}})}(\hat{P}_M + \hat{P}_\mu \cdot D_j), \quad (9)$$

where D_j is given in (8). For simplicity, we only consider the effect of path loss in (5). Note that the total transmission power of the base station is dependent on the summation of the power allocated for each user. Note that $\hat{q}_M$ indicates the power level allocated to a user at the macrocell boundary. From (6) and (9), the maximal downlink allocating power for a microcell user can be obtained as

$$\hat{q}_\mu = \hat{q}_M \cdot \frac{L_{M,j}}{L_{\mu,j}}. \quad (10)$$

In this paper, we adopt the maximum ratio combining in the downlink soft handoff. Thus, based on [7], the optimal received E_b/N_o for user j during soft handoff is given by

$$\Gamma(q_{M,j},\ q_{\mu,j}) = \Gamma(q_{M,j}) + \Gamma(q_{\mu,j}), \quad (11)$$

where $\Gamma(q_{M,j},\ q_{\mu,j})$ denotes the E_b/N_0 after the maximum ratio combining for macrocell transmitting at the power level $q_{M,j}$ and microcell transmitting at $q_{\mu,j}$, respectively; $\Gamma(q_{M,j})$ and $\Gamma(q_{\mu,j})$ are the received E_b/N_0 from the macrocell base station and that from the microcell base station before combining, respectively.

3. Related work

A downlink handoff process consists of three different aspects: (1) decide when to execute the handoff; (2) manage resources among the base stations in the active set; (3) optimize handoff parameters. In this paper, we consider the second issue. To manage resources during downlink soft handoff is actually the issue of allocating power from multiple cells to a user. In the literature, different downlink power allocation techniques have been proposed, such as EPA [20], QBPA [11], SSDT) [6], and LPPA [21]. In the following, we denote q_i, Γ_i, and L_i as transmission power, the received SIR and the link gain from base station i in an active set Υ , respectively. Represent $|\Upsilon|$ as the size of the active sect and SIR_{req} as the required link quality for a handoff user.

3.1. Equal power allocation

When a user requests handoff, it is implied that other base stations in the active set can provide better link quality than the original base station. Based on the EPA technique, base stations allocate power to a handoff user in the following two steps:

- From the link quality of the original serving base station i, obtain the required allocated power (denoted as q_i) for a particular user.
- All the base stations in the active set will allocate $\frac{q_i}{|\Upsilon|}$ to the handoff user.

3.2. Quality balancing power allocation

In [11], a simple quality balancing power allocation (QBPA) technique was introduced from a power control perspective. The basic idea of QBPA is to allocate more power to a user with poor link quality, while assigning less power to a user with better link quality. The QBPA technique allocates power to a handoff user according to the following principle:

$$q_1 L_1 = q_2 L_2 = \cdots = q_{|\Upsilon|} L_{|\Upsilon|}. \quad (12)$$

3.3. Site selection diversity transmission (SSDT)

Another interesting downlink transmission technique is the site selection diversity transmission (SSDT). The SSDT

technique always selects the best base station to serve the handoff users. Because of this, it can transmit the least power, thereby decreasing the downlink interference. Let q'_i ($i = 1, \cdots, |\Upsilon|$) be the required transmission power for base station i to achieve the required link quality SIR_{req}. According to the SSDT technique, transmission power is allocated as follows:
if

$$\ell = \arg_i \min\{q'_1, q'_2, \cdots, q'_{|\Upsilon|}\}, \tag{13}$$

then

$$q_i = \begin{cases} \min\{q'_1, q'_2, \ldots, q'_{|\Upsilon|}\}, & \text{if } i = \ell \\ 0, & \text{if } i \neq \ell \end{cases} \tag{14}$$

3.4. Link proportional power allocation (LPPA)

The link proportional power power allocation (LPPA) technique was suggested in [21]. According to LPPA, the transmission power of a base station during handoff should be proportional to the link gain between the handoff user to its serving base stations. In other words, LPPA aims to find a set of q_i ($i = 1$ to $|\Upsilon|$) such that $\sum \Gamma_i \geq SIR_{\text{req}}$ and

$$q_1 : q_2 : \cdots : q_{|\Upsilon|} = L_1 : L_2 : \cdots : L_{|\Upsilon|}. \tag{15}$$

4. The power exhausting issue

In this section, we will illustrate the power exhausting issue of a CDMA system with mixed-sized cells, as shown in figure 3. We assume that a macrocell M and a microcell μ simultaneously serve user h at the cell boundary who is moving from the macrocell to the microcell. In the figure, the height of the blocks is defined as the maximal allocation power level of the cell and the width of the blocks is proportional to the link quality, where $L_{M,h}$ and $L_{\mu,h}$ represent link quality from user h to macrocell base station M and that to microcell base station μ, respectively. We represent the equivalent received signal quality of user h by the product of multiplying the allocation power and the link quality. For example, for the homogeneous cellular systems case as shown in figure 3(a), the required received signal quality equals 12 (6 × 2) units before handoff. Here, we compare the following power allocation techniques: (1) EPA, (2) QBPA, (3) SSDT, and (4) LPPA.

For the homogeneous cellular systems as in figure 3(a), assume that user h has equal link quality between macrocell and microcell, and it receives the same signal strength from macrocell and microcell, respectively. In this case, all the three power allocation methods will be the same.

Consider a heterogeneous cellular systems as shown in figure 3(b). Let the link quality to the microcell be two times of that to the macrocell, i.e. $L_{\mu,h} = 2L_{M,h}$, and the maximum transmission power in the macroell be two times of that in the microcell. Then the distributions of power allocation from the two serving base stations based on different techniques are discussed as follows.

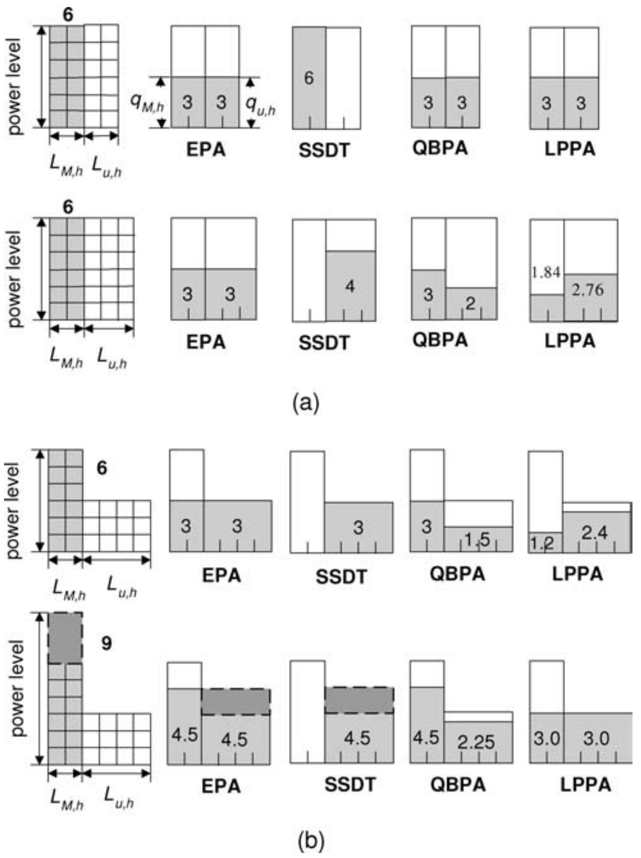

Figure 3. Example for different soft handoff downlink power allocation techniques. (a) homogeneous cellular system and (b) heterogeneous cellular system.

- Equal power allocation (EPA):
  $q_{M,h} = q_{\mu,h} = 3$,
  $\Rightarrow \Gamma_h = 18$,
  where $q_{M,h}$ and $q_{\mu,h}$ are the allocated power from the macrocell and that from the microcell, respectively; and Γ_h is the received signal quality.

- Quality balancing power allocation (QBPA) [11]:
  $q_{M,h} = \frac{(12/2)}{L_{M,h}} = 3$, $q_{\mu,h} = \frac{(12/2)}{L_{\mu,h}} = 1.5$,
  $\Rightarrow \Gamma_h = 12$.

- Site Selection Diversity Transmission (SSDT):
  $q_{M,h} = 0$, $q_{\mu,h} = 3$,
  $\Rightarrow \Gamma_h = 12$.

- Link proportional power allocation (LPPA):
  $\frac{q_{M,h}}{q_{\mu,h}} = \frac{L_{M,h}}{L_{\mu,h}} = \frac{1}{2}$,
  $q_{M,h}L_{M,h} + q_{\mu,h}L_{\mu,h} = 12$.
  $q_{M,h} = 1.2$, $q_{\mu,h} = 2.4$,
  $\Rightarrow \Gamma_h = 12$.

Note that EPA will ask the serving base stations to allocate the same power in the two active links, thereby making a "microcell" waste too much power to obtain higher received signal quality. Thus, the handoff users from a macrocell will be very likely to exhaust most of the power budget in the microcell. This is so called "power exhausting issue". Based on the QBPA technique, the total allocated power to the user is 4.5, whereas the LPPA technique only require the total power of 3.6 to maintain the same signal quality before handoff. As for SSDT, we find that SSDT can allocate the least power to achieve the required signal quality for a handoff user. However, when considering measurement errors during the base station selection procedure, SSDT many select a wrong base station, thereby consuming more power to serve handoff users. The impact of measurement errors on SSDT and other power allocation techniques will be compared in Section 7.

5. Capacity analysis

5.1. Modeling

In this section, we evaluate the capacity of a CDMA system with soft handoff in a simplified heterogeneous cellular environment with only one macrocell and one microcell, as shown in figure 2. Consider user h at location H. Let $M \rightarrow \mu$ represent the event of soft handoff when user h moves from the originally serving macrocell M to the adjacent microcell μ.

According to the EPA technique, base stations in the active set transmit the same power. Thus, the serving base station M will allocate transmission power for user h according to (7) with an upper limit defined in (9). Denote $q'_{\mu,h}$ and $q'_{M,h}$ as the transmitted power during handoff for macrocell M and microcell μ, respectively. Then, $q'_{\mu,h}$ and $q'_{M,h}$ can be written as

$$q'_{M,h} = q'_{\mu,h} = \frac{1}{2}\min(q_{M,h},\ \hat{q}_M), \text{for } M \rightarrow \mu. \tag{16}$$

Note that $q'_{M,h}$ indicates the allocated power during soft handoff, and $q_{M,h}$ is that before soft handoff. The factor of $\frac{1}{2}$ in (16) is related to the number of base stations involved in soft handoff, i.e. two base stations in our case.

If the unequal power allocation principle is used, the two serving base stations will transmit signal power at different levels according to (7) and (9). That is,

$$\begin{aligned} q'_{M,h} &= \frac{1}{2}\min(q_{M,h},\ \hat{q}_M) \text{ for } M \rightarrow \mu \\ q'_{\mu,h} &= \frac{1}{2}\min(q_{\mu,h},\ \hat{q}_\mu) \text{ for } M \rightarrow \mu \end{aligned} \tag{17}$$

For a microcell user moving into a macrocell, i.e. $\mu \rightarrow M$, we can simply swap M and μ in (16) and (17) to obtain the allocated power for the macrocell and the microcell during handoff.

In this paper, we define handoff gain (or diversity gain) as the enhancement of the received E_b/N_o with handoff as compared to the case without handoff. For hard handoff, a user is connected to the cell with better link gain. The hard handoff gain G_{hard} can be written as

$$\begin{aligned} G_{\text{hard}(M\rightarrow\mu)} &= \max\{\Gamma(q_{M,h})_{(dB)},\ \Gamma(q_{\mu,h})_{(dB)}\} \\ &\quad -\Gamma(q_{M,h})_{(dB)}\,. \\ G_{\text{hard}(\mu\rightarrow M)} &= \max\{\Gamma(q_{M,h})_{(dB)},\ \Gamma(q_{\mu,h})_{(dB)}\} \\ &\quad -\Gamma(q_{\mu,h})_{(dB)}\,. \end{aligned} \tag{18}$$

For the soft handoff case, according to (11), the soft handoff gain G_{soft} can be obtained by

$$\begin{aligned} G_{\text{soft}(M\rightarrow\mu)} &= \Gamma(q'_{M,h})_{(dB)} + \Gamma(q'_{\mu,h})_{(dB)} - \Gamma(q_{M,h})_{(dB)}. \\ G_{\text{soft}(\mu\rightarrow M)} &= \Gamma(q'_{M,h})_{(dB)} + \Gamma(q'_{\mu,h})_{(dB)} - \Gamma(q_{\mu,h})_{(dB)}. \end{aligned} \tag{19}$$

5.2. Capacity analysis

Soft handoff can improve the outage performance thanks to diversity gain, thereby increasing system capacity. In [20], the downlink outage probability is defined the probability of the total requested transmission power from all serving users of a base station exceeding the maximum total transmission power at a base station. That is,

$$P_{otg}^{(M)} = \text{Prob}\{P_M > \hat{P}_M\}. \tag{20}$$

Recall that soft handoff is initiated when the following condition is satisfied:

$$\tilde{P}_M \cdot L_{M,j} - \tilde{P}_\mu \cdot L_{\mu,j} \leq \eta, \tag{21}$$

where $L_{M,j}$ and $L_{\mu,j}$ are the link gains from user j to base stations M and μ, respectively; η is the handoff threshold. Denote N_M and N_μ as the number of users in the macrocell and microcell, respectively. Let N_M^{sh} and N_μ^{sh} be the number of soft handoff users in the macrocell M and microcell μ, respectively. Thus, the total transmission power of mactocell M in (20) can be calculated as

$$P_M = \sum_{j=1}^{N_M - N_M^{sh}} q_{M,j} + \sum_{j=1}^{N_M^{sh}} \hat{q}_M/2 + \sum_{j=1}^{N_\mu^{sh}} \hat{q}_\mu/2, \tag{22}$$

where the sum of the second and the third terms (denoted as $P_{sh}^{(M)}$) is equal to the total transmission power for soft handoff users . From (9) and (10) we can obtain $P_{sh}^{(M)}$. We further substitute (7) for $q_{M,j}$ in (22), and obtain

$$Y_M = \sum_{j=1}^{N_M - N_M^{sh}} D_j \cdot 10^{(\xi_\mu - \xi_M)/10}, \tag{23}$$

where D_j is defined in (8). Let

$$\chi = \frac{\hat{P}_M - K \cdot P_M \cdot (N_M - N_M^{sh}) - P_{sh}^{(M)}}{K \cdot P_\mu}, \tag{24}$$

where $K = \gamma_{\text{req}}/(G + \gamma_{\text{req}})$. Then $P_{otg}^{(M)}$ in (20) becomes

$$\begin{aligned} P_{otg}^{(M)} &= \text{Prob}\left(Y_M > \frac{\hat{P}_M - KP_M(N_M - N_M^{sh}) - P_{sh}^{(M)}}{KP_\mu}\right), \\ &= Q\left(\frac{\chi - m_y}{\sigma_y}\right), \end{aligned} \tag{25}$$

where $Q(x) = \frac{1}{2}\int_x^\infty e^{-t^2/2}dt$. Note that since Y_M is a sum of independent log-normal random variables, it can be approximated by another log-normal random variable Y_M with mean

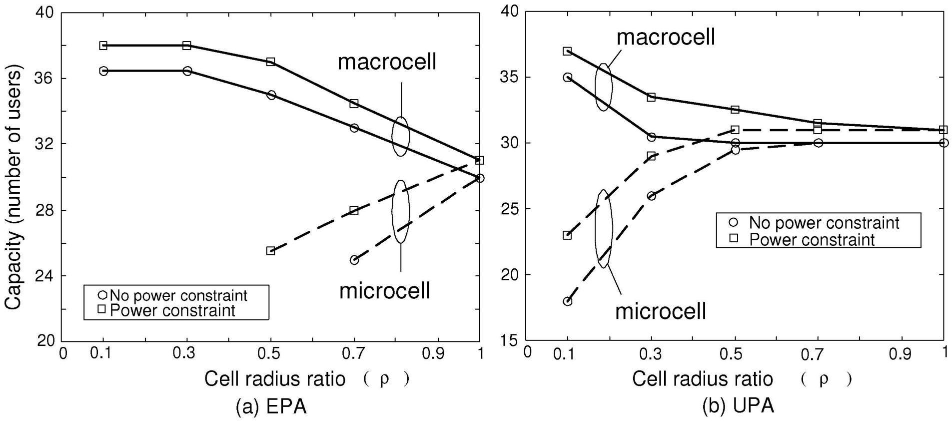

Figure 4. Capacity of (a) equal power allocation (EPA) and (b) unequal power allocation (UPA) with soft handoff against the ratio of radius of the microcell to that of the macrocell ρ.

m_y and standard deviation σ_y by using the techniques in [15]. The outage probability for the microcell users in the forward link can be also obtained by using the same method. The system capacity is defined as the maximal number of users subject to the constraint of outage probability less than a certain value, say $P_{otg}^{(M)} < 0.05$. Thus we can obtain the capacity of macrocell and microcell.

5.3. Analytical results

Figure 4(a) shows the capacity by using EPA for downlink soft handoff against the cell radius ratio ρ. In the figure, the capacity is defined as the maximal number of users subject to the constraint of outage probability less than 0.05. To get some insights through analysis, we consider a simplified two cell model in figure 2 and apply (25) to calculate the system capacity. We observe that the power exhausting issue occurs in the microcell when $\rho < 0.7$ without any power constraint and when $\rho < 0.5$ with a power constraint. One can see that the smaller the value of ρ, the higher the macrocell capacity will be. The increase of macrocell capacity as the value of ρ decreases is mainly because interference from the microcell is reduced. Constraining the maximum transmission power can relieve the power exhausting issue in the microcell slightly although the improvement is not significant. Figure 4(b) demonstrates the capacity of a system using the unequal power allocation in soft handoff against the cell radius ratio. Unlike the EPA method, the UPA can maintain a good capacity for both microcell and macrocell from $\rho = 0.5 \sim 1.0$. The power exhausting issue does not occur even with $\rho = 0.1$. It is also noted that the power constraint can improve the capacity, especially when the ρ is small. For $\rho = 0.1$ the capacity for the constrained UPA method increases microcell capacity about 30%.

6. Joint resource allocation mechanism

In this section, we discuss a joint resource allocation mechanism, which incorporates downlink power allocation technique and other resource allocation algorithms, such as, soft handoff, power control, and removal procedures. In particular, we use LPPA as an example in this joint resource allocation mechanism. One can use other downlink power allocation techniques in this joint resource allocation mechanism.

Figure 5 shows the flowchart of the procedures of the joint resource allocation mechanism. As mentioned, this joint resource allocation mechanism includes four key algorithms. First, based on soft handoff algorithm, an active set of candidate handoff base stations is determined for each user. Second, the necessary allocated downlink power to each user is pre-estimated according to different techniques, i.e. EPA, QBPA, SSDT, and LPPA. Third, based on quality balancing strategy, a distributed constrained power allocation is adopted for non-handoff users. Four, if the balanced signal quality is lower than the required signal quality for all users in the system, removal algorithm is activated to release the system resources from users with poor link conditions. The iteration of power allocation stops when the signal quality meets the requirement. In the following, we detail the design for each algorithm.

6.1. Soft handoff algorithm

The soft handoff algorithm is used to determine the active set Υ for each user j. If the difference of the received signal strength of the pilot signal between the serving cell i and adjacent cell k is less than the soft handoff threshold η, i.e.

$$\tilde{P}_i \cdot L_{i,j} - \tilde{P}_k \cdot L_{k,j} < \eta, \quad \text{for} \quad i \neq k, \tag{26}$$

then base station k should be added into the active set Υ of user j.

6.2. Downlink power allocation for soft handoff users

We suggest to distinguish the handoff users from the non-handoff users. By doing so, the system can allocate resources more efficiently. All the existing downlink power allocation techniques for handoff, such as EPA, QBPA, SSDT, and LPPA, can be implemented in this joint resource allocation mechanism. In this paper, we focus on LPPA since LPPA with an

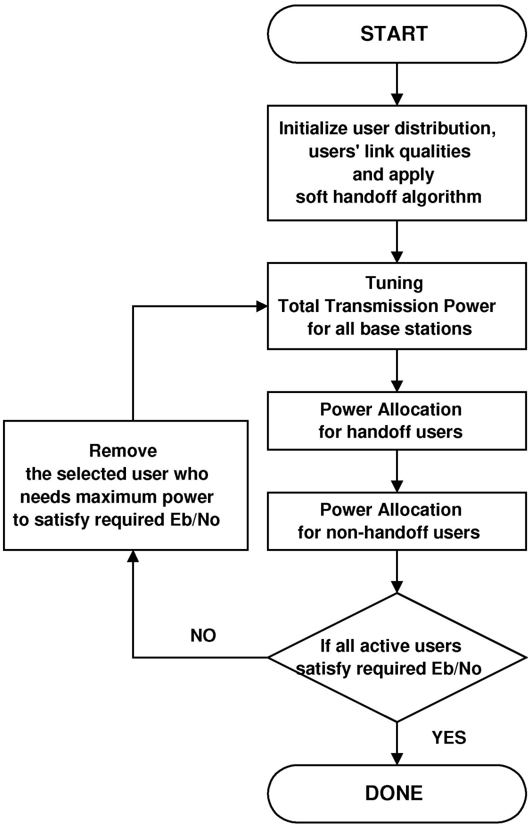

Figure 5. Flowchart of a generic joint resource allocation mechanism integrating four key techniques: (1) soft handoff, (2) downlink power allocation for handoff users, (3) downlink power control for non-handoff users, and (4) removal procedures.

iterative form and the convergence of the iterative LPPA algorithm have not been reported in the literature. In this section, we detail how LPPA can be implemented in an iterative manner and the convergence of the iterative LPPA algorithm will be proved in Appendix I.

As mentioned in [21], the principle of LPPA is to allocate more power to a link with better quality among the active set. Assume that all serving base stations in the active set Υ allocate power $q_{i,h}$ for user h. Denote $\hat{q}_i$ as the maximal allocation power for an individual user in cell i, and $\Gamma(q_{i,h})$ as the received E_b/N_o from cell i. Considering the maximal ratio combining for the downlink soft handoff, then we express the received E_b/N_o for us h during soft handoff as

$$\Gamma_h = \sum_{i\in\Upsilon} \Gamma(q_{i,h}). \tag{27}$$

LPPA can be implemented in an iterative manner as follows:

- Step 0: [Initialize]
  Let $Y_h(0)$ equal the maximum total allocation power $\tilde{Y}_h$, where $\tilde{Y}_h = \sum_{i,i\in\Upsilon} \hat{q}_i$.
- Step 1: [Set weighting factors $w_{i,h}$]
  For each serving base station i, based on link gain, determine

$$w_{i,h} = \frac{L_{i,h}}{\sum_{i,i\in\Upsilon} L_{i,h}}, \forall\, i \in \Upsilon. \tag{28}$$

- Step 2: [Distribute allocating power $q'_{i,h}(n)$]
  For each serving base station $i \in \Upsilon$, calculate the allocation power

$$q_{i,h}(n) = \text{Min}\{Y_h(n) \times w_{i,h}, \hat{q}_i\}, \forall\, i \in \Upsilon. \tag{29}$$

- Step 3: [Calculate E_b/N_o, and set tuning factor ρ_h]
  Calculate the received E_b/N_o. Then set the tuning factor $\rho_h(n) = \gamma_{\text{req}}\Gamma_h(n)$.

- Step 4: [Check Stop Criterion]
  IF ($\rho_h(n) \neq 1.0$ and $Y_h(n) \neq \tilde{Y}_h$)
  $Y_h(n+1) = \rho_h(n) \times Y_h(n)$,
  GOTO Step 2.
  ELSE DONE.

Note that in (28), the allocated power is proportional to the link quality.

6.3. Downlink power control for non-handoff users

After allocating power to the handoff users, it is important to adopt an efficient resource allocation scheme to serve the non-handoff users. We suggest adopting QBPA of [11] to serve non-handoff users, but with a slight modification. We incorporate the concept of the constrained power control mechanism of [8] into QBPA by constraining the power allocated to each user to a maximum allowable power. By doing so, each non-handoff user can achieve the same signal quality in the downlink. Meanwhile, if a user who requests the power exceeding the the maximum allowable power, it is better to initiate soft handoff to serve such a user. In other words, the downlink power allocation for soft handoff, such as LPPA, can be applied in this situation.

Table 1
System parameters.

System parameters	value
macrocell's radius(km), R_M	3
microcell's radius(km), R_μ	1.5
cell radius ratio(R_μ/R_M), ρ	1/2
mobile's antenna height(m), h_{ms}	1.5
macrocell antenna height(m), h_M	20
microcell antenna height(m), h_μ	10
macrocell's max. transmission power(watt), $\hat{P}_M$	20
macrocell's max. allocating power(watt), $\hat{q}_M$	1
2 slope path loss exponent, α, β	2, 2
Standard deviation of 2-slope shadowing, σ_1, σ_2	4.0, 8.0
Soft handoff threshold(dB), η	2
Maximum active set size	3

6.4. Removal algorithm

After allocating power to handoff and non-handoff users, if the signal quality of the serving users is still below the required threshold, then the system may executes the removal algorithm. This means power resource is insufficient to support all the serving users. Thus, removal algorithm is activated to remove the user with the weakest link quality. The system can thus utilize the extra power from this user to serve other users who can improve their link quality to a satisfactory level. The pilot power in heterogeneous cellular systems is dependent on cell sizes. The criterion for selecting a user to be removed can simply choose the user with the largest ratio of allocating power to user j over the maximum allowable power for each user in cell i, i.e. $\max\{\frac{q_{i,j}}{\hat{q}_i}\}$, where the denominator $\hat{q}_i$ is dependent on the cell sizes.

In this paper, we develop two removal algorithms. For Removal Algorithm 1 (RV1), the system will remove the selected user based on the above criterion no matter if the selected one is handoff user or not. Removal Algorithm 2 (RV2), the system will only remove non-handoff users and leave handoff users a higher priority to remain in the system. Numerical results will be given in the next section to compare the performance of these two removal algorithms.

7. Simulation results

7.1. Simulation model

In this, we compare the performance of the link proportional power allocation (LPPA), the equal power allocation (EPA), the quality balancing power allocation (QBPA), and the site selective diversity transmission (SSDT) techniques in a CDMA system with various cell sizes subject to measurement errors. Figures 6(a) and (b) illustrate our simulation platform, in which a central macrocell is split to four or nine microcells. That is, we study the cases of $\rho = 1$, $1/2$ and $1/3$, where ρ represents the cell radius ratio between the microcell and the macrocell.

The simulation methodology and assumptions are summarized as follows:

- We consider squared-shaped cells to simplify the cell splitting issue. Since this work emphasizes the comparison of downlink power allocation techniques in soft handoff for CDMA systems with various cell sizes, the main conclusions drawn from the simulation using the squared-shaped cells will not be significantly different from those using the hexagonal-shaped cells.
- The snapshot simulation method is adopted in this work as [3,7,11,18]. Although the snapshot evaluation method can not capture the time correlation of a fading channel, it is still a viable approach to compare the relative performance differences between power allocation techniques considered in this paper.
- Users are assumed to be uniformly distributed in each cell.

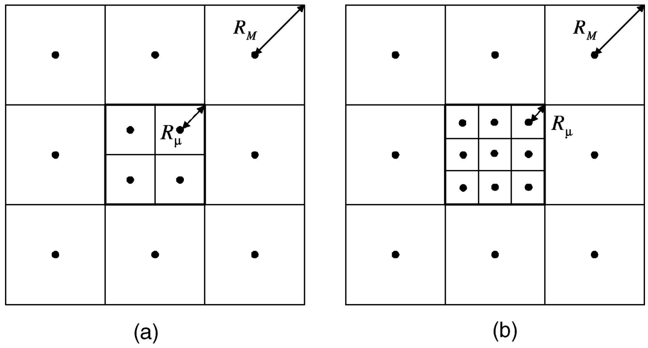

Figure 6. Examples of heterogeneous cellular network (a) $\rho = 1/2$, (b) $\rho = 1/3$.

- Other important system parameters are listed in Table 1, in which the soft handoff threshold $\eta = 2$ dB, the maximum active set size $|\Upsilon| = 3$, and the values of the pilot power design and the maximum allocation power for each user are obtained according to (6), and (10), respectively.
- The system capacity is defined as the number of serving users with outage probability less than 0.05. Because in this paper a performance outage event occurs when serving base stations have insufficient power to provide the required signal quality, we can also define the outage probability as the ratio of the number of disconnected (removed) users to the total number of users. Thus the total capacity C_{tot} is defined as the sum of macrocells and microcells capacity.

$$C_{tot} = \begin{cases} N_c \times C_c, & \rho = 1.0 \\ N_M \times C_M + N_\mu \times C_\mu, & \rho < 1.0 \end{cases}$$

where C_c is the system capacity per cell. Note that N_c is the number of cells in the homogeneous cellular systems, where $N_c = 9$ in our homogeneous cellular model. For the heterogeneous cellular systems, C_M and C_μ represent macrocell and microcell capacity, respectively. Here, we consider two cases as shown in figure 6, where (a) is for $\rho = 1/2$, $N_M = 8$ and $N_\mu = 4$, and (b) is for $\rho = 1/3$, $N_M = 8$ and $N_\mu = 9$.

7.2. Homogeneous cellular case

Figure 7 compares system capacity versus average outage probability for five different soft handoff power allocation techniques, including EPA, SSDT, QBPA, LPPA-RV1, and LPPA-RV2. In a homogeneous CDMA cellular system, one can observe that QBPA, SSDT and LPPA are better than EPA. The LPPA-RV2 technique enhances 23.1 and 8.5% capacity over the EPA and QBPA techniques, respectively. Furthermore, SSDT outperforms LPPA-RV1 and LPPA-RV2 up to 9.1 and 10%, respectively. Note that SSDT has been viewed as the optimal downlink transmission scheme in a homogeneous CDMA network.

In order to observe the impact of the measurement error on the downlink power allocation techniques, we consider a measurement error of 3 dB during cell-selection process.

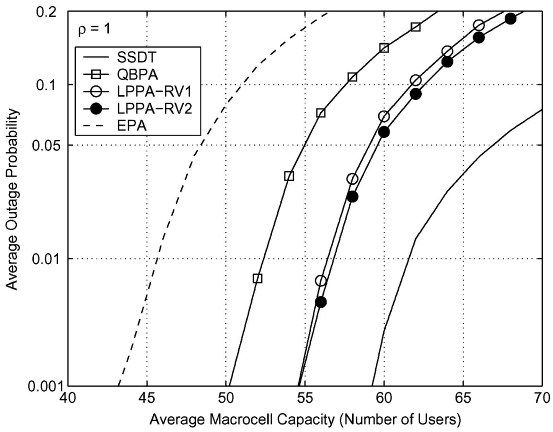

Figure 7. Averaged outage performance in the homogeneous cellular systems ($\rho = 1.0$) for the EPA, QBPA, SSDT, LPPA-RV1 and LPPA-RV2 techniques.

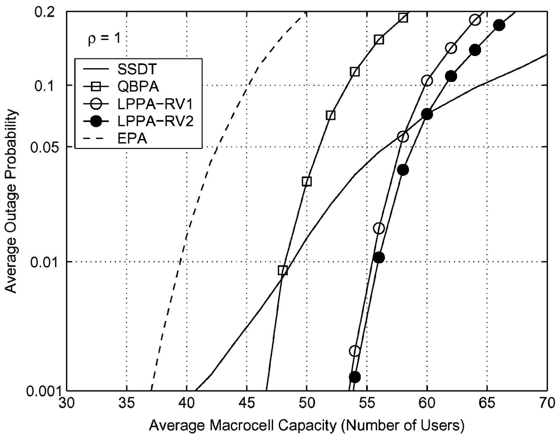

Figure 8. Averaged outage performance in the homogeneous cellular systems ($\rho = 1.0$) with measurement error for the EPA, QBPA, SSDT, LPPA-RV1 and LPPA-RV2 techniques.

Comparing figure 7 to figure 8, we observe that measurement errors degrade system capacity by 18.1, 13.7, 7.7, 2.2, and 1.3% for SSDT, EPA, QBPA, LPPA-RV1, and LPPA-RV2, respectively. As shown in the figure, SSDT is the most sensitive to the measurement error since only one link is adopted for transmissions. If the selected link is not the best link due to measurement errors, more transmission power may be wasted. On the other hand, subject to measurement errors and for the outage probability equal to 0.05, LPPA-RV1 and LPPA-RV2 improve system capacity by 1.8 and 3.8% as compared to SSDT, respectively. Note that in a more stringent requirement on outage probability, the capacity gain of applying the LPPA technique becomes more significant.

7.3. Heterogeneous cellular case

Figure 9 compares the system capacity of all the aforementioned downlink power allocation techniques in soft handoff under the heterogeneous cellular systems with $\rho = 1/2$. Figures 9(a) and (b) are the average macrocell and microcell capacity, respectively. As shown in the figure, because EPA may

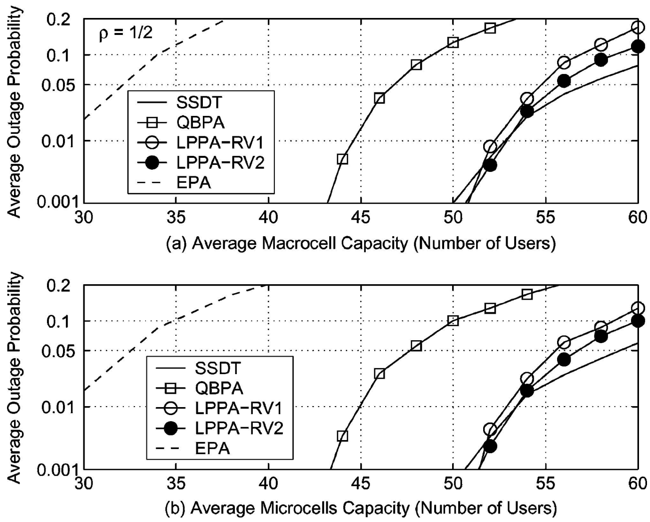

Figure 9. Averaged outage performance in the heterogeneous cellular systems ($\rho = 1/2$) for the EPA, QBPA, SSDT, LPPA-RV1 and LPPA-RV2 techniques.

waste too much power in serving soft handoff users, the system with EPA encounters the "power exhausting issue". This problem would get worse in the heterogeneous cellular systems where adjacent cells have different cell sizes. Thus, based on (30), all the power allocation techniques deliver higher total capacity than EPA. The capacity improvements of LPPA-RV2 relative to EPA and QBPA are 76.9 and 19.3% respectively. Compared to SSDT, the capacity of LPPA-RV2 is 2.9% less in the heterogeneous cellular systems with $\rho = 1/2$.

Next we evaluate the impact of measurement errors on the performance of the heterogeneous cellular system with $\rho = 1/2$. As shown in figure 10, measurement errors degrade system capacity by 23.4, 17.6, 8.4, 2.2, and 1.0% for EPA, SSDT, QBPA, LPPA-RV1, and LPPA-RV2, respectively. For

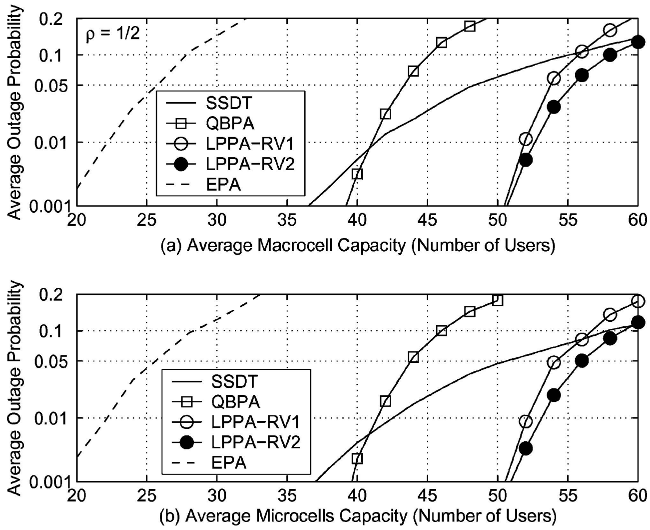

Figure 10. Averaged outage performance in the heterogeneous cellular systems ($\rho = 1/2$) subject to measurement errors for EPA, QBPA, SSDT, LPPA-RV1 and LPPA-RV2 techniques.

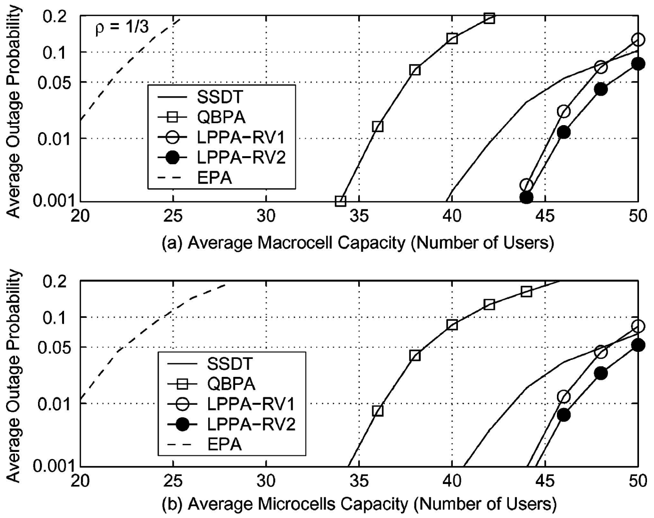

Figure 11. Averaged outage performance in the heterogeneous cellular systems ($\rho = 1/3$) for the EPA, QBPA, SSDT, LPPA-RV1 and LPPA-RV2 techniques.

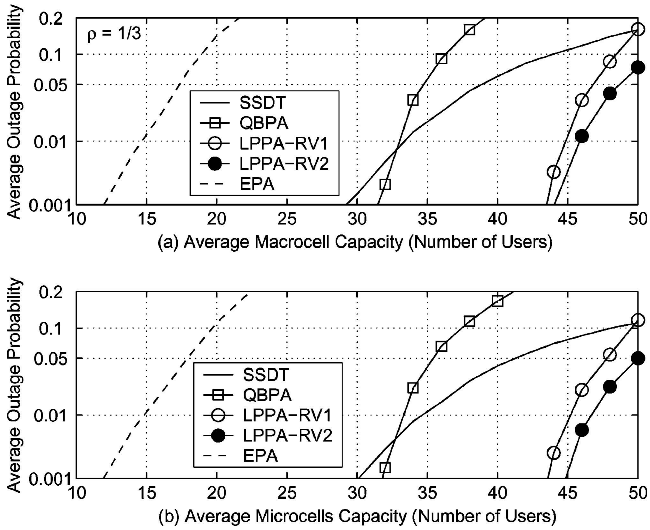

Figure 12. Averaged outage performance in the heterogeneous cellular systems ($\rho = 1/3$) subject to measurement errors for the EPA, QBPA, SSDT, LPPA-RV1 and LPPA-RV2 techniques.

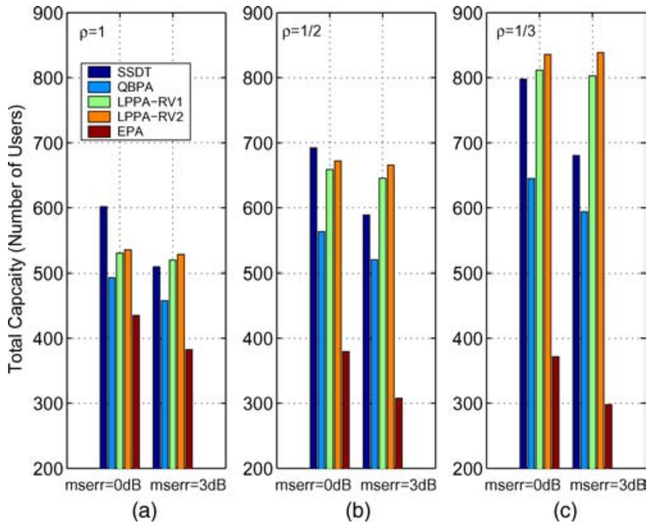

Figure 13. Total capacity performance with and without measurement error for EPA, QBPA, SSDT, LPPA-RV1 and LPPA-RV2 techniques in the (a) homogeneous cellular system, (b) heterogeneous cellular system with $\rho = 1/2$, (c) heterogeneous cellular system with $\rho = 1/3$.

EPA, the power exhausting issue occurs more easily , thereby having insufficient power to serve other regular non-handoff users, especially in the microcell. Clearly, the measurement error may worsen the impact of the power exhausting issue. On the other hand, since LPPA can distribute the required allocation power among serving base stations, the sensitivity on measurement errors is relatively smaller than SSDT. When comparing to the system capacity including the impact of measurement errors, both LPPA-RV1 and LPPA-RV2 improve the system capacity of the SSDT technique by 9.6 and 13.1%, respectively.

Figure 11 compares the performance of different power allocation techniques in the case of $\rho = 1/3$. In the case without measurement errors, LPPA-RV2 and LPPA-RV1 improve the system capacity by 4.8 and 1.7% over SSDT. Furthermore, the capacity of t LPPA-RV2 is 29.6 and 124.8% higher than the QBPA and EPA techniques.

Figure 12 shows the same cellular environment as figure 11 but includes measurement errors. As shown in the figure, the measurement error exacerbates the impact of the power exhausting issue for EPA, QBPA, and SSDT. We find that LPPA-RV2 improves system capacity by 22.8%, 40.7%, 181.4% compared to SSDT, QBPA, and EPA. Therefore, it is concluded that LPPA-RV1 and LPPA-RV2 can successfully overcome the power exhausting issue in the heterogeneous cellular systems, even with measurement errors.

Based on the previous discussions, we have three important observations.

- For the heterogeneous cellular systems with smaller cell radius ratio, the system capacity is increased because of cell splitting. However, serving soft handoff users may also easily cause the serious power exhausting issue.
- We find that measurement errors will degrade system capacity. Both EPA and SSDT are more sensitive to the measurement error than LPPA and QBPA. This is because the LPPA can effectively distribute the required allocation power among the serving base stations.
- Measurement errors exacerbate the power exhausting issue in the heterogeneous cellular systems. Therefore, the system capacity of EPA, QBPA, SSDT techniques are degraded even more seriously.

Figure 13 shows the total system capacity for the considered power allocation techniques with soft handoff. For the case without measurement errors, SSDT outperforms other techniques except in the heterogeneous cellular case, e.g. $\rho = 1/3$. For SSDT in the heterogeneous cellular system, because the maximum allocation power constraint is more stringent, the required allocation power may easily exceed the power constraint when serving soft handoff users. When incorporating measurement errors, the SSDT performance is significantly degraded because only one single link is used to serve the soft handoff user. If the selected link is not the best link, SSDT may waste too much transmission power in serving a soft handoff user, thereby more likely causing the power exhausting issue especially in the heterogeneous cellular systems. From the figure, we have the following observations:

- Compared to the SSDT, QBPA and LPPA techniques, EPA is the least efficient technique, and very sensitive to measurement errors. Thus, the system capacity using EPA is the lowest among all the considered power allocation techniques.
- For QBPA, the basic idea is to allocate less power in a better link, or vice versa. If using QBPA for both non-handoff and handoff users, it may waste too much power in serving soft handoff users. QBPA can slightly ease the power exhausting issue and result in higher system capacity than EPA.
- As for LPPA, the required allocation power for the soft handoff users will be distributed jointly by all base stations in the active set. If the allocated power of one active link is larger than the maximal allowable power, the rest of the required allocation power will be in charge by other active base stations. This is the reason why the LPPA technique is less sensitive for the measurement error.
- For the homogeneous cellular systems, LPPA-RV2 improves capacity over EPA, QBPA, and SSDT by 38.1, 15.4, and 3.8%. Meanwhile, for the heterogeneous cellular systems with $\rho = 1/3$, LPPA-RV2 further improves the capacity by 181.4, 40.7, and 22.8% as compared to EPA, QBPA, SSDT, respectively.
- LPPA outperforms other power allocation techniques in both the homogeneous and the heterogeneous cellular systems even with measurement errors. Note that LPPA-RV2 is always slightly better than LPPA-RV1 because it provides protection for soft handoff in the removal algorithm. This kind of protection strategy for soft handoff is a useful technique to enhance the efficiency of utilizing radio resource.

8. Concluding remarks

In this paper, we have evaluated different downlink power allocation techniques, including EPA, SSDT, QBPA, and LPPA, for soft handoff of a CDMA system with mixed-sized cells. Our simulation results demonstrate that LPPA can more effectively alleviate the power exhausting issue than others. Specifically, by taking account of the effects of different cell sizes, LPPA can prevent a microcell base station from wasting too much transmission power in serving handoff users. Consequently, the LPPA technique can deliver higher system capacity than other downlink power allocation techniques in both the homogeneous and heterogeneous cellular systems even with measurement errors. In summary, we find that it is important to design a handoff mechanism from both power efficiency and link reliability perspectives. This concept and the methodology can be useful in developing other radio resource algorithms for mobile wireless networks.

Appendix: Proof of convergence of the LPPA technique

Here, we prove the convergence of the link proportional power allocation (LPPA) technique in Section 3. Assume that $q_{i,h}$ is allocation power for one soft handoff user h among all serving base stations i in the active set Υ.

Proposition. If a power control algorithm has an "effective" solution, then for any initial power vector, a "standard" power control algorithm will converge to a unique power vector that achieves γ_{req} for any power level $q_{i,h}$ [23]. The power control algorithms that have iterative nature can be described by the following general function:

$$Y_h(n+1) = I(Y_h(n)). \tag{30}$$

where I is the interference function. In the following, we brief $Y_h(n)$ to Y_h for convenience. Thus, we define the interference function as:

$$I(Y_h) = \frac{\gamma_{\text{req}}}{\sum_{i,\in D} \Gamma(\min(q_i, \hat{q}_i))} \times Y_h. \tag{31}$$

Definition: Assume all the link gain and background noise for users are positive. An interference function I is "standard" if it is satisfies the following conditions for all non-negative power vectors:

- Positivity : $I(Y_h) > 0$.
- Monotonicity : $Y_h \geq Y\prime_h$
  $\Rightarrow I(Y_h) \geq I(Y\prime_h)$.
- Scalability : $\forall \alpha > 1,\ I(Y_h) \geq I(\alpha Y_h)$.

Since all the link gains and background noise between soft handoff user h and serving base stations $i,\ i \in \Upsilon$ are positive, the positivity and monotonicity properties are trivial satisfied. For the scalability property, consider the effect of power constraint, there are two kinds of cases in the resulting power vector:

Case 1:

$$\begin{aligned}
\forall\, q_{i,h} &= \min(Y_h \cdot w_{i,h}, \hat{q}_{i,h}) < \hat{q}_i \\
\forall\, q_{i,h} &= \alpha Y_h \cdot w_{i,h} < \hat{q}_i \\
&\Rightarrow \alpha Y_h \cdot w_{i,h} > Y_h \cdot w_{i,h} \\
&\Rightarrow \Gamma(\alpha Y_h \cdot w_{i,h}) > \Gamma(Y_h \cdot w_{i,h}) \\
&\Rightarrow \sum_{i,i\in\Upsilon} \Gamma(\alpha Y_h \cdot w_{i,h}) > \sum_{i,i\in\Upsilon} \Gamma(Y_h \cdot w_{i,h}).
\end{aligned}$$

Thus,

$$I(\alpha Y_h) = \frac{\gamma_{\text{req}}}{\sum_{i,i\in\Upsilon}\Gamma(\alpha Y_h\cdot w_{i,h})}(\alpha Y_h) < \alpha\, I(Y_h). \quad (32)$$

Case 2:

$$\begin{aligned}
&\exists\ k,\ k\in\Upsilon \\
&\qquad \text{s.t. } q_{k,h} = \min(Y_h\cdot w_{k,h}, \hat{q}_{k,h}) = \hat{q}_k \\
\sum_{i,i\in\Upsilon}\Gamma(Y_h\cdot w_{i,h}) &= \sum_{\substack{i\neq k,\\ i\in\Upsilon}}\Gamma(Y_h\cdot w_{i,h}) + \sum_k \Gamma(\hat{q}_k) \\
&\Rightarrow \sum_{i,i\in\Upsilon}\Gamma(\alpha Y_h\cdot w_{i,h}) \\
&= \sum_{\substack{i\neq k,\\ i\in\Upsilon}}\Gamma(\alpha Y_h\cdot w_{i,h}) + \sum_k \Gamma(\hat{q}_k) \\
&> \sum_{i,\,i\in\Upsilon}\Gamma(Y_h\cdot w_{i,h}).
\end{aligned}$$

From case 1, we can also obtain the same results as (32) in case 2. Therefore, the scalability property is also proved. After the preceding discussion, we can prove that the proposed LPPA algorithm is a standard power control algorithm so that always exist an effective solution Y_h for one soft handoff user h.

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