Decentralized Intercell Interference Coordination in Uplink Cellular Networks using Adaptive Sub-band Exclusion

Min Suk Kang and Bang Chul Jung
KAIST Institute for Information Technology Convergence,
373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, KOREA
Email: minsuk.kang@kaist.ac.kr; bcjung@kaist.ac.kr

***Abstract*— In this paper, we proposed an adaptive sub-band exclusion (ASE) scheme as a means of intercell interference coordination (ICIC) technique to improve the performance of wireless cellular systems in a decentralized manner. It excludes some portion of orthogonal frequency division multiplexing (OFDM) sub-bands inducing the most significant interference to othercell base staions (BSs). Moreover, the scheme determines the exclusion ratio according to how much intercell interference the MS induces to its neighbor cells. Since ICIC is done at each MS, the proposed ASE scheme can be called a decentralized ICIC scheme. Compared to conventional centralized ICIC schemes, our decentralized ASE scheme has the following advantages: cell and user coordinations are easier in our decentralized scheme, the complexity of ICIC at BSs is reduced, and more detailed othercell interference characteristics, such as frequency selectivity, can be used in ICIC. Through extensive computer simulations, we show that the proposed ASE scheme is effective in improving cell edge user performance by eight times at a reasonable degradation of average user performance.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) technique has attracted extensive attention for its high spectral efficiency [1]. Now, OFDM technique dominates almost all physical layer techniques of the fourth generation (4G) wireless communication systems.

OFDM based systems do not suffer from interference among multiplexed users within a cell given perfect frequency synchronization. However, when it comes to a multi-cell environment, heavy intercell interferences between adjacent cells are induced and they significantly reduce the system performance and, especially, cell edge user performance [3] [4] [5]. As the future wireless communication systems prefer universal frequency reuse to satisfy increasing demand for high data rate, intercell interference mitigation is now a very important issue in designing future mobile wireless communication systems. For examples, IEEE 802.16m and 3GPP LTE systems explicitly require intercell interference mitigation techniques as the basic system functionalities [6] [7].

Intercell interference mitigation techniques are classified by three types: intercell interference randomization, intercell interference cancellation, and intercell interference coordination [2]. *Intercell interference randomization* is aimed at randomizing the interference and allowing interference mitigation through processing gain. *Intercell interference cancellation* techniques are proposed to cancel interference at receivers by using multiple antenna techniques or interleaved division multiple access (IDMA) schemes. *Intercell interference coordination* (ICIC) is based on the concept that a well-designed coordination of resource among users in adjacent cells can reduce interference and improve user capacity and coverage at cell edge. Most of the techniques are based on *fractional frequency reuse* (FFR), one of the most promising technique for ICIC. Since a universal reuse system is inherently interference limited, the spectral efficiency of these cell edge users is poor. To solve this problem, FFR classifies users in a cell into multiple classes based on the geometrical information of users, e.g., center cell users, mid cell users, or cell edge users, and then assigns different bandwidth allocation patterns for different user classes [9] [10] [11]. Transmissions of all users in the system are carefully coordinated by base stations or even higher network entities to effectively coordinate interference. FFR based ICIC is now considered as a baseline method for mitigating interference in current standards [8].

However, FFR has some limitations in practical systems. First, it has lower trunking efficiency, since fixed amount of frequency bands is assigned for each user according to its location. Second, it has reduced frequency diversity due to its narrow bandwidth allocation for cell edge user. Third, it is inflexible to the advent of a new cell because it uses centralized frequency band planning. Especially, in uplink cellular systems, this centralized FFR scheme is not practical, since uplink scheduling, which has longer feedback loop than downlink scheduling, is difficult to be coordinated by adjacent base stations.

Thus, we claim that decentralized techniques are more preferable for ICIC in uplink cellular systems. In addition, paradigm for network management has been rapidly shifting from centralized to decentralized. Decentralized (or self-optimized) network management schemes (including interference reduction) are already chosen as a study item of 3GPP LTE-advanced system [12].

In this paper, we propose an Adaptive Sub-band Exclusion (ASE) scheme for *decentralized* ICIC in frequency selective fading channel environment. Using ASE, each user decides the portion of total frequency resource it occupies and a set of sub-bands used for transmission by excluding sub-bands considering its interference characteristics to neighboring cells.

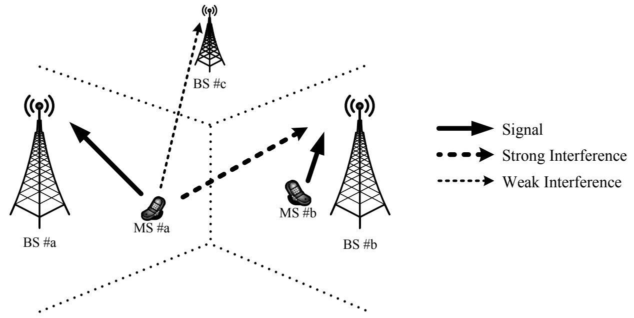

Fig. 1. System Model

Adaptive sub-band nulling concept that excludes some sub-bands in transmission depending on channel conditions was proposed in a single cell environment [13]. The authors showed that the scheme approaches the optimal water-filling scheme given an optimal parameter. In [14], the concept was extended to a two-cell uplink model and it allowed each MS performs sub-band nulling in time domain according to time-varying interference channel gain. In the ASE scheme proposed in our study, we extend the concept of adaptive sub-band nulling to frequency domain. Moreover, we devise a systematic operating rule for the ASE in a multi-cell structure. Extensive numerical experiments prove that the ASE scheme is effective to considerably improve cell edge performance by eight times with acceptably small degradation of system capacity. Moreover, the proposed scheme is a completely distributed scheme so that it minimizes network overhead for ICIC.

The rest of this paper is organized as follows. In Section II, we introduce our OFDM based uplink cellular system model. In Section III, we introduce the proposed adaptive sub-band exclusion scheme. In Section IV, the performance of the proposed scheme in the OFDM uplink cellular system is evaluated through computer simulations. Finally, conclusions are presented in Section V.

II. System Model

As shown in Fig. 1, we assume a multi-cell OFDM-based uplink cellular system. It is assumed that multiple mobile stations (MSs) are attached to one of the base stations (BSs) and only one of the MSs in a cell is selected at a certain symbol time and allowed to transmit to its BS. All BSs and MSs are assumed to be equipped with a single antenna. Round robin scheduling is assumed to guarantee each user's fairness. We consider large scale fading as well as small scale fading. For large scale fading, propagation loss and shadow fading are considered and, for small scale fading, frequency selective, time varying fading is considered.

Each MS is assumed to have channel characteristics of both signal channel and interference channels. Interference channel information can be easily measured in a time division duplex (TDD) system by listening downlink preambles from neighboring BSs due to channel reciprocity.

The uplink channel capacity of a user in a cell #0 is given by

$$C = \sum_{k=1}^{N_{sub}} C(k), \tag{1}$$

where N_{sub} is the number of OFDM subcarriers. The channel capacity of k-th subcarrier, $C(k)$, is given as

$$C(k) = \log_2 \left(1 + \frac{S^0(k)}{N_0 + \sum_{n=1}^{N_I} I_n^0(k)} \right). \tag{2}$$

The term N_0 represents thermal noise power density and the signal term, S^0, and the interference term, I_n^m, in the cell #0 are given by

$$S^0(k) = P_{TX} \times G_0^0 \times F_0^0(k), \tag{3}$$

$$I_n^m(k) = P_{TX} \times G_n^m \times F_n^m(k), \tag{4}$$

where P_{TX} represents the transmit power at an MS, G_n^m represents average channel gain from an active MS in the n-th cell to m-th cell BS, and $F_n^m(k)$ represents the frequency selective channel gain at k-th subcarrier from an active MS in the n-th cell to m-th cell BS. We assume there exist N_I of interfering MSs.

In uplink cellular systems, it is highly likely that that the amount of interferences from MSs located at neighboring cells exceed the amount of the thermal noise at a receiving BS. In the so-called *interference limited* case, we can simply write $C(k)$ in Eq.(2) as

$$C(k) \cong \log_2 \left(1 + \frac{G_0^0 \times F_0^0(k)}{\sum_{n=1}^{N_I} G_n^0 \times F_n^0(k)} \right). \tag{5}$$

III. Proposed Adaptive Sub-band Exclusion Scheme

We propose an Adaptive Sub-band Exclusion (ASE) scheme as a decentralized uplink ICIC technique. The centralized ICIC technique has several advantages over decentralized ICIC techniques. First, the overall amount of feedback signalling is reduced because no feedback information is needed for intercell interference coordination. Second, in a decentralized technique, intelligent tasks, such as frequency band selection or power control, which would have been performed at the BS in a centralized ICIC technique, can be performed in MS and this makes ICIC more efficiently. The proposed ASE scheme utilizes interference channel information, especially frequency selective characteristics, at an MS and it allows the MS a permission to determine its sub-band selection. In a centralized scheme, it is not practical to use frequency selective characteristics of interference channel in uplink systems, since too much feedback information should be sent back to the BS.

Since every MS is assumed to have all the frequency selective channel gains of its interference channels, it can perform an optimal transmission strategy to maximize its transmission rate while minimizing interference. However, it has not even proven that, in terms of system capacity, the existence of optimality of the multi-cell interference management problem in a frequency selective channel fading environment. Thus, instead, in the ASE, each MS simply excludes some sub-bands according to the channel gain of the interference channel

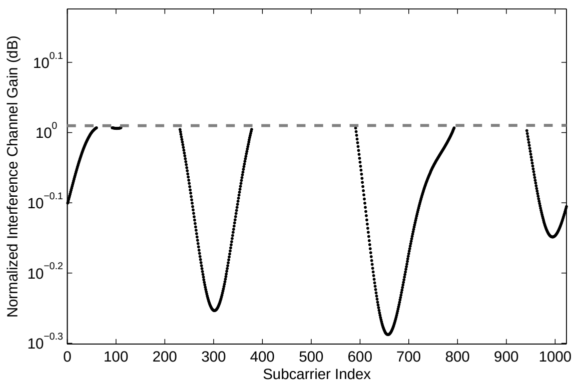

Fig. 2. An example of normalized received interference of an MS located in an adjacent cell to a target BS. The MS induces the largest interference to the target BS and it excludes a certain portion of sub-bands according to the channel characteristics. The MS has the exclusion ratio of 0.50.

that has the largest channel gain among all other interference channels. For example, in Fig. 1, since the MS#a located adjacent to the cell#b induces strong interference to the BS#b and week interference to the BS#c, the MS#a performs the ASE according to the channel toward the BS#b.

In the ASE, every MS first measures the largest interference channel gain, $I_{\max}$, and identifies the index, $x_{\max}$, of which its interference channels has the largest channel gain. The two terms are defined as

$$I_{\max} = \max I_x^0, \tag{6}$$

$$x_{\max} = \arg\max_x I_x^0. \tag{7}$$

Then, it determines the exclusion ratio, $0 \leq \alpha \leq 1$, according to the measured maximum interference channel gain, $I_{\max}$. Finally, it excludes a set of sub-bands that have channel gain values of upper ($\alpha \times 100$) % among total OFDM sub-bands.

Fig. 2 shows an example of normalized received interference at the BS in uplink mode. In this example, the index, $x_{\max}$ of the MS is 0, i.e., the target BS#0 is the biggest victim of the transmission of the MS. About upper fifty percent of sub-bands are excluded according to the channel between the MS and the BS#0. Using the ASE, the total received interference reduction is expected, since the subcarriers that generates severe interferences are excluded. In the mean time, the total power of signals also reduced, since the degrees-of-freedom for every MS is reduced by the factor of α. The overall performance gain or loss is hard to be mathematically analyzed. Through extensive simulation results, we prove the effectiveness of the proposed ASE scheme.

In the ASE scheme, each MS sets its exclusion ratio based on the maximum interference channel gain, $I_{\max}$. Given that the MS has obtained the statistics of $I_{\max}$ from its history, it determines the percentile of the current $I_{\max}$ value, $p_{\max}(0 \leq p_{\max} \leq 1)$. The percentile can be calculated by

$$p_{\max} = F_{I_{\max}}(i_{\max}), \tag{8}$$

where $F_{I_{\max}}(\cdot)$ represents the cumulative distribute function of $I_{\max}$ and $i_{\max}$ is the current value of the maximum interference channel gain. In the ASE scheme, the MS translates $p_{\max}$ value into the exclusion ratio, α, using a mapping function $M(\cdot)$. In this study, we apply a linear mapping function for simple operation. That is,

$$\alpha = M(p_{\max}) = p_{\max}. \tag{9}$$

When the MS induces large interference to other cell BSs and has very large $I_{\max}$ values, it obtains $p_{\max}$ and α values close to 1. On the other hand, an MS generating small amount of interference can have very low value of α. Using the ASE scheme, an MS, which induces little amount of interference to other cell BSs, can use more sub-bands for its transmission while an MS, which induces enormous amount of interference, can has limited use of sub-bands. From the behavior of MSs with the ASE scheme, we can consider the ASE scheme a real FFR scheme in that it reuse the frequency resource according to the interference environments more flexibly and adaptively.

TABLE I
THE SYSTEM-LEVEL SIMULATION ENVIRONMENT

Parameters	Assumption
Cell layout	19 cell-site, single sector
Path loss	$L = 128.1 + 37.6 \log_{10}(R)$, R in kilometers
Inter-site distance	0.866 km
Shadowing standard deviation	8.0 dB
Bandwidth	10 MHz
FFT size	1024
Subcarrier spacing	15 kHz
Maximum MS tx power	23 dBm
Thermal noise density	-174 [dBm/Hz]
Antenna configuration	SISO, Omni-directional

IV. SIMULATION RESULTS

In this section, we present our simulation environment and numerical examples.

A. Simulation Environment

The simulation is performed in the standard hexagonal cell structure. We use a 19 cell, two-tier multi-cell model. MSs are uniformly distributed. As explained in Section II, only one MS is selected at a certain symbol time to transmit its data. Table I summarizes the parameters of the system-level simulator used in this paper. We utilize the typical system parameters of IEEE 802.16m evaluation methodology document [15]. Short-term fading is modelled as ITU Pedestrian A model [16]. We assume 100 users in a cell with full buffer, i.e., all users always have traffic to send.

To observe the fundamental performance gain of the proposed ASE scheme, we assume the basic unit of a single sub-band is a single subcarrier, i.e., a sub-band contains only one subcarrier. The assumption provides the upper bound performance of the proposed ASE scheme with a sub-band containing more than one sub-carrier.

B. Numerical Examples

Fig. 3 and Fig. 4 show the average uplink user capacity and 5-percentile uplink user capacity for varying global exclusion

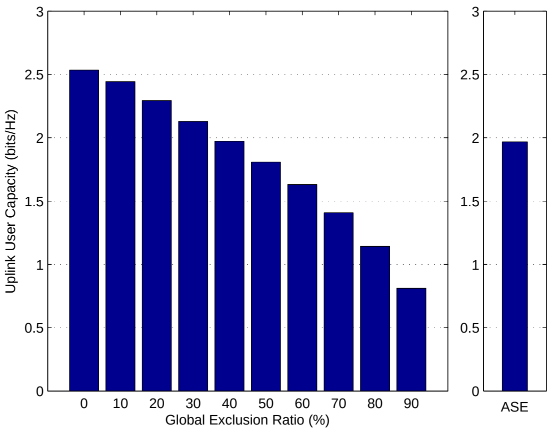

Fig. 3. Average uplink user capacity for varying exclusion ratios and the proposed ASE scheme.

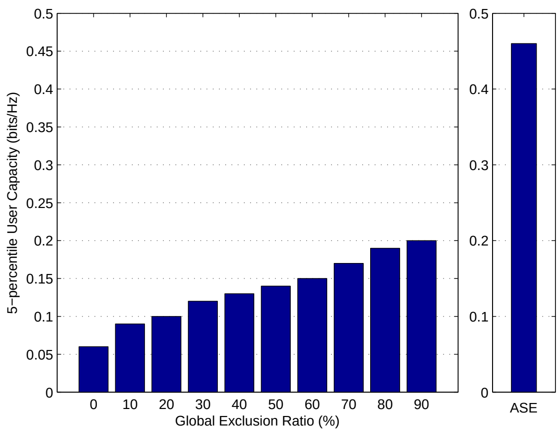

Fig. 4. 5-percentile uplink user capacity for varying exclusion ratios and the proposed ASE scheme.

ratios and the proposed ASE scheme, respectively. In the numerical experiments, for a given global exclusion ratio, all users use the same exclusion ratio. The global exclusion ratio 0 implies the conventional scheme that allows all users use all the possible frequency band for their uplink transmissions. The higher the global exclusion ratio is given, the less degrees-of-freedom in uplink transmission and the less othercell interference.

As shown in Fig. 3, as the exclusion ratio increases the average uplink user capacity is decreases. On the other hand, in Fig. 4, 5-percentile uplink user capacity, a measure of cell edge performance, increases as the exclusion ratio increases. The different trends are obtained because the dominant contributors of the two performance metrics are different and lie in the different SINR range. The major contributors to the average user capacity are those who achieve high SINR and are located in the center of cell and they are in the power-limited condition. For the power-limited users, the

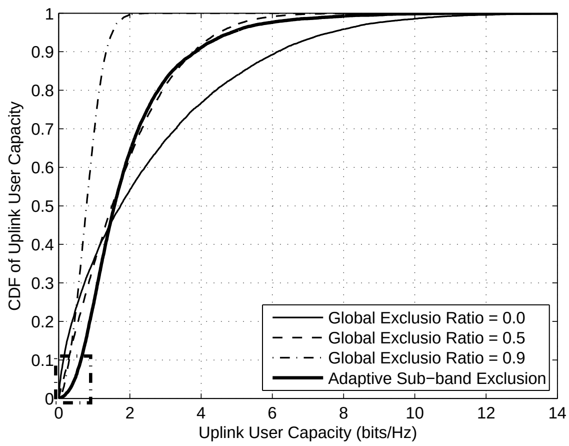

Fig. 5. CDF of uplink user capacities for some global exclusion ratios and the ASE scheme.

performance gain from the interference reduction is negligible while the performance loss from the reduced degrees-of-freedom is considerable. However, for 5-percentile uplink user capacity, the major contributors have low SINRs and are located in cell edge and they are in the interference-limited condition. For the interference-limited users, the performance gain from the interference reduction is much larger than the loss from the reduced degrees-of-freedom. Applying the global exclusion ratio has the intrinsic trade-off problem; the system performance is reduced while the cell edge performance is improved.

The proposed ASE scheme is shown to effectively compromise the trade-off problem. We have set the mapping function $M(p_{\max}) = p_{\max}$ as the simple linear function in Eq. (9), so the expected exclusion ratio for all users is 0.5. However, shown in Fig. 3, the average uplink user capacity of the ASE scheme outperforms that of the global exclusion ratio of 0.5 and it is about 80% of performance of the conventional scheme. Moreover, Fig. 4 shows that the 5-percentile uplink user capacity of the ASE is almost eight times improved compared to that of the conventional scheme.

The effectiveness of the proposed ASE scheme can also be found in cumulative distribution function (CDF) analysis shown in Fig. 5. It provides the CDF curves of uplink user capacities for some global exclusion ratios and the ASE scheme. In the figure, the reduction of average uplink user capacity and the increase of 5-percentile uplink user capacity are observed. For more details, Fig. 6 provides highlight for lower range of the CDF of the previous figure.

V. Conclusions

We proposed a decentralized intercell interference coordination (ICIC) scheme by means of an Adaptive Sub-Band Exclusion (ASE) which can be applied to practical OFDM-based uplink cellular systems. The proposed scheme is designed in a decentralized manner so that the ICIC can be performed at each MS. It excludes some portion of OFDM sub-bands inducing the most significant interference to othercell base

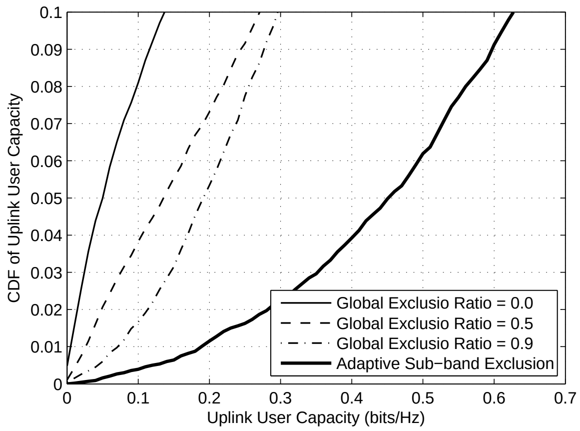

Fig. 6. Highlight for lower range of CDF of uplink user capacities for some global exclusion ratios and the ASE scheme.

staions (BSs). Moreover, the scheme determines the exclusion ratio according to how much intercell interference the MS induces to its neighbor cells. Compared to conventional centralized ICIC schemes, our decentralized ASE scheme has several advantages in coordinating cells and users, reducing complexity of BSs, and utilizing frequency selective channel gains of interference channels in ICIC. We performed extensive computer simulations and showed that the proposed ASE scheme is effective in improving cell edge user performance by eight times at a reasonable degradation of average user performance.

REFERENCES

[1] R. Van Nee and R. Prasad, *OFDM for wireless multimedia communications*, Artech House Publishers, 2000.

[2] 3GPP, TR 25.814 V7.1.0, "Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA)," Sept., 2006.

[3] Sergey N. Moiseev et al., "Analysis of the Statistical Properties of the Interference in the IEEE 802.16 OFDMA Network," *IEEE Wireless Communications and Networking Conference*, 2006.

[4] Suman Das and Harish Viswanathan, "A Comparison of Reverse Link Access Schemes for Next-Generation Cellular Systems," *IEEE Journal on Selected Areas in Comm.*, Vol. 24, No. 3, March 2006.

[5] Changqin Huo, Abu B. Sesay and Abraham O. Fapojuwo, "Co-Channel Diversity Schemes for an OFDM Based Cellular System with One-cell Frequency Reuse," *IEEE Wireless Communications and Networking Conference*, 2006.

[6] IEEE 802.16m-07/002r5, "IEEE 802.16m System Requirements," August 2008.

[7] 3GPP, TR 25.913 V7.3.0, "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)," March 2006.

[8] IEEE 802.16m-08/003r4, "The Draft IEEE 802.16m System Description Document," June 2008.

[9] 3GPP, R1-050896, "Description and simulations of interference management technique for OFDMA based E-UTRA downlink evaluation," Sept., 2005.

[10] Hyukmin Son and Sanghoon Lee, "The Cell Planning Scheme for ICI Mitigation," *IEEE International Symposium on Personal, Indoor and Mobile Radio Communication*, 2007.

[11] Romeo Giuliano, Pierpaolo Loreti, Franco Mazzenga, and Giovanni Santella, "Fractional Frequency Reuse Planning for WiMAX over Frequency Selective Channels," *International Wireless Communications and Mobile Computing Conference*, 2008.

[12] 3GPP TR 36.902 V0.0.1, "Self-configuring and self-optimizing network use cases and solutions," Feb., 2008.

[13] B. C. Jung, Y.-J. Hong, D. K. Sung, S.-Y. Chung, "Adaptive Sub-band Nulling for OFDM-Based Wireless Communication Systems," *IEEE Wireless Communications and Networking Conference*, 2007.

[14] B. C. Jung, Y.-J. Hong, D. K. Sung, S.-Y. Chung, "Fixed Power Allocation with Nulling for TDD-Based Cellular Uplink," *IEEE Communications Letters*, Vol. 12, No. 4, April 2008.

[15] IEEE 802.16m-08/004r2, "IEEE 802.16m Evaluation Methodology Document (EMD)," June 2008.

[16] Recommendation ITU-R M.1225, "Guideline for Evaluation of Radio Transmission Technologies for IMT-2000," 1997.