Cell Grouping and Autonomous Channel Assignment for Cooperative Multi-Cell MIMO Systems

Li-Chun Wang and Chu-Jung Yeh
National Chiao Tung University, Taiwan
Email : lichun@cc.nctu.edu.tw and teensky.cm93g@nctu.edu.tw

***Abstract*— In this paper, we propose a three-cell network multiple-input multiple-output (MIMO) scheme to mitigate the inter-cell interference in an orthogonal frequency division multiple access (OFDMA) system with each cell using the same spectrum. One fundamental question to apply the network MIMO technique in such a high interference environment is: how many base station should coordinate together to provide sufficient signal-to-interference plus noise ratio (SINR) performance? We find that on top of the tri-sector directional antenna and fractional frequency reuse (FFR), the network MIMO based on the proposed three-cell coordination strategy can already improve SINR performance significantly compared to the 19-cell coordination network MIMO without FFR and tri-sector cellular architecture.**

***Index Terms*— network MIMO, fractional frequency reuse, interference cancellation.**

I. INTRODUCTION

Orthogonal frequency division multiple access (OFDMA) is considered to be a promising multiple access technique for future broadband wireless communications and is adopted by the standards such as the Third Generation Partnership Project (3GPP) Long-Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX). In a multi-cell OFDMA network, the inter-cell interference is a more serious issue compare to the intra-cell interference.

To avoid inter-cell interference, the most commonly used technique is to avoid using the same set of frequencies in neighboring cells, that is, a larger cluster of cells sharing the whole spectrum. This approach leads to the decrease of the number of available channels within each cell. Hence, the concept of fractional frequency reuse (FFR) is suggested to improve spectrum efficiency by applying the reuse partition technique, where the inner region of the cell is assigned with the whole frequency spectrum and the outer region is only assigned with a small fraction of the frequency spectrum. [1].

Recently, the network multiple-input multiple-output (MIMO) technique becomes a hot topic, which aims to mitigate the inter-cell interference by coordinating the multi-cell transmission among a few geographically separated antennas (base stations). In the early work [2], the concept of co-processing at transmitting end in a cellular system was proposed. [3] proposed a distributed network beamforming in a cellular system and analyzed the performance based on Wyner's circular array model [4]. More analysis about coordination strategies with grouped cell interior and edges users based on Wyner's circular array model were studied in [5]. Network MIMO with more general channel model was addressed in [6], [7]. [8] compared network MIMO coordination with a denser base station deployment. To effectively cancel inter-cell interference, the network MIMO requires a reliable and high-speed backbone connection among base stations to obtain the channel state information (CSI) and mobile messages among those cooperating cells.

Although both the concept of FFR and inter-base station coordination already are considered for one of possible inter-cell interference cancellation technique in both WiMAX and LTE [9], to our knowledge, combining network MIMO with FFR to mitigate inter-cell interference is still an open issue. Therefore, the objective of this paper is to propose a FFR-based network MIMO interference cancellation scheme for a multi-cell OFDMA system. A fundamental issue for network MIMO arises: how many cells should be coordinated to provide sufficient signal-to-interference plus noise ratio (SINR) performance. Intuitively, it is impractical to cooperate too many cells. The huge computational complexity and synchronization among a huge number of cells are quite challenging. In addition, a group of coordinated cells will still cause interference to neighboring coordinated group of cells with each other. It is a coordination boundary problem for network MIMO. In this paper, we try to explore the potential gain of network MIMO by using a near minimum number of coordinated cells, i.e. only three cells.

The rest of this paper is organized as follows. Section II introduces the FFR scheme. In Section III, we briefly review the concept of network MIMO. Section IV presents the proposed three-cell network MIMO architecture with FFR. In Section V, we show numerical results and give concluding remarks in Section VI.

The work was supported jointly by the National Science Council, and the MOE program for promoting university excellence under the contracts NSC 96-2628-E-009-004-MY3, NSC97-2221-E009-099-MY3, and MOE ATU Program 97W803C.

978-1-4244-5213-4/09/ $26.00 ©2009 IEEE

II. Fractional Frequency Reuse

Fractional frequency reuse, also called reuse partition, allows different frequency reuse factors to be applied over different frequency partitions during the designed period for transmission. Figure 1 shows the general FFR for a tri-sector cellular system [10], [11]. The FFR partitions frequency band into inner frequency bands f_A and outer frequency bands f_B, where f_B is further partitioned into three subbands f_{B_1}, f_{B_2}, and f_{B_3} (the light blue, yellow, and green area, respectively). In general, the inner frequency bands f_A adopts a reuse factor of one and is used by interior cell users; the outer frequency bands f_B adopts a reuse factor of 1/3 for each sector for cell edge users. By means of FFR, the intra-cell interference can be avoided due to four orthogonal subbands, and the inter-cell interference can be significantly reduced.

We assume that f_{B_1}, f_{B_2}, and f_{B_3} have the same bandwidth and there are n frequency units in each outer subband, i.e., $f_{B_i} = \{f_{B_{i,1}}, \ldots, f_{B_{i,n}}\}$ for $i = 1, 2, 3$. Note that FFR is usually integrated with other functions like power control or antenna technologies for adaptive control.

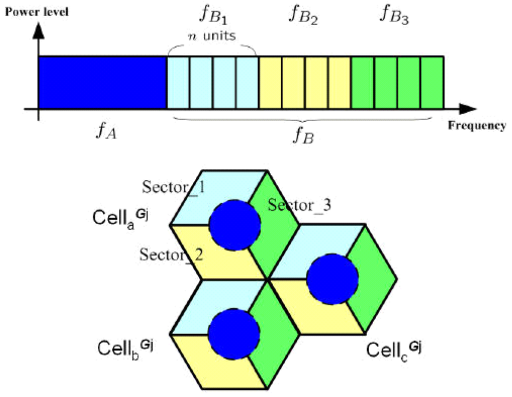


Fig. 1. Frequency partition for a tri-sector cell layout.

III. Network MIMO

Network coordination is a means to eliminate the inter-cell interference and improve spectral efficiency in a downlink multi-cell system [6], [7]. With a high-speed backbone, the base stations can be connected and synchronized. Assume that all base stations can cooperate via the central coordinator by each cell site reports CSI. With full base station cooperation, the downlink transmission can be modelled as a MIMO broadcast system. Consider a network MIMO system with M coordinated base stations (each site with single transmit antenna) each of which transmits data stream to its own target mobile station. The received signal is given by

$$\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{n} \ , \tag{1}$$

where $\mathbf{H} = [h_{i,j}]_{M \times M}$ denotes the channel matrix with element $h_{i,j}$ being the channel response between mobile i and base station j, and $\mathbf{n}$ denotes the noise vector. The transmitted signals vector is denoted by $\mathbf{x} = \mathbf{W}\mathbf{s} = [\mathbf{w}_1 \ldots \mathbf{w}_M][s_1 \ldots s_M]^T$, where s_i is the i-th mobile user's data symbol, $\mathbf{w}_i$ is the corresponding precoding weight column vector, and $(\cdot)^T$ is the transpose operation. For a network MIMO system, the antenna output of the j-th transmission site is a linear combination of M data symbols, i.e., $x_j = \sum_{i=1}^{M} w_{ji} s_i$. Denote p_i as the power of the data symbol s_i. According to the network MIMO principle, the following constraint should be satisfied: $\mathrm{E}[|x_i|^2] \le P_T$ for $i = 1, \ldots, M$.

$$\begin{bmatrix} |w_{11}|^2 & \cdots & |w_{1M}|^2 \\ \vdots & \ddots & \vdots \\ |w_{M1}|^2 & \cdots & |w_{MM}|^2 \end{bmatrix} \begin{bmatrix} p_1 \\ \vdots \\ p_M \end{bmatrix} \le P_T \mathbf{1} \ , \tag{2}$$

where P_T is the maximum transmit power of each base station.

It is well known that dirty paper coding (DPC) can achieve the capacity of a MIMO broadcast system. Due to high complexity of DPC, some suboptimal but practical schemes were proposed. In this paper, we consider two suboptimal network MIMO schemes, including zero-forcing (ZF) and zero-forcing dirty paper coding (ZF-DPC).

A. Network MIMO: ZF Transmission

The goal of ZF transmission is to invert the channel to obtain $\mathbf{HW} = \mathbf{I}$. This function can be achieved by using the pseudo-inverse of the channel matrix as the weight matrix $\mathbf{W}$. The received signal vector is hence given by

$$\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{n} = \mathbf{H}\mathbf{W}\mathbf{s} = \mathbf{s} + \mathbf{n} \ . \tag{3}$$

For the network MIMO system (2), the objective is to maximize the minimum received SINR subject to the power constraint. The corresponding solution is [7]

$$p_i = \frac{P_T}{\max_j [\mathbf{W}\mathbf{W}^*]_{(j,j)}} = \frac{P_T}{\max_j \sum_i |w_{ji}|^2} \ , \quad \text{for all} \quad i \ . \tag{4}$$

B. Network MIMO: ZF-DPC Transmission

The ZF-DPC transmission constructs the linear weight matrix $\mathbf{W} = \mathbf{Q}^*$ through the QR decomposition of the channel matrix $\mathbf{H} = \mathbf{L}\mathbf{Q}$, where $\mathbf{L}$ is a lower triangular matrix, $\mathbf{Q}$ is a unitary matrix with $\mathbf{Q}\mathbf{Q}^* = \mathbf{Q}^*\mathbf{Q} = \mathbf{I}_M$, and $(\cdot)^*$ is the conjugate transpose operation. The received signal is written as

$$\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{n} = \mathbf{L}\mathbf{Q}\mathbf{Q}^*\mathbf{s} = \mathbf{L}\mathbf{s} + \mathbf{n} \ , \tag{5}$$

and the corresponding i-th mobile's received signal is $y_i = L_{ii} s_i + \sum_{j<i} L_{ij} s_j + n_i$. Note that the weight matrix $\mathbf{W} = \mathbf{Q}^*$ guarantees no interference from data symbols with indices $j > i$. The remaining interference from data symbols $j < i$ are taken care of by successive interference cancellation of DPC.

Based on the result of ZF transmission, if we set $p_i = p$ for all i, the per-site power constraint (2) becomes $[\mathbf{W}\mathbf{W}^*]_{(j,j)} p = \sum_j |w_{ij}|^2 p \le P_T$ for all i. Recall that the weight matrix $\mathbf{W} = \mathbf{Q}^*$. We have $[\mathbf{W}\mathbf{W}^*]_{(j,j)} = [\mathbf{Q}^*\mathbf{Q}]_{(j,j)} = [\mathbf{I}]_{(j,j)} = 1$. Thus, we can set $p_i = P_T$ for each coordinated base station. Note that there exists an excessive transmission power penalty for ZF transmission due to the required interference cancellation power of weight matrix $\mathbf{W}$.

IV. THREE-CELL FFR-BASED NETWORK MIMO

A. Combination of Network MIMO and FFR

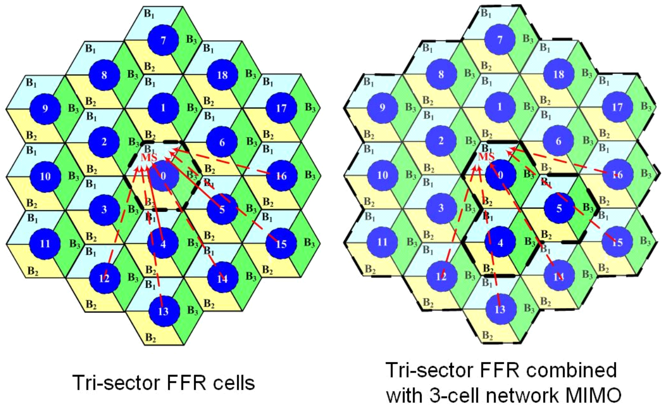
In this section, we propose a novel multi-cell architecture combined FFR with network MIMO for broadband OFMDA systems. As mentioned before, the whole frequency band are partitioned into different zones by FFR frequency planning. Usually, designing a larger group of cells to share the whole spectrum can mitigate the co-channel interference at the cost of lower frequency usage. Compared to conventional 19-cell layout, the tri-sector cellular system combined with FFR can significantly reduce the interference sources, while fulling utilizing the frequency band at each cell. As an example in Fig. 2, when a mobile user of cell 0 uses frequency band $f_{B_{1,j}}$, the interference comes from cells 4, 5, 12, 13, 14, 15, and 16. In the conventional systems, the mobile is interfered by all the other 18 cells. Here, the question is how we can further improve the SINR on top of FFR? The solution proposed in this paper is to integrate FFR with the network MIMO technique.

From Fig. 2, we find that the seven interfering sources consists of two critical interferers comes form neighboring cells 4 and 5 and five weaker interferers due to larger path loss. Therefore, we use the network MIMO technique to cancel the two most severe interference. Instead of huge number of coordinated cells, we propose a coordination scheme with only three coordinated cells. We define those coordinated cells as a group shown in Fig. 1. For arbitrary group G_j, we label the three cells as $\mathrm{Cell}_a^{G_j}$, $\mathrm{Cell}_b^{G_j}$, and $\mathrm{Cell}_c^{G_j}$, respectively. For the three-cell coordination structure, we can apply network MIMO transmission to each subband $f_{B_{i,j}}$ for $i = 1, 2, 3$ and $j = 1, \ldots, n$. In Fig. 2, under the assumption of perfect sectorization by directional antenna, the channel matrix of $f_{B_{1,j}}$ in the group $\{0, 4, 5\}$ is

$$\mathbf{H}(f_{B_{1,j}}) = \begin{bmatrix} h_{0,0} & h_{0,4} & h_{0,5} \\ 0 & h_{4,4} & 0 \\ 0 & 0 & h_{5,5} \end{bmatrix} . \tag{6}$$

We eliminate the interference caused by $h_{0,4}$ and $h_{0,5}$ (comes from cells 4 and 5) by network MIMO. As a result, the two most severe interference is cancelled through a small-size (3×3) matrix computation. This cooperation can be applied to all cells not only for particular cooperated group. For example, at certain time slot we have many cooperated group among 19-cell layout: cells $\{0, 4, 5\}$, $\{8, 2, 1\}$, $\{10, 11, 3\}$, and $\{18, 6, 17\}$. Not only the middle cell (cell 0) is coordinated with its neighboring cells, but the cells in the outer layer are also coordinated.

B. Cells Regrouping and Partner Selection



Tri-sector FFR cells

Tri-sector FFR combined with 3-cell network MIMO

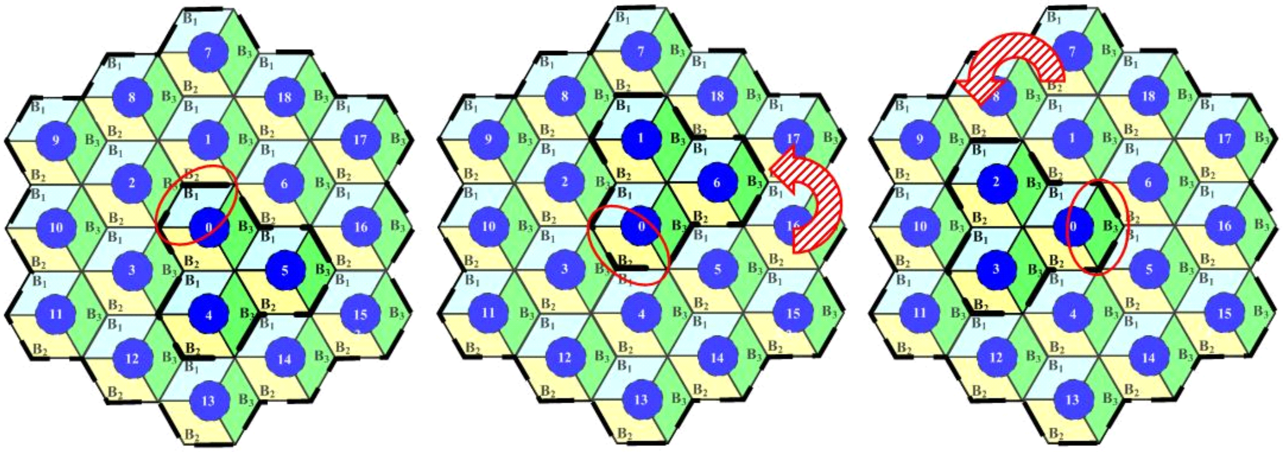
Fig. 2. Interference of a two-tier 19 cells layout: (1) tri-sector FFR architecture (2) integrated tri-sector FFR and 3-cell network MIMO architecture.

Note that $\mathrm{Cell}_a^{G_j}$ can achieve intra-group interference free within whole subband $f_{B_1} = \{f_{B_{1,1}}, \ldots, f_{B_{1,n}}\}$ under network MIMO. That is, the two most severe interfering sources are cancelled via network MIMO. However, subbands f_{B_2} and f_{B_3} will still suffer from seven interferers. The inter-group interference from other groups is still existent. We therefore define f_{B_1} as the primary band of $\mathrm{Cell}_a^{G_j}$ for arbitrary group G_j. Similarly, we define f_{B_2} and f_{B_3} as the primary band of $\mathrm{Cell}_b^{G_j}$ and $\mathrm{Cell}_c^{G_j}$, respectively.

We propose a cells regrouping and partner selection scheme to address the inter-group interference problem and resolve the service fairness issue. Assume that cell 0 is grouped with cells 4 and 5 with primary band f_{B_1} at certain time slot one as shown in Fig. 3. Cell 0 will regroup with cells 1 and 6 at the next time slot two by counterclockwise rotating way to reselect coordinated partner. After this regroup, the primary band of cell 0 becomes f_{B_2}. Similarly, cell 0 regroups with cells 2 and 3 at time slot three by counterclockwise reselecting coordinated partner again and the corresponding primary band becomes f_{B_3}. In this way, all cells will simultaneously "rotate" and regroup with two new neighboring cells at a new time slot, where "rotate" means the coordinated partner reselection procedure. Take the three cells $\{0, 4, 5\}$ an example, those cells form a group at time slot one. At time slot two, cell 0's regroup set is now becoming as $\{1, 0, 6\}$, cell 4's regroup set is $\{3, 12, 4\}$, and cell 5's regroup set is $\{5, 14, 15\}$. Similarly, cell 0's regroup becomes $\{2, 3, 0\}$, cell 4's regroup set is $\{4, 13, 14\}$, and cell 5's regroup set is $\{6, 5, 16\}$ at time slot three. Each cell has the chance to cooperate with neighboring six cells in order and each sector has the opportunity to become the primary band under this kind of TDMA-based regrouping and partner selection scheme.

C. Algorithm Flowchart

Figure 4 illustrates the algorithm flow chart of our scheme. At first, we partition frequency bands into inner band f_A and outer band f_B. Then we determine the cell groups set G_1, G_2, $\ldots$ of the multi-cell system. By means of FFR, we partition the tri-sector cellular system into inner and outer region. Since FFR is mainly designed for improving the signal quality of cell edge users, an obvious



Slot one: group with cells 4 and 5
Primary band f_{B_1} (Sector_1)

Slot two: group with cells 1 and 6
Primary band f_{B_2} (Sector_2)

Slot three: group with cells 2 and 3
Primary band f_{B_3} (Sector_3)

Fig. 3. Example of cells regrouping and partner selection for cell 0.

parameter will be the mobiles location distribution. Therefore, SINR distribution parameters should be considered when determining the inner circle radius. In this paper, we mainly focus on the effect of jointly network MIMO and FFR scheme. For simplicity, we set the inner circle radius equal to $R/2$ (R is cell radius). The block, three-cell network MIMO FFR-based algorithm, contains the joint network MIMO and FFR scheme in section IV-A. Then cells regrouping and partner selection scheme as seen in section IV-B addresses the boundary problem of network MIMO.

V. Numerical Results

TABLE I
Simulation Parameter.

Parameters	Values
Cellular layout	Hexagonal 19-cell layout
FFT size	1024
Site-to-site distance	1.5 km
Carrier frequency	2.5 GHz
Operating bandwidth	10 MHz
BS transmit power	43 dBm
BS height	32 m
MS height	1.5 m
Path loss model (dB)	$130.19 + 37.6 \log_{10}(R)$ (R in km)
Shadowing standard deviation	8 dB
Thermal noise	-174 dBm/Hz

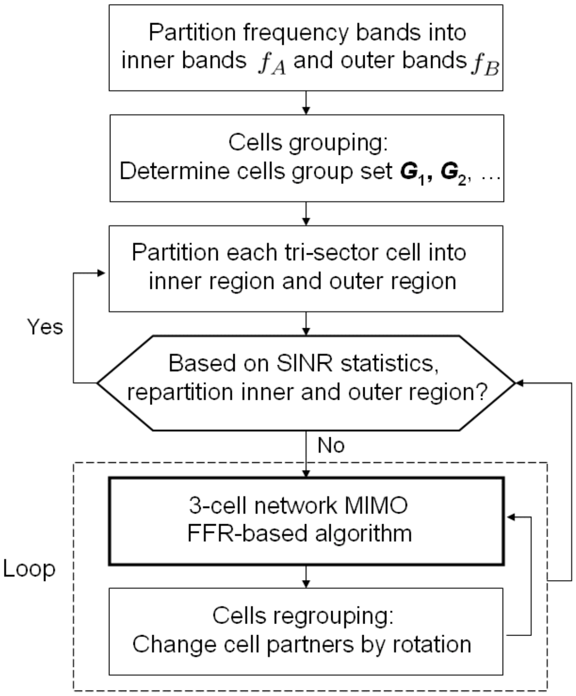


Fig. 4. The flowchart of the proposed algorithm.

In this section, we investigate the effects of the tri-sector FFR, pure network MIMO, and jointly network MIMO and FFR by comparing their received SINR distributions on a frequency unit (a subcarrier). Table I shows the simulation parameters based on [12].

Figure 5 shows the cumulative distributed function (CDF) of the received SINR of three different cellular architectures including conventional 19-cell layout with pure reuse one, tri-sector FFR scheme introduced in section II, and fully 19-cell coordinated network MIMO. Comparing black dotted line with bold line, we find that the gain of interference sources reduction (from 18 reduce to 7) by tri-sector FFR is quite significant, which is about 11 dB improvement at 90 percentile of the received SINR. We also show the performance of network MIMO with full 19-cell coordination for ZF (blue line) and ZF-DPC (red line) transmissions. We find that both schemes can indeed improve the received SINR especially for ZF-DPC scheme. However, the gain of ZF scheme is not very significant at the 90-th percentile of the received SINR, and is actually

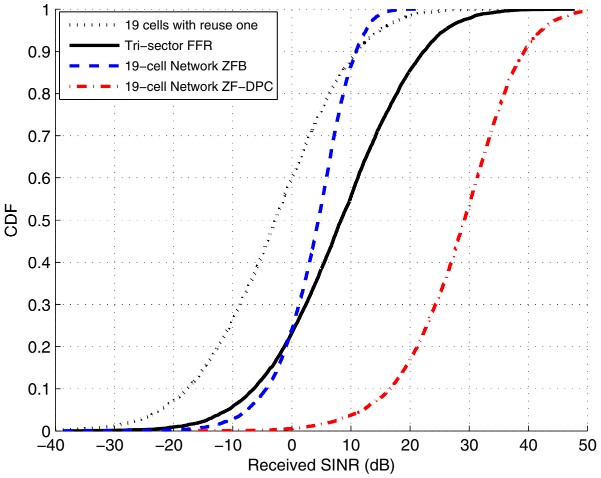


Fig. 5. The CDFs of received SINR for conventional, tri-sector FFR, and 19-cell coordinated network MIMO systems.

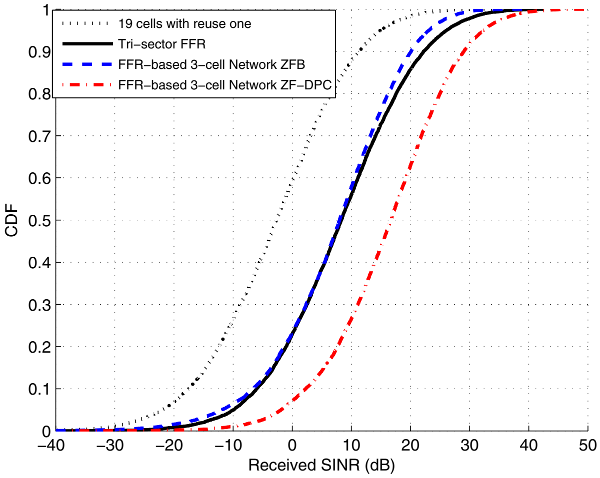


Fig. 6. The CDFs of received SINR for conventional, tri-sector FFR, and proposed tir-sector based three-cell network MIMO systems.

lower than that by using tri-sector FFR scheme. Because of the transmission power penalty of ZF, the actual data symbol power (4) become weaker even if no interference achieved through cooperation. Note that there is no power penalty for ZF-DPC so that the gain at 90-th percentile of the received SINR is more than 20 dB compared with the tri-sector FFR scheme. Note that the outstanding gain comes from a large amount of cells coordination and ignores the interference from other 19-cell groups.

Taking tri-sector FFR as a benchmark and 19-cell coordinated network MIMO as a upper bound, we present the proposed three-cell coordination architecture in Fig. 6. From this figure, the ZF-DPC scheme obtains about 10 dB gain over the tri-sector FFR scheme at 90-th percentile of the received SINR under the proposed three-cell coordination. Although the improvement is not as large as the 19-cell coordination, it implies that the potential benefit of using a small number of coordinated cells is already sufficient. Note that the power penalty of ZF causes a degraded SINR which is similar to the tri-sector FFR scheme even if the most two severe interference have been eliminated. In fact, a larger number of coordinated cells may cause the symbol power weaker and results in poorer signal quality.

VI. Conclusions

In the paper, we propose a jointly FFR and network MIMO architecture for multi-cell OFDM systems. Taking advantage of FFR to reduce co-channel interference by partitioning frequency band into different zones, we further exploit the performance gain of the coordinated network MIMO technique. We provide a three-cell coordinated scheme for network MIMO instead of unlimited coordinated size. We demonstrate that using a small number of coordinated cells can obtain noticeable performance improvement and be more practical in future multi-cell broadband systems.

References

[1] WiMAX Forum. (2006, Aug.) Mobile WiMAX - Part I: A technical overview and performance evaluation. [Online]. Available: www.wimaxforum.org

[2] S. Shamai and B. M. Zaidel, "Enhancing the cellular downlink capacity via co-processing at the transmitting end," *IEEE Vehicular Technology Conference*, vol. 3, pp. 1745 – 1749, May 2001.

[3] O. Somekh, O. Simeone, Y. Bar-Ness, and A. M. Haimovich, "Distributed multi-cell zero-forcing beamforming in cellular downlink channels," *IEEE Global Telecommunications Conference* , pp. 1 – 6, Nov. 2006.

[4] A. D. Wyner, "Shannon-theoretic approach to a Gaussian cellular multiple-access channel," *IEEE Trans. on Information Theory*, vol. 40, pp. 1713 – 1727, Nov. 1997.

[5] S. Jing, D. N. C. Tse, J. Hou, J. B. Spriag, J. E. Smee, and R. Padovani, "Multi-cell downlink capacity with coordinated processing," *in Proc. Inform. Theory and Application Workshop*, Jan. 2007.

[6] M. K. Karakayali, G. J. Foschini, R. A. Valenzuela, and R. D. Yates, "On the maximum common rate achievable in a coordinated network," *IEEE International conference of communications*, vol. 9, pp. 4333 – 4338, Jun. 2006.

[7] M. K. Karakayali, G. J. Foschini, and R. A. Valenzuela, "Network coordination for spectrally efficient communications in cellular systems," *IEEE Trans. on Wireless Commun.*, vol. 13, no. 4, pp. 56 – 61, Aug. 2006.

[8] Y. Liang, A. Goldsmith, G. Foschini, R. Valenzuela, and D. Chizhik, "Evolution of base stations in cellular networks: denser depolyment versus coordination," *IEEE International conference of communications*, pp. 4128 – 4132, Jan. 2008.

[9] S. Hamiti, "IEEE 802.16m System Description Document," *IEEE 802.16 Broadband Wireless Access Working Group*, Feb. 2009.

[10] H. Lei, L. Zhang, X. Zhang, and D. Yang, "A novel multi-cell OFDMA system structure using fractional frequency reuse," *Proceedings of IEEE International Symposium Personal, Indoor and Mobile Radio Communications*, pp. 1 – 5, Sept. 2007.

[11] C.-S. Chiu and C.-C. Huang, "Combined partial reuse and soft handover in OFDMA downlink transmission," *IEEE Vehicular Technology Conference*, pp. 1707 – 1711, May 2008.

[12] R. Srinivasan, J. Zhuang, L. Jalloul, R. Novak, and J. Park, "IEEE 802.16m Evaluation Methodology Document (EDM)," *IEEE 802.16 Broadband Wireless Access Working Group*, Nov. 2008.