PAPER

A Hybrid Inter-Cell Interference Mitigation Scheme for an OFDMA Downlink System*

Che-Sheng CHIU[†a)], *Student Member and* **Chia-Chi HUANG**[††], *Nonmember*

SUMMARY A number of inter-cell interference coordination schemes have been proposed to mitigate the inter-cell interference problem for orthogonal frequency division multiple access (OFDMA) systems and among them, partial frequency reuse is considered one of the most promising approaches. In this paper, we propose an inter-cell interference mitigation scheme for an OFDMA downlink system, which makes use of both partial frequency reuse and soft handover. The basic idea of this hybrid scheme is to dynamically select between a partial frequency reuse scheme and a soft handover scheme to provide better signal quality for cell edge users. Compared with the standard partial frequency reuse scheme, simulation results show that approximately one quarter of cell edge users can get improvements in signal quality as well as link spectral efficiency from using the proposed hybrid scheme. We also observe that by using our approach, there is a significant cell edge throughput gain over the standard partial frequency reuse scheme. Furthermore, based on a well defined data rate fairness criterion, we show that our method achieves higher overall system capacity as compared with the standard partial frequency reuse scheme.

key words: *OFDMA, inter-cell interference, interference coordination, partial frequency reuse, soft handover*

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a transmission technique that has been widely accepted as a suitable solution for broadband wireless communications. As an extension, OFDM could be used not only as a modulation scheme, but also as part of the multiple access technique as well, namely orthogonal frequency division multiple access (OFDMA). Recently, OFDMA is considered a most promising multiple access technique to improve spectral efficiency in future mobile communication systems. Several communication standards, such as 3rd Generation Partnership Project (3GPP) LTE (Long Term Evolution), 3rd Generation Partnership Project 2 (3GPP2) UMB (Ultra Mobile Broadband), and Mobile WiMAX (Worldwide Interoperability for Microwave Access), all exclusively choose OFDMA as the downlink transmission scheme [1]–[3]. With orthogonality within the cell, the main interference in an OFDMA system comes from inter-cell interference. The inter-cell interference is particularly disadvantageous to user equipments (UEs) located at cell edge, especially for a multi-cell OFDMA system with universal frequency reuse.

Important criteria for system evaluation and performance requirements are given in a 3GPP technical report [4]. This document lists different requirement items among which we highlight the particular one which says, "Increase cell edge bit rate whilst maintaining same site locations as deployed today." This criterion indicates that the cell edge quality of service (QoS) is an important performance requirement. For delivering a uniform user throughput across the whole cell area, inter-cell interference is the main limitation factor as it causes a low cell edge bit rate. Therefore, it is important to consider techniques to mitigate inter-cell interference for cell edge users.

To deal with this interference problem, several pre-4th generation (pre-4G) systems, like 3GPP LTE, 3GPP2 UMB, and Mobile WiMAX, employ inter-cell interference coordination as an interference mitigation scheme. The common theme of inter-cell interference coordination is to apply restrictions to the usage of downlink/uplink resources e.g., time/frequency resources and/or transmit power resources. Such coordination will provide a way to avoid severe inter-cell interference, and thus provide more balanced bit rates among UEs. Several inter-cell interference coordination schemes have been proposed for OFDMA systems, including partial frequency reuse [5], [6], soft frequency reuse [7], [8], inverted frequency reuse [9], etc. Among them, partial frequency reuse (also known as fractional frequency reuse), one of the most promising approaches, is considered in 3GPP LTE, and it is supported in Mobile WiMAX and 3GPP2 UMB.

To improve radio coverage at cell borders in 3rd generation (3G) code division multiple access (CDMA) systems (e.g., WCDMA, cdma2000), soft handover which exploits macro diversity has already been used to address the inter-cell interference problem. Moreover, the processing gain in CDMA also helps to alleviate the cell edge interference problem. In order to maintain a simplified radio access network (RAN) architecture, it is agreed that soft handover will not be included in 3GPP LTE. Nevertheless, soft handover is supported in the IEEE 802.16e-2005 standard as an option (known as macro diversity handover in IEEE 802.16e-2005) [3].

Conventionally, frequency reuse scheme is used in OFDMA, and soft handover scheme (exploiting macro diversity) in CDMA. In this paper, we introduce a hybrid inter-cell interference mitigation scheme for an OFDMA system, and in particular we concentrate on the downlink transmis-

---

Manuscript received December 4, 2008.
Manuscript revised August 3, 2009.

[†] The author is with Telecommunication Laboratories, Chunghwa Telecom Co., Ltd., Taiwan.

[††] The author is with the Department of Communication Engineering, National Chiao-Tung University, Taiwan.

[*] This paper is the revised and extended version of a paper presented at IEEE VTC2008-Spring, May 2008 [24].

a) E-mail: robinson@cht.com.tw

DOI: 10.1587/transcom.E93.B.73

sion. The proposed scheme makes use of both partial frequency reuse and soft handover. The motivation for developing this hybrid method is that, for a cell edge user, it is possible that a soft handover scheme may provide higher signal quality than a partial frequency reuse scheme and thus, it gives the possibility of improving cell edge bit rate. Simulation results show that this hybrid scheme can actually bring some capacity gains for the whole system as well as improve signal quality for cell edge users.

The rest of this paper is organized as follows. In Sect. 2, we describe the partial frequency reuse scheme. In Sect. 3, we illustrate the soft handover scheme. In Sect. 4, we explain the proposed hybrid system concept. In Sect. 5, we present the system model, measures and assumptions for the performance evaluation. Our simulation results and discussions are given in Sect. 6. Finally, we give conclusions in Sect. 7.

2. Partial Frequency Reuse Description

In order to maximize spectral efficiency, the emerging OFDMA systems like 3GPP LTE, 3GPP2 UMB and Mobile WiMAX all assume that a frequency reuse factor of 1 should be used, i.e., the same frequency band can be used in any cell (sector) of the system[†]. Although full frequency reuse may ensure the best throughput, it brings low signal quality for cell edge users due to inter-cell interference. A more realistic frequency reuse scheme which adopts a frequency reuse factor of 3 in a tri-sector network significantly reduces inter-cell interference but induces a reduction to the accessible frequency resources in each cell. In a tri-sector network, a frequency reuse factor of 3 means that a frequency subchannel can only be reused in one of the three sectors of the same site. Frequency reuse factors of 1 and 3 are usually used to generate frequency reuse patterns of the nowadays OFDMA systems, as they well suit the conventional tri-sector cellular architecture. For CDMA systems, a frequency reuse factor of 1 is normally used because CDMA takes advantage of processing gain achieved through using nearly orthogonal spreading codes.

Partial frequency reuse or simply partial reuse (PR) is an inter-cell coordination scheme that applies restrictions to the frequency resources in a coordinated way among cells. The idea of partial frequency reuse is to partition the whole frequency band into two parts, F_1 and F_3, where F_3 is further divided into three subsets; and thus, it results in four orthogonal subbands, F_1, F_{3A}, F_{3B} and F_{3C} (see Fig. 1). Note that it is reasonable to assume that F_{3A}, F_{3B} and F_{3C} have the same bandwidth. The frequency subband F_1 is called the cell center band, for which a frequency reuse factor of 1 (reuse-1) is adopted, and it is used by the cell interior users only. On the other hand, the frequency subband F_3 is called the cell edge band, for which a frequency reuse factor of 3 (reuse-3) is implemented, and the cell edge users are restricted to use this frequency subband only. Nevertheless, when the cell edge band is not occupied by the cell edge users, it can also be used by the cell interior users.

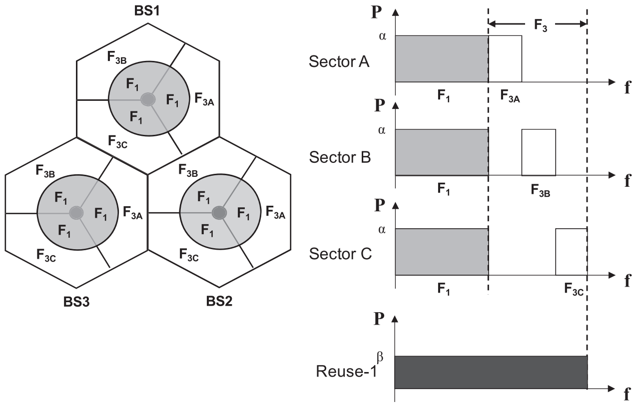


Fig. 1 Spectrum setting for partial frequency reuse in a tri-sector cellular layout.

In [11], an effective reuse factor (ERF) r_{eff} is introduced to represent the ratio of the total spectrum to the spectrum that can be used in each cell, and it can be expressed by

$$r_{eff} = BW_{all}/BW_{cell} = \frac{BW_{F_1} + BW_{F_3}}{BW_{F_1} + (1/3) \cdot BW_{F_3}}, \qquad (1)$$

where BW_{all} denotes the whole bandwidth; BW_{cell} denotes the available bandwidth in each cell; BW_{F_1} and BW_{F_3} denote the bandwidth of reuse-1 and reuse-3 subbands, respectively. Note that the whole bandwidth is the sum of bandwidth BW_{F_1} and BW_{F_3}, and each cell can use the entire BW_{F_1} and 1/3 of BW_{F_3}, i.e., $BW_{F_{3A}}$, $BW_{F_{3B}}$ or $BW_{F_{3C}}$.

In this study, we assume that each cell always uses its maximum transmission power, which is kept as a constant, and we also assume that transmit power is equally spread over the whole available bandwidth in each cell (i.e. a flat transmission power spectrum density is assumed). Figure 1 shows the spectrum setting for partial frequency reuse in a tri-sector cellular layout. As we have the constant total power assumption, the transmit power level α can be increased in partial frequency reuse scheme as compared with the pure reuse-1 scheme (i.e. $\alpha > \beta$ in Fig. 1) and in this case, the power amplification factor α/β would be the same as the effective reuse factor.

3. Soft Handover Description

One of the main macro diversity methods in 3G CDMA downlink is soft handover (SH). Exploiting macro-diversity with a soft handover scheme is indeed a good method to reduce the influence of inter-cell interference. When soft handover is in use, an UE is connected simultaneously to several cells, which constitute its active set. An active set is the set of cells with which an UE is communicating at a given time. The active set includes the best cell (serving cell with highest path gain) and all the cells which satisfy the soft

---

[†] Normally, the geographical areas that are controlled by the same base station (or Node B) are known as sectors. However, the terms cell and sector are interchangeable in this paper.

handover requirement, i.e., whose path gain are larger than the highest path gain minus the add threshold (Window_add [12]). Note that a soft handover scheme allows for more than one cell in the active set, while in a hard handover scheme, there is only one cell in the active set. With soft handover, the same signal is simultaneously transmitted to an UE from multiple cells through the same frequency subchannels. The benefit of soft handover comes from the fact that the dominant interferers become desired signals, and therefore, the cell edge transmission quality can be remarkably improved.

The soft handover overhead [12] is an important metric used to quantify the soft handover activity in a network, and it is regarded as a measure of additional transmission resources required. Note that a large soft handover overhead also implies a large number of control signaling and it decreases the system capacity. The soft handover overhead (η) is defined as

$$\eta = \sum_{n=1}^{N_{MAS}} n \cdot P_n - 1, \tag{2}$$

where N_{MAS} denotes the maximum active set size and P_n is the probability of an UE being in n-way soft handover. In this study, 1-way soft handover indicates the case that an UE is connected to only one cell, while 2-way soft handover indicates that the UE is connected to two cells, and so forth.

4. A Hybrid System Concept

4.1 Cell Interior/Edge Users Partition

In the partial frequency reuse scheme, one part of the spectrum has a frequency reuse factor of 1 and the other part has a frequency reuse factor of 3. This spectrum partition works together with the split of users into cell interior users (CIUs) using the reuse-1 part of spectrum and cell edge users (CEUs) using the reuse-3 part of spectrum. Accordingly, for realizing the partial frequency reuse in an OFDMA system, we need to classify UEs into CIUs and CEUs.

A widely accepted approach to partition UEs is based on the geometry factor (G-factor). The G-factor is the wideband average SINR (signal to interference plus noise power ratio) measured by an UE from pilot subcarriers over the reuse-1 part of the spectrum (F_1). The G-factor is then compared with a predefined threshold to determine whether the UE is a cell interior user or a cell edge user [8], [13]–[15]. This is because a cell edge user always suffers from noticeable SINR degradation. The average SINR of an UE is defined as the ratio of totally received wideband own-cell power and other-cell interference plus noise power at the UE. It should be noted that the SINR is averaged over short-term fading, but not shadowing. In this paper, we consider an UE as a cell edge user which has to be protected by an inter-cell interference mitigation scheme, e.g., by a reuse-3 scheme or a soft handover scheme, if the G-factor measured at the UE is smaller than a threshold of 0 dB [13], [15], [16]; otherwise, the UE is regarded as a cell interior user.

4.2 Problem Formulation

We consider an OFDMA downlink system with partial frequency reuse; and further, we assume that soft handover (including softer handover) is supported. Assume that an UE is a cell edge user and there is more than one cell in the UE's handover list. The handover list is the list of cells whose link quality satisfies the soft handover requirement, and thus every cell in the list can be added to active set. Note that the serving cell is certainly a member of the handover list, thus the size of handover list is always greater than or equal to one. In this situation, the OFDMA downlink system can use either of the following two methods to send the intended data to the UE. The first method is based on soft handover and the OFDMA downlink system sends data from all the cells that are in the UE's active set to the UE by using the frequency subchannels that belong to reuse-1 subband F_1. We name this method *Scheme A*. The second method is based on partial frequency reuse (through a frequency reuse factor of 3) and the OFDMA downlink system sends data from the serving cell to the UE by using the frequency subchannels that belong to reuse-3 subband of the cell, i.e. F_{3A}, F_{3B}, or F_{3C}. We denote this method as *Scheme B*. Note that in *Scheme A*, the active set is exactly the set of cells in the handover list, and in *Scheme B*, the active set corresponds to only the serving cell.

In the above scenario, two remaining questions are: 1) Which scheme (*Scheme A* or *Scheme B*) could provide higher signal quality (SINR) for the UE? 2) As compared with the standard partial frequency reuse scheme (i.e. without soft handover option), can we generate some throughput gains by dynamically choosing between *Scheme A* and *Scheme B*? These two questions are addressed in the following sections.

4.3 A Hybrid System of PR and SH

To enhance cell edge bit rate and overall system capacity, we develop an inter-cell interference mitigation scheme that dynamically chooses between *Scheme A* and *Scheme B* according to which scheme provides better signal quality (SINR). For the standard partial frequency reuse scheme, a serving cell will first classify an UE as a CIU or a CEU according to the UE's G-factor. If the G-factor is greater than a predefined threshold (e.g., 0 dB in this paper), the UE is considered as a cell interior user and the serving cell will transmit the intended data to the UE through the frequency subchannels in the reuse-1 subband; otherwise, the UE is treated as a cell edge user and the serving cell will use the frequency subchannels with a reuse factor of 3 (i.e. *Scheme B*) to send the intended data to the UE.

Figure 2 shows the operational flow chart of the proposed hybrid scheme. For the proposed scheme, a cell edge user may be allocated either frequency subchannels with a reuse factor of 3 or frequency subchannels with a reuse factor of 1 and use soft handover. We note that the operations of

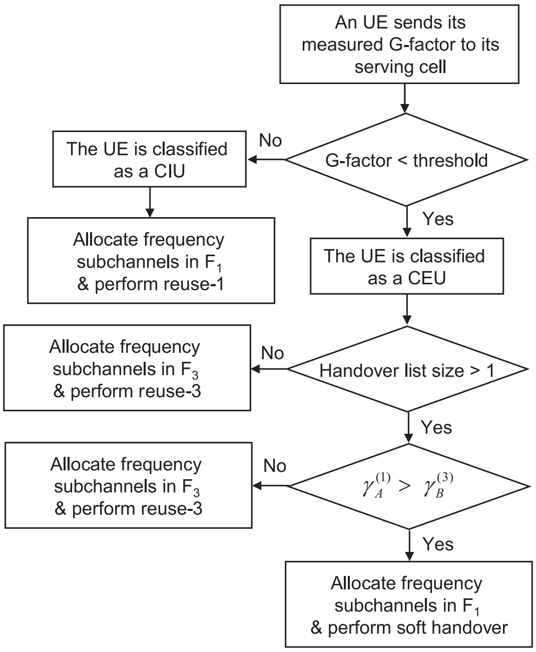


Fig. 2 Operational flow chart of the proposed hybrid scheme.

CIUs are the same for the standard partial frequency reuse and the proposed hybrid schemes. With Fig. 2, when an UE is classified as a cell edge user, the serving cell will use *Scheme B* to transmit the intended data to the UE if there is only one cell in the UE's handover list. On the other hand, if the UE's handover list size is larger than one, then the serving cell will dynamically select either *Scheme A* or *Scheme B* to transmit the intended data to the UE and the selection criterion is based on signal quality comparison, which can be expressed as

$$\begin{aligned}&\textit{If}\ \ \gamma_A^{(1)} > \gamma_B^{(3)},\ \textit{choose Scheme A};\\ &\textit{otherwise},\ \textit{choose Scheme B}.\end{aligned} \tag{3}$$

where $\gamma_A^{(1)}$ and $\gamma_B^{(3)}$ are the SINR measured by the UE with *Scheme A* (soft handover applied) and *Scheme B* (partial frequency reuse applied), respectively. Here, the superscript x ($x = 1$ or 3) of $\gamma^{(x)}$ indicates that the SINR is measured on the reuse-x subband.

5. System Model, Measures and Assumptions

Partial frequency reuse can be achieved by either static coordination or dynamic coordination. Since dynamic coordination introduces large signaling overhead and scheduling complexity, a static coordination is highly recommended [17], [18]. In this paper, only static coordination is considered.

5.1 Modeling of Downlink Average SINR

In our SINR calculation, we do not consider fast fading and assume radio link is subject to propagation loss and log-normally distributed shadowing. We further assume that the serving cell is the one from which the received signal is the strongest after accounting for pathloss, shadow fading, and antenna gain patterns.

Suppose all frequency subchannels designated for each cell are fully utilized (i.e. a fully loaded system) and we have the equal power allocation assumption, the transmission power spectrum density P_t (or transmit power level α, see Fig. 1) is given by

$$P_t = P_T/BW_{all} \cdot r_{eff} (= P_T/BW_{cell}), \tag{4}$$

where P_T denotes total transmission power. Thus, the average SINR for an (non-soft handover) UE can be written as

$$\gamma^{(x)} = \frac{P_t \cdot L_s \cdot S_s \cdot A_s}{\sum\limits_{i\in\Phi_x} P_t \cdot L_i \cdot S_i \cdot A_i + P_N},\ (x = 1, 3) \tag{5}$$

where L_j, S_j, and A_j are the pathloss, shadow fading and antenna gain from the cell j to the UE, respectively; the subscripts s and i stand for the serving cell and the interfering cells, respectively; Φ_1 and Φ_3 are the sets of interfering cells with a reuse factor of 1 and a reuse factor of 3, respectively; P_N denotes the received noise power spectrum density.

Moreover, when the UE is in soft handover, its average SINR can be expressed as

$$\gamma_A^{(1)} = \frac{\sum\limits_{s\in\Phi_{AS}} P_t \cdot L_s \cdot S_s \cdot A_s}{\sum\limits_{i\in(\Phi_1-\Phi_{AS})} P_t \cdot L_i \cdot S_i \cdot A_i + P_N}, \tag{6}$$

where Φ_{AS} denotes the active set of the UE and the subscript s stands for the cells in the active set. In order to evaluate condition (3), we note that $\gamma_A^{(1)}$ can be calculated directly from (6) and $\gamma_B^{(3)}$ can be calculated by setting $x = 3$ in (5).

5.2 Link Spectral Efficiency Evaluation

According to Shannon's capacity formula [19], the achievable link spectral efficiency C (bps/Hz) from a BS to a particular user is a function of the average received SNR (signal to noise ratio). In general, Shannon's formula gives the capacity of an additive white Gaussian noise (AWGN) channel and it is not applicable to a multipath channel. Assume that other-cell interference can be modeled as AWGN and we do not consider other-cell interference cancellation techniques in the receiver, a modified Shannon formula has been introduced in [20] to calculate link capacity in a cellular mobile radio communication system. This formula is given as

$$\tilde{C}(\gamma) = \xi \cdot \log_2(1 + \gamma/\varsigma)\ \text{bps/Hz}. \tag{7}$$

where ξ and ς are constants that account for the system bandwidth efficiency and the SINR implementation efficiency, respectively, and γ denotes the average received SINR. For Typical Urban (TU) channel model and Single-Input Single-Output (SISO) antenna scheme, it has been shown in [20] that Eq. (7) with $\xi = 0.56$ and $\varsigma = 2$ achieves a good match to the link capacity performance of 3GPP LTE from simulation. Therefore, we adopt this modified Shannon capacity equation with parameters $\xi = 0.56$ and $\varsigma = 2$ to evaluate the link spectral efficiency.

5.3 System Capacity Estimation

We assume that the users are uniformly distributed within cell coverage, and each user has unlimited traffic to transmit on the downlink. Moreover, it is assumed that a Round Robin (RR) scheduler is applied to cell center/edge bands. Under the RR scheduling policy, the system capacity T can be calculated as [20], [21]

$$T = BW \cdot \nu \cdot \int \tilde{C}(\gamma) f_{\gamma}(\gamma) d\gamma, \tag{8}$$

where ν is a loss factor that accounts for the system overhead, $f_{\gamma}(\gamma)$ is the probability density function of SINR γ, and BW denotes the allocated bandwidth. In this paper, the loss factor ν is set to 1; this yields optimistic results, but is deemed acceptable for relative comparison purposes.

In a fully loaded system, it becomes unlikely that CIUs would be able to access the cell edge band (i.e. F_3), and they would thus be confined to cell center band (i.e. F_1). This causes a separation of user groups such that the CIUs occupy the cell center band only while the CEUs use the cell edge band only. From (8), the average cell interior throughput ($T_{Interior}$) and cell edge throughput (T_{Edge}) for the partial frequency reuse scheme can be calculated by (9) and (10), respectively,

$$T_{Interior} = BW_{F_1} \cdot \int \tilde{C}(\gamma_I) f_{\gamma_I}(\gamma_I) d\gamma_I, \tag{9}$$

$$T_{Edge} = \frac{1}{3} BW_{F_3} \cdot \int \tilde{C}(\gamma_E) f_{\gamma_E}(\gamma_E) d\gamma_E, \tag{10}$$

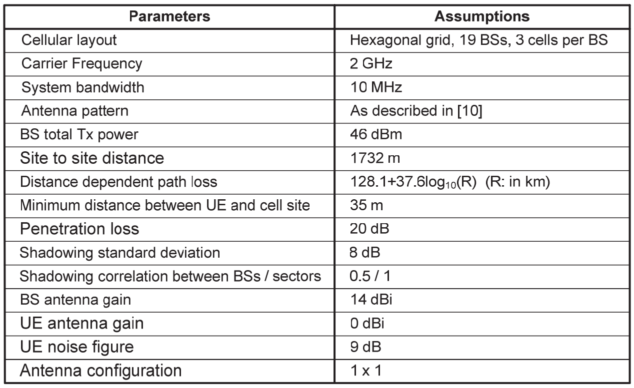
in which the subscripts I and E stand for the CIUs and CEUs, respectively.

With the proposed hybrid scheme, as we have a RR scheduling policy on the cell center band, two user groups, the CIUs and the CEUs with *Scheme A*, will have equal chance of access to the frequency subchannels on the cell center band. Accordingly, the average cell interior throughput and cell edge throughput can be calculated by (11) and (12), respectively,

$$T_{Interior} = BW_{F_1} \cdot \frac{P_I}{P_I + P_2 + P_3} \cdot \int \tilde{C}(\gamma_I) f_{\gamma_I}(\gamma_I) d\gamma_I, \tag{11}$$

$$\begin{aligned} T_{Edge} = {} & \frac{1}{3} BW_{F_3} \cdot \int \tilde{C}(\gamma_{E,B}) f_{\gamma_{E,B}}(\gamma_{E,B}) d\gamma_{E,B} \\ & + \sum_{n=2}^{3} \left(\frac{1}{n} \cdot BW_{F_1} \cdot \frac{P_n}{P_I + P_2 + P_3} \right. \\ & \left. \cdot \int \tilde{C}(\gamma_{E,A,n}) f_{\gamma_{E,A,n}}(\gamma_{E,A,n}) d\gamma_{E,A,n} \right), \end{aligned} \tag{12}$$

Table 1 Simulation parameters.



Parameters	Assumptions
Cellular layout	Hexagonal grid, 19 BSs, 3 cells per BS
Carrier Frequency	2 GHz
System bandwidth	10 MHz
Antenna pattern	As described in [10]
BS total Tx power	46 dBm
Site to site distance	1732 m
Distance dependent path loss	128.1+37.6log$_{10}$(R) (R: in km)
Minimum distance between UE and cell site	35 m
Penetration loss	20 dB
Shadowing standard deviation	8 dB
Shadowing correlation between BSs / sectors	0.5 / 1
BS antenna gain	14 dBi
UE antenna gain	0 dBi
UE noise figure	9 dB
Antenna configuration	1 x 1

in which P_I denotes the (statistically) probability of CIUs (ratio of CIUs to total users in number); P_n denotes the (statistically) probability of an UE being in n-way soft handover (that is the ratio of users with n-way soft handover to total users in number); and subscripts A and B represent *Scheme A* and *Scheme B* users, respectively. Note that in (15), $1/n$ that appears on the right hand side represents the capacity loss factor that is induced by performing a n-way soft handover. In this paper, a maximum active set size of 3 cells ($N_{MAS} = 3$) [22] and an add threshold of 4 dB (Window_add = 4 dB) [22] are assumed.

After obtaining the average throughput of the cell interior users and cell edge users, the average (total) cell throughput (T_{Cell}) thus becomes

$$T_{Cell} = T_{Interior} + T_{Edge}. \tag{13}$$

5.4 Simulation Method and Simulation Parameters

Static snapshot simulations have been used. The average SINR distribution (i.e. $f_{\gamma}(\gamma)$) is obtained through Monte Carlo simulations involving 2000 random placement of users geographically. Simulation assumptions and parameters basically follow the 3GPP evaluation criteria [10]. The available downlink bandwidth is fixed at 10 MHz. We consider a multi-cell system consisting of 19 base stations (BSs). A BS controls the three sectors (cells), i.e., 57 sectors (cells) in total are considered. The radio links are subject to distance-dependent propagation loss and lognormal shadowing fading. A distance-dependent path loss with a propagation loss exponent of 3.76 and a lognormal shadowing with a standard deviation of 8 dB are assumed. The sector antenna pattern used in our simulation is adopted from [10]. All the simulation results are collected from the three sectors of the central BS and the remaining 54 sectors act as a source of inter-cell interference. Table 1 summarizes the main simulation parameters.

6. Numerical Results and Discussions

The simulation results are conducted for the standard partial frequency reuse (PR hereafter in this chapter) and the proposed hybrid scheme (PR+SH hereafter in this chapter).

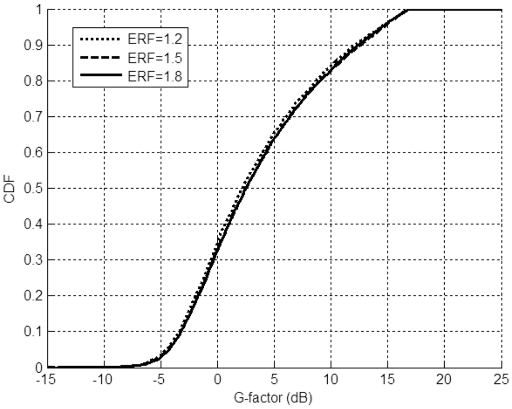


Fig. 3 G-factor distributions over cell area.

Furthermore, we consider the effective reuse factor (ERF) r_{eff} ranged between 1.1 and 2. Note that allocating a large number of frequency subchannels in the cell edge band will also cause a large loss in bandwidth utilization in each cell. Thus, we limit the effective reuse factor to 2, which in turn about 3/4 frequency resources are reserved for cell edge band F_3.

To begin with, it is beneficial to know the percentages of CIUs and CEUs in the simulation system. The cumulative distributed functions (CDFs) of downlink G-factor over the whole cell area are plotted in Fig. 3 for r_{eff} = 1.2, 1.5, and 1.8. With a classification threshold of 0 dB, one can see that the percentage of CEUs within a cell is about 34% ($P_E \approx 0.34$) and that value for CIUs is about 66% ($P_I \approx 0.66$). Furthermore, since we assume that site-to-site distance is equal to 1732 m (see Table 1), the evaluation system will be interference limited, and thus one can find that the CDF is almost not changed with different effective reuse factors.

6.1 Soft Handover Overhead Estimation

Here, we study the soft handover overhead (η) of the proposed hybrid scheme. For feasibility reason, an important requirement of the PR+SH scheme is to have a low soft handover overhead as compared with the current 3G CDMA systems. Table 2 shows the probability of an UE being in n-way soft handover (P_n) for the simulated system. Applying the simulation results to (2), we found that the induced soft handover overhead of the PR+SH scheme is about 0.15. It is known that in a WCDMA network, the soft handover overhead is around 0.2–0.4 for a standard hexagonal cell grid with three sector sites [12]; and furthermore, in a live WCDMA network in a dense urban area, the typical value of the average overhead is about 0.38 [12]. Thus we conclude that the soft handover overhead of the simulated PR+SH scheme is relatively small.

6.2 Average SINR Comparison

Table 2 Probability of an UE being in n-way SH.

# of SH Branches	$n=1$	$n=2$	$n=3$
P_n	~0.91	~0.03	~0.06

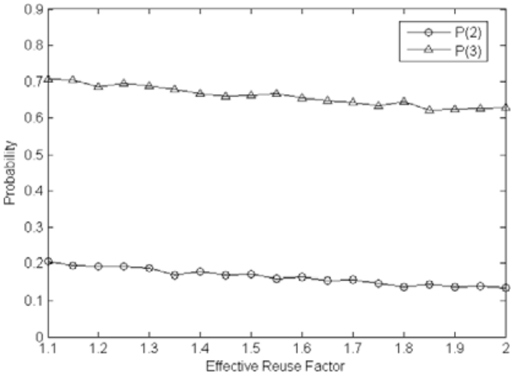


Fig. 4 Simulation results of $P(n)$.

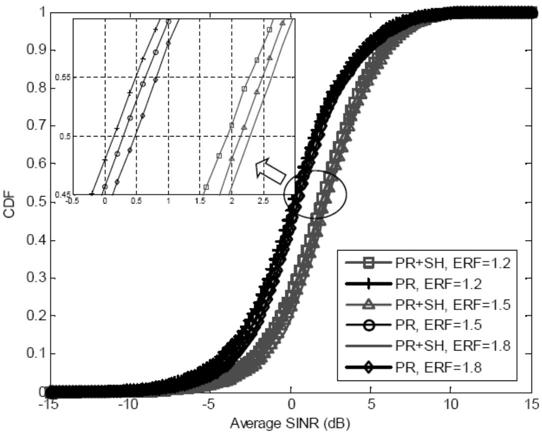


Fig. 5 Average SINR distributions of CEUs with handover list size > 1.

Given a cell edge UE with $n \geq 2$ cells in its handover list, the probability that the received SINR of the UE with n-way (n = 2, 3) soft handover (i.e. *Scheme A*) will be larger than that with a reuse-3 scheme (i.e. *Scheme B*) can be written as

$$P(n) = P(\gamma_A^{(1)} > \gamma_B^{(3)} | N_{AS} = n), \tag{14}$$

where N_{AS} denotes the active set size of the UE.

Our simulation results of the probability as defined in (14) with different effective reuse factors are shown in Fig. 4. It can be observed that $P(2)$ is ranged between 0.14 and 0.20 and $P(3)$ is ranged between 0.62 and 0.70. Hence, we conclude that as the number of soft handover cells (i.e. n) increases, the probability that the soft handover scheme will outperform a reuse-3 scheme in average SINR will also be increased.

The average SINR distributions of CEUs with handover list size greater than one are shown in Fig. 5 for r_{eff} = 1.2, 1.5, and 1.8. It is observed that by using the PR+SH scheme, the average SINR of the CEUs with handover list size greater than one is increased by approximately 1.8 dB, on average, when comparing with the standard PR scheme.

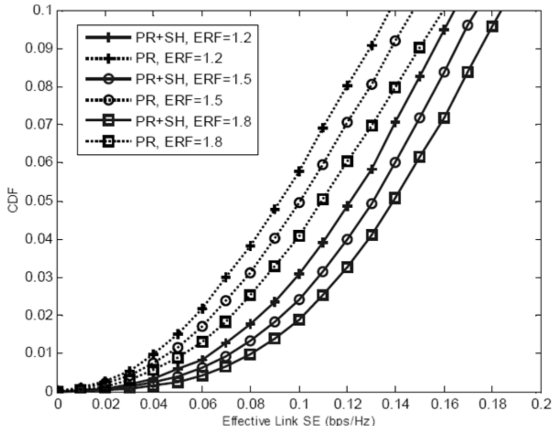


Fig. 6 Effective link SE $\tilde{C}_{eff}$ distribution.

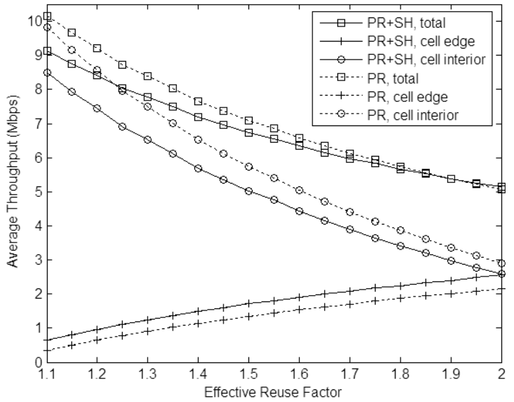


Fig. 7 Average throughput performance.

To link up the results with Table 2, we conclude that about 9% ($P_2 + P_3$) of total users or 26% ($(P_2 + P_3)/P_E$) of CEUs will get SINR improvement by using the PR+SH scheme, and the relative gain is about 1.8 dB, on average.

6.3 Link Spectral Efficiency Comparison

A more meaningful metric to look at is the improvement in link spectral efficiency (SE) by accounting for the bandwidth loss effect from the soft handover scheme and the reuse-3 scheme. The condition for this link spectral efficiency improvement can be expressed as

$$\frac{1}{n} \cdot \log_2(1 + \gamma_A^{(1)}/\varsigma) > \frac{1}{3} \cdot \log_2(1 + \gamma_B^{(3)}/\varsigma), \tag{15}$$

where n denotes the number of soft handover cells. It is noted that for a cell edge UE with 2-way or 3-way soft handover, the event $\gamma_A^{(1)} > \gamma_B^{(3)}$ does imply that inequality (15) holds and thus leads to link capacity improvement. To capture the link capacity improvement, we further define the *effective link SE* $\tilde{C}_{eff}$ as

$$\tilde{C}_{eff} = \frac{1}{m}\tilde{C}(\gamma), \tag{16}$$

where m is a bandwidth loss factor accounting for a reuse-3 scheme ($m = 3$) or a soft handover scheme ($m = 2$ or 3). We note that the loss factor m is set to 1 for the CIUs.

For 3GPP LTE, the link SE at 5% point of its CDF (i.e. 95% coverage), called 5% user SE, is an important criterion for performance evaluation of different inter-cell interference mitigation schemes [10], [21], [23]. Therefore, we adopt this criterion as a performance comparison indicator here. Figure 6 demonstrates the effective link SE $\tilde{C}_{eff}$ distributions with $r_{eff} = 1.2$, 1.5, and 1.8; and in particular we focus on the low user SE region. From the figure we observe that the 5% user SE of the PR+SH scheme is about 1.3 times of that of the standard PR scheme.

6.4 System Capacity Comparison

Figure 7 shows the average (total) cell throughput (T_{Cell}), cell interior throughput ($T_{Interior}$) and cell edge throughput (T_{Edge}) for the standard PR scheme and the PR+SH scheme with different effective reuse factors. From this figure we can have three observations. First, the larger the effective reuse factor is, the smaller the total cell throughput becomes. This is due to the fact that as the effective reuse factor increases, the available bandwidth in each cell is decreased and it results in lower frequency resource utilization. Second, the PR+SH scheme provides a significant cell edge throughput gain (about 18–92%) over the PR scheme, and the gain is more significant when the effective reuse factor is reduced. Third, with the same effective reuse factor, the PR+SH scheme causes about 11–13% cell interior throughput loss as compared with the PR scheme, and this further results in total cell throughput degradation when the effective reuse factor is less than 1.85 (roughly). This is because in the PR+SH scheme, the cell center band (F_1) is shared between all CIUs and some CEUs (who are performing soft handover), thus the amount of frequency resource allocated to a CIU, on average, is less than that in the PR scheme. From the above observations, one can conclude that the PR+SH scheme is an appropriate method to improve cell edge bit rate and achieve data rate fairness among users.

In a wireless communication system, it is very important to consider data rate fairness among users. Here, we define a parameter f, called *data rate fairness index*, as

$$\frac{T_{Interior}}{N_u \cdot P_I} = f \cdot \frac{T_{Edge}}{N_u \cdot P_E}, \tag{17}$$

where N_u denotes the number of active users in one cell and P_E is the (statistically) probability of CEUs (ratio of CEUs to total users in number). In this study, we consider three data rate fairness cases [11]: the first one is $f = 1$, which is called *fair*; the second case is $f = 2$, which is called *less fair*; and the last one is $f = 3$, which is called *least fair*. In the above three cases, the average user throughputs of CEUs are approximately 100%, 50%, and 33.3% of the average user throughputs of CIUs, respectively.

Our simulation results of the average cell throughput at different data rate fairness index f are presented in Fig. 8. For comparison, we also show the pure reuse-1 deployment

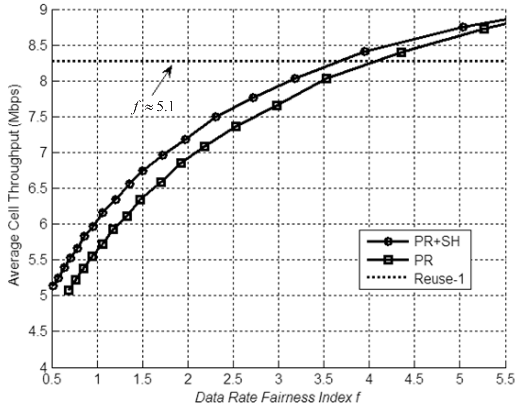


Fig. 8 Average cell throughput performance vs. data rate fairness.

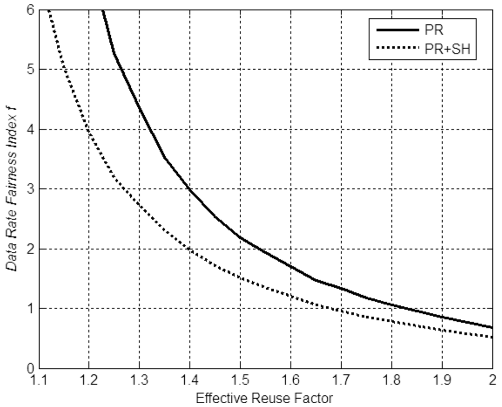


Fig. 9 Data rate fairness vs. effective reuse factor.

result in the figure. Note that in reuse-1 deployment case the value of f is fixed and is approximately 5.1 from our simulation. As shown in Fig. 8, both PR and PR+SH schemes outperform reuse-1 assuming $f = 5.1$. This result implies that the influence of accessible bandwidth loss caused by using PR or PR+SH scheme can be regained, and it further leads to an improvement in throughput. From Fig. 8 one can observe that, as compared with the standard PR scheme, the PR+SH scheme can achieve about 8%, 5%, and 3% average cell throughput gains in the *fair*, *less fair*, and *least fair* cases, respectively. The performance improvement can be explained as follows: due to the consideration of the data rate fairness among users, the PR+SH scheme can distribute the user throughput more evenly to the users than the standard PR scheme. In other words, the PR+SH scheme can meet a given data rate fairness index by using a smaller effective reuse factor as compared with the standard PR scheme. Figure 9 shows data rate fairness index f as a function of the effective reuse factors. Take the $f = 1$ case as an example, the corresponding effective reuse factors are 1.83 and 1.68 for the PR scheme and the PR+SH scheme, respectively.

7. Conclusions

In this paper, we proposed an inter-cell interference mitigation scheme for a multi-cell OFDMA system, and in particular we focus on downlink transmission. The basic idea of the proposed scheme is to dynamically choose between a partial frequency reuse scheme (with a reuse factor of 3) and a soft handover scheme to provide better signal quality for cell edge users. Our simulation results show that compared with standard partial frequency reuse scheme, the proposed scheme helps to improve the link quality and link spectral efficiency of cell edge users. By using our approach, there is a significant cell edge throughput gain over the standard partial frequency reuse scheme and it introduces a relatively low soft handover overhead. Considering data rate fairness among users, the proposed hybrid method also outperforms the standard partial frequency reuse scheme in total cell throughput. Therefore, we conclude that the proposed scheme is a competitive choice to enhance cell edge bit rate and overall system capacity.

References

[1] 3GPP TS 36.201 V8.1.0, “Evolved universal terrestrial radio access (E-UTRA); LTE physical layer — General description,” Nov. 2007.

[2] 3GPP2 C.S0084 v. 2.0, “Ultra mobile broadband (UMB) air interface specification,” Sept. 2007.

[3] IEEE 802.16e-2005, Part 16: Air Interface for Fixed Broadband Wireless Access Systems, Amendment for Physical and MAC Layers for Combined Fixed and Mobile Operation in Licensed Bands, 2005.

[4] 3GPP TR 25.913 V7.0.0, “Requirements for evolved UTRA (E-UTRA) and evolved UTRAN (E-UTRAN),” June 2005.

[5] Siemens, “Interference mitigation — Considerations and results on frequency reuse,” 3GPP R1-050738, 3GPP TSG RAN WG1 Meeting #42, Sept. 2005.

[6] M. Sternad, T. Ottosson, A. Ahlen, and A. Svensson, “Attaining both coverage and high spectral efficiency with adaptive OFDM downlinks,” Proc. IEEE 58th Veh. Technol. Conf., vol.4, pp.2486–2490, Oct. 2003.

[7] Huawei, “Soft frequency reuse scheme for UTRAN LTE,” 3GPP R1-050507, 3GPP TSG RAN WG1 Meeting #41, May 2005.

[8] B. Fan, Y. Qian, K. Zheng, and W. Wang, “A dynamic resource allocation scheme based on soft frequency reuse for OFDMA systems,” Proc. Int. Symp. Microwave, Antenna, Propagation and EMT Tech. for Wireless Commun., pp.1–4, Aug. 2007.

[9] Alcatel, “Interference coordination in new OFDM DL air interface,” 3GPP R1-050407, 3GPP TSG RAN WG1 Meeting #41, May 2005.

[10] 3GPP TR 25.814 v7.1.0, “Physical layer aspects for evolved UTRA,” Sept. 2006.

[11] Siemens, “Interference mitigation by partial frequency reuse,” 3GPP R1-060135, 3GPP TSG RAN WG1 Ad Hoc Meeting on LTE, Jan. 2006.

[12] H. Holma and A. Toskala, WCDMA for UMTS, 3rd ed., Wiley, 2002.

[13] R. Zhu, X. Zhang, and W. Wang, “Scheduling based controllable interference coordination in OFDMA systems,” Proc. First International Conference on Communications and Networking, pp.1–5, Oct. 2006.

[14] Y.-J. Choi, C.S. Kim, and S. Bahk, “Flexible design of frequency reuse factor in OFDMA cellular networks,” Proc. IEEE Int. Conf. Commun., vol.4, pp.1784–1788, June 2006.

[15] H. Lei, Z. Lei, X. Zhang, and D. Yang, “A novel multi-cell OFDMA system structure using fractional frequency reuse,” Proc. IEEE Symp. PIMRC, Sept. 2007.

[16] Texas Instruments, “Performance of inter-cell interference mitigation with semi-static frequency planning for EUTRA downlink,” 3GPP R1-060368, 3GPP TSG RAN WG1 Meeting #44, Feb. 2006.

[17] H. Jia, Z. Zhang, G. Yu, P. Cheng, and S. Li, “On the performance of IEEE 802.16 OFDMA system under different frequency reuse and subcarrier permutation patterns,” Proc. IEEE Int. Conf. Commun., pp.5720–5725, June 2007.

[18] Texas Instruments, “Inter-cell interference mitigation for EUTRA,” 3GPP R1-051059, 3GPP TSG RAN WG1 Meeting #42 bis, Oct. 2005.

[19] C.E. Shannon, Sloane & Wyner, Collected Papers, ed., IEEE Press, 1993.

[20] P. Mogensen, W. Na, I.Z. Kovacs, F. Frederiksen, A. Pokhariyal, K.I. Pedersen, T. Kolding, K. Hugl, and M. Kuusela, “LTE capacity compared to the Shannon bound,” Proc. IEEE 65th Veh. Technol. Conf., pp.1234–1238, April 2007.

[21] Qualcomm Europe, “Description and simulations of interference management technique for OFDMA based E-UTRA downlink evaluation,” 3GPP R1-050896, 3GPP TSG RAN WG1 Meeting #42, Sept. 2005.

[22] NTT DoCoMo, NEC, SHARP, “Intra-node B macro diversity using simultaneous transmission with soft-combining in evolved UTRA downlink,” 3GPP TSG RAN WG1 Meeting #42, Sept. 2005.

[23] Siemens, “LTE interference coordination — Downlink system simulation results,” 3GPP R1-062374, 3GPP TSG RAN WG1 Meeting #46, Sept. 2006.

[24] C.-S. Chiu and C.-C. Huang, “Combined partial reuse and soft handover in OFDMA downlink transmission,” Proc. IEEE VTC’08, pp.1707–1711, May 2008.

Che-Sheng Chiu was born in Chiayi, Taiwan, R.O.C., in 1975. He received B.S. degree in applied mathematics from National Chiao-Tung University (NCTU), Hsinchu, Taiwan, in 1997, the M.E. degree in communication engineering from NCTU, in 1999, and is currently working toward the Ph.D. degree in communication engineering from NCTU. He has been with Telecommunication Laboratories, Chunghwa Telecom Company, Chung-Li, Taiwan, since 2000. His research interests include radio network resource management, mobile network system-level performance evaluation, and cross-layer optimization for high-speed wireless networks.

Chia-Chi Huang was born in Taiwan, R.O.C. He received the B.S. degree in electrical engineering form National Taiwan University in 1977, and the M.S. and Ph.D. degrees in electrical engineering from the University of California, Berkeley, in 1980 and 1984, respectively. From 1984 to 1988, he was a RF and Communication System Engineer with the Corporate Research and Development Center, General Electric Co., Schenectady, NY, where he worked on mobile radio communications. From 1989 to 1992, he was with IBM T.J. Watson Research Center, Yorktown Heights, NY, as a Research Staff Member. In 1992, he joined National Chiao-Tung University, Hsinchu, Taiwan, where he is currently a professor.