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Research Article

Interference Coordination in Multiple Antenna Based LTE-Advanced Heterogeneous Systems

Yuan Li, Li Zhang, Hua Chen, and Mugen Peng

Wireless Signal Processing and Network Lab, Key Laboratory of Universal Wireless Communications (Ministry of Education), Beijing University of Posts and Telecommunications, Beijing 100876, China

Correspondence should be addressed to Yuan Li; liyuanbupt@gmail.com

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With picocells deployed in the coverage of a macrocell in heterogeneous networks (HetNets), the macrocell evolved NodeB (MeNB) may receive interference signals from the picocell users, which results in more severe co-channel interference (CCI) problem in the uplink. In this paper, the spatial uplink interference coordination is investigated in multiple antenna systems, according to which the receiver coding matrix is generated by MeNB to mitigate the CCI from picocell users. Two interference coordination (IC) schemes are proposed based on whether the receiver coding matrix is full rank or not, named as full coding (IC-FC) and part coding (IC-PC), respectively. The application of the proposed schemes is discussed in single picocell and multiple picocell scenarios. The CCI can be totally canceled in single picocell scenario, and an algorithm is developed in multiple picocell networks to mitigate the most severely interfering picocell. Link level and system level simulations are applied, and it is shown that significant performance gain is achieved by our proposed schemes over traditional IC receivers.

1. Introduction

With more and more wireless subscribers nowadays, the data traffic demand in wireless networks is increasing exponentially, especially in hotspot areas. In order to meet this increasing demand for the unrelenting wireless data rate and enhance the hotspot and indoor coverage, third generation partnership project (3GPP) long term evolution (LTE) has been put into practice by operators [1, 2]. 3GPP has been working on LTE-Advanced (LTE-A) since Release 10 to further improve the network throughput by efficient techniques. Since the capacity of the point-to-point link has been approached to its theoretic limits, it is promising to deploy the low-cost transmission nodes, such as picos, relays, femtos, and remote radio units (RRUs) underlaying the existing conventional macrocell layout in a more compact manner, which is known as the heterogeneous network (HetNet).

The deployment of the low-cost nodes could make use of cell splitting gains and therefore improve the capacity and coverage of cellular networks. Full frequency reuse could be applied to further enhance the spectrum efficiency. Compared with homogeneous network, however, more severe cochannel interference (CCI) is caused in both downlink and uplink transmission due to the introduction of low-cost nodes [3], and it is significant to employ interference management techniques to mitigate CCI and improve the performance of HetNets.

As the interference problem in HetNet is challenging, much importance has been attached to the standardization for enhanced intercell interference coordination (eICIC) techniques in HetNets, which consists of enhanced fractional frequency reuse [4], application of almost blank subframes (ABSFs) [5], and enhanced reference signal design [6]. Conventional interference coordination techniques are generally performed in the time and frequency domain [7, 8]. Furthermore, based on the development of multiple input multiple output (MIMO) technologies in LTE-A systems [9], spatial domain interference coordination has been widely discussed [10], where the CCI could be mitigated by adjusting the transmit or receive beamforming with the exchange of channel state information (CSI) via backhaul [11]. An interference cancelation scheme was proposed in [12] based on coordinated transmit beamforming and user selection algorithm. The effect of the proposed scheme was evaluated,

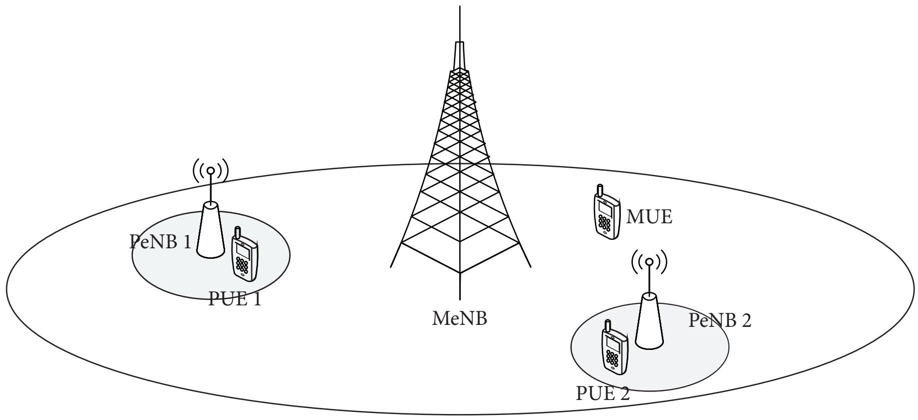

Figure 1: Uplink heterogeneous network composed of macrocell and picocells.

and the trade off between interference nulling and number of simultaneously scheduled users was revealed. Adaptive downlink spatial interference coordination was considered to mitigate CCI in cellular networks in [13], and the average throughput analysis was performed for perfect CSI and limited feedback scenarios, respectively.

However, most of the eICIC techniques mentioned above are studied for the downlink. In the uplink, the eICIC has been investigated based on the power control and range expansion (RE) [14]. The optimization of uplink power control for interference coordination was studied in [15] for relay based deployment, by which it is applicable to enhance the cell edge throughput as well as to adjust the receiver dynamic range. The authors in [16] evaluated the off-loading benefits of RE and investigated the impact of RE bias to the capacity as well as fairness in HetNets. In multiple antenna systems, it is beneficial to explore the advantage of coordinated receive beamforming in uplink transmission. In contrast with downlink coordinated beamforming, the CSI of interfering user equipments (UEs) can be directly obtained by the evolved NodeB (eNB) in uplink by the use of the training sequences instead of feedback or reciprocity [17], and is suitable in practical systems for low cost. To fully exploit the benefits of advanced multiple antenna technologies of LTE-A, the spatial interference coordination schemes should be investigated in uplink HetNets where multiple antennas are configured at both eNB and UE.

In this paper, we focus on the spatial domain interference coordination in uplink HetNets, where both eNBs and UEs are configured with multiple antennas. A receiver coding matrix is employed at the macrocell eNB (MeNB), which lies in the null space of the interference channels. Based on whether the coding matrix is full rank or not, two interference coordination schemes, named part coding (IC-PC) and full coding (IC-FC), are proposed to perform the receiver coding matrix for the MeNB. The application of the receiver coding matrix is investigated for both single picocell scenario and multiple picocells scenario, and an algorithm is developed to mitigate the most significant CCI from PUE in the multiple picocells scenario. It is shown by simulations that significant gains can be obtained by the proposed receiver coding matrix over conventional uplink receiver schemes, especially for single picocell scenario. The reason is that the CCI from picocells to the macrocell can be totally canceled in this scenario where the number of interference channels is less than that of receive antennas.

The rest of this paper is organized as follows. The system model for uplink CCI coordination in HetNets and two traditional receiver schemes are presented in Section 2. In Section 3, the single picocell scenario is analyzed, and the CCI coordination schemes are proposed. We further study the scenario of multiple picocells in Section 4, and an algorithm is presented to mitigate the most severe CCI from PUEs. In Section 5, the simulation results are given, and the conclusions are presented in Section 6.

Notations. Let bold-face letters represent matrices and vectors. Superscripts $(\cdot)^H$ and $(\cdot)^T$ denote the Hermitian transpose and transpose, respectively, and $\|\mathbf{X}\|^2$ denotes the norm of $\mathbf{X}$.

2. System Model

The uplink of a heterogeneous network is shown in Figure 1, where a high-power base station is overlaid with K low-power picocells. The MeNB is equipped with n_M receive antennas and picocell eNB (PeNB) has n_P receive antennas. Single user MIMO transmission is assumed, where one UE configured with n_{UE} transmit antennas transmits signals in a cell at each resource block. The macrocell and picocells share the same frequency resource, and K picocells are randomly located within macrocell coverage. The MUE and the kth PUE transmit with power P_M and $P_P^{(k)}$, respectively.

To be simple, we focus on the uplink CCI cancelation at MeNB side, but the results can be easily extended to the interference cancelation at the PeNB side. The received signal of MeNB can be expressed as

$$\mathbf{r}_M = \underbrace{\sqrt{P_M}\mathbf{H}_M\mathbf{W}_M\mathbf{x}_M}_{\text{Desired signal}} + \underbrace{\sum_{k=1}^{K}\sqrt{P_P^{(k)}}\mathbf{H}_P^{(k)}\mathbf{W}_P^{(k)}\mathbf{x}_P^{(k)}}_{\text{Cochannel interference}} + \underbrace{\mathbf{n}_M}_{\text{Noise}}, \quad (1)$$

where the matrix $\mathbf{H}_M \in \mathbb{C}^{n_M \times n_{\mathrm{UE}}} = \sqrt{L_M^M}\widetilde{\mathbf{H}}_M$ represents the uplink CSI from MUE to MeNB, where L_M^M denotes the pathloss from MUE to MeNB and each element of $\widetilde{\mathbf{H}}_M$ is modeled as complex Gaussian random variable $\mathcal{CN} \sim (0,1)$. The matrix $\mathbf{H}_P^{(k)} \in \mathbb{C}^{n_M \times n_{\mathrm{UE}}} = \sqrt{L_M^k}\widetilde{\mathbf{H}}_P^{(k)}$ is the CSI from the kth PUE to MeNB. The item $\mathbf{W}_M \in \mathbb{C}^{n_{\mathrm{UE}} \times r}$ is the beamforming vector of MUE in which r is the rank of MUE, and $\mathbf{x}_M \in \mathbb{C}^{r\times 1}$ denotes the transmit data from MUE. The second part indicates the CCI from picocells. Each element of $\mathbf{n}_M$ indicates the terminal noise at MeNB side, which is modeled as additive white Gaussian noise (AWGN) vector with zero mean and variance σ^2.

Most of early works employ linear minimum mean squared error (MMSE) receiver and zero forcing (ZF) receiver to eliminate the interstream interference. The ZF receiver at MeNB can be denoted as

$$\mathbf{G}_{\mathrm{ZF}} = \left(\widehat{\mathbf{H}}_M^H \widehat{\mathbf{H}}_M\right)^{-1} \widehat{\mathbf{H}}_M^H, \tag{2}$$

where $\widehat{\mathbf{H}}_M = \mathbf{H}_M \mathbf{W}_M$ is the equivalent channel at the MeNB side. The CCI from PUEs could be suppressed by the interference rejection combining MMSE (IRC-MMSE) receiver if the interference channels could be detected by MeNB. Considering the CCI from PUEs as noise, the IRC-MMSE receiver can be expressed as

$$\mathbf{G}_{\mathrm{MMSE}} = \left(\widehat{\mathbf{H}}_M^H \widehat{\mathbf{H}}_M + \sum_{k=1}^{K} \frac{P_P^{(k)}}{P_M} \widehat{\mathbf{H}}_P^{(k)H0} \widehat{\mathbf{H}}_P^{(k)} + \frac{1}{\gamma'}\mathbf{I}\right)^{-1} \widehat{\mathbf{H}}_M^H, \tag{3}$$

where $\mathbf{I}$ is a unit matrix and γ' is the signal to noise ratio (SNR). After the receiver matrix, the signal to interference plus noise ratio (SINR) of the mth stream can be achieved as

$$\begin{aligned}\gamma_m = {} & P_M \left|\mathbf{g}_m \mathbf{H}_M \mathbf{w}_m\right|^2 \\ & \times \left(\left|\mathbf{g}_m \mathbf{n}_M\right|^2 + \sum_{\substack{n=1\\ n\neq m}}^{r} P_M \left|\mathbf{g}_m \mathbf{H}_M \mathbf{w}_n\right|^2 \right. \\ & \left. + \sum_{k=1}^{k}\sum_{n=1}^{r} P_P^{(k)} \left|\mathbf{g}_m \mathbf{H}_P^{(k)} \mathbf{w}_n^{(k)}\right|^2 \right)^{-1},\end{aligned} \tag{4}$$

where $\mathbf{g}_m$ and $\mathbf{w}_m$ denote the corresponding vector of receiver coding matrix and transmit beamforming of the mth stream, respectively, and $\mathbf{w}_n^{(k)}$ is the nth transmit beamforming vector of the kth interfering PUE. Although the interstream interference could be well suppressed by ZF and MMSE receivers, the CCI from picocells are not taken into consideration, or simply treated as white noise, according to which the performance could not be further improved. Based on multiple antenna technologies, spatial interference coordination schemes are proposed in later sections to mitigate both interstream and intercell interference.

3. Cochannel Interference Cancelation for Single Picocell (K=1)

We first focus on CCI cancelation schemes when the number of picocells is $K = 1$ and assume that the receiver coding is performed at MeNB to eliminate CCI from transmitting PUEs. Define the coding matrix at receiver side as $\mathbf{G}$, then the signal $\mathbf{y}_M$ after detection can be written as

$$\begin{aligned}\mathbf{y}_M = \mathbf{G}\cdot\mathbf{r}_M = {} & \sqrt{P_M}\mathbf{G}\mathbf{H}_M\mathbf{W}_M\mathbf{x}_M \\ & + \sqrt{P_P^{(1)}}\mathbf{G}\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}\mathbf{x}_P^{(1)} + \mathbf{G}\mathbf{n}_M.\end{aligned} \tag{5}$$

For the scenario where only one picocell is located in the coverage of one macrocell, the interference from picocell accounts for large amount of total interference and noise. The target of CCI cancelation is to construct a suitable receiver coding matrix $\mathbf{G}$, which should satisfy

$$\mathbf{G}\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)} = \mathbf{0}. \tag{6}$$

The CSI from interfering PUEs could be detected by the MeNB by the use of the training sequences, and the pattern of pilot as well as the scheduled PUE index have to be conveyed to the MeNB via backhaul, which could be viewed as the uplink interference coordination. Two schemes are proposed in this section based on the demand of (6).

3.1. Part Coding for Interference Cancelation. The singular value decomposition (SVD) is employed in this subsection to generate the coding matrix. Through SVD of the channel matrix $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$ of PUE, the channel matrix is expressed as

$$\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)} = \mathbf{U}_P \begin{bmatrix}\Sigma_P\\ 0\end{bmatrix} \mathbf{V}_P^H = \left[\mathbf{U}_e,\ \mathbf{U}_0\right] \begin{bmatrix}\Sigma_P\\ 0\end{bmatrix} \mathbf{V}_P^H, \tag{7}$$

where each diagonal element of the diagonal matrix $\Sigma_P = \mathrm{diag}\{\lambda_i\}$ is a nonnegative eigenvalue of the channel matrix $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$ with a descending order. The matrix $\mathbf{U}_e$ is the left singular matrix of the channel matrix $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$, and $\mathbf{U}_\mathbf{P}$ is composed of n_M unit column vectors. $\mathbf{U}_e$ constructs the subspace of $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$ and each column corresponds to an eigenvalue in Σ_P. As the dimension of $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$ is $n_M \times r$, and $n_M \geq r$ for practical systems, the dimension of $\mathbf{U}_e$ is $n_M \times r$. The matrix $\mathbf{U}_0$ lies in the null space of $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$ with dimension $(n_M - r)\times r$, that is, $\mathbf{U}_0\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)} = \mathbf{0}$ so that the CCI could be mitigated. ZF operation could be applied to $\mathbf{U}_0\mathbf{H}_M$ to further cancel the interstream interference. Therefore, the receiver coding matrix is evaluated as $\mathbf{G}_{\mathrm{PC}} = [(\mathbf{U}_0^H\mathbf{H}_M)^H\mathbf{U}_0^H\mathbf{H}_M]^{-1}(\mathbf{U}_0^H\mathbf{H}_M)^H\mathbf{U}_0^H$, and the signal after receiver coding $\mathbf{y}_M$ can be rewritten as

$$\mathbf{y}_M = \mathbf{G}_{\mathrm{PC}}\mathbf{H}_M\mathbf{W}_M\mathbf{x}_M + \mathbf{G}_{\mathrm{PC}}\mathbf{n}_M. \tag{8}$$

With the operation of coding matrix at receiver side in this way, the CCI can be totally eliminated, and the SINR of the mth stream can be represented as

$$\gamma_m = \frac{P_M\left|\mathbf{g}_{m,\mathrm{PC}}\mathbf{H}_M\mathbf{w}_m\right|^2}{\left|\mathbf{g}_{m,\mathrm{PC}}\mathbf{n}_M\right|^2}. \tag{9}$$

It should be noted that the number of MeNB receiving antennas n_M and the rank of transmitting data r should satisfy $n_M > r$, otherwise the left singular matrix $\mathbf{U}_P$ does not contain the null space of $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$ and the coding matrix $\mathbf{G}$ cannot be obtained through SVD. Therefore, the coding matrix is not full rank, which reduces the multiplexing gain of the spatial channel.

3.2. Full Coding for Interference Cancelation. To take full use of the multiplexing gain by receiver coding, we propose the IC-FC scheme, which is formulated as

$$\text{maximize} \sum_{m=1}^{r} \log\left(1 + \frac{P_M\left|\mathbf{g}_{m,\mathrm{FC}}\mathbf{H}_M\mathbf{w}_m\right|^2}{\left|\mathbf{g}_{m,\mathrm{FC}}\mathbf{n}_M\right|^2}\right), \tag{10}$$

$$\text{subject to } \mathbf{G}_{\mathrm{FC}} = \begin{bmatrix}\mathbf{G}_{\mathrm{PC}}\\ \mathbf{G}_s\end{bmatrix} \in \mathbb{C}^{n_M\times n_M}, \tag{11}$$

$$\mathbf{G}_s\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)} = \mathbf{0}, \tag{12}$$

$$\left\|\mathbf{g}_m\right\|^2 = 1, \tag{13}$$

$$n_M > r, \tag{14}$$

where $\mathbf{g}_{m,\mathrm{FC}}$ is the mth row of $\mathbf{G}_{\mathrm{FC}}$, and $\mathbf{G}_s$ represents the supplement matrix composed of r rows $\mathbf{g}_i \in \mathbb{C}^{1\times n_M}$, to guarantee that $\mathbf{G}_{\mathrm{FC}}$ is full rank. The condition (12) guarantees the orthogonality between $\mathbf{G}_s$ and $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$, so that the whole matrix $\mathbf{G}_{\mathrm{FC}}$ satisfy $\mathbf{G}_{\mathrm{FC}}\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)} = \mathbf{0}$ to totally eliminate the CCI from PUEs. As the rows of matrix $\mathbf{G}_{\mathrm{PC}}$ in IC-PC are unit vectors, each row vector $\mathbf{g}_m$ of $\mathbf{G}_s$ should being unit vector for keep conformity, as constrained with condition (13). It is clear that the proposed IC-FC method makes use of the supplement matrix and the matrix $\mathbf{G}_{\mathrm{PC}}$ of method IC-PC to construct a receiver coding unitary matrix with full rank, aiming at maximizing the SINR as well as eliminating CCI.

4. Cochannel Interference Coordination for Multiple Picocells ($K > 1$)

In this section, we study the CCI coordination scheme for multiple picocells scenario. Similar to the scheme for single picocell scenario, the receiver coding matrix $\mathbf{G}$ should satisfy

$$\begin{gathered}\text{maximize} \sum_{m=1}^{r} \log\left(1 + \frac{P_M\left|\mathbf{g}_m\mathbf{H}_M\mathbf{w}_m\right|^2}{\left|\mathbf{g}_m\mathbf{n}_M\right|^2}\right),\\ \text{subject to } \mathbf{G}\mathbf{H}_P^{(k)}\mathbf{W}_P^{(k)} = \mathbf{0} \quad (\forall k = 1,2,\ldots,K),\\ \left\|\mathbf{g}_k\right\|^2 = 1,\\ \mathbf{G} \in \mathbb{C}^{n_M\times n_M},\\ n_M > Kr.\end{gathered} \tag{15}$$

However, these four conditions usually cannot be satisfied at the same time in practical system due to the constraint of dimensions, especially for the scenario with very large K. So the CCI cannot be totally eliminated via receiver coding. We propose a suboptimal algorithm to reduce the interference through receiver coding for multiple picocells scenario.

In LTE system, power control is applied in the uplink to keep a balance between the demand to achieve the required quality-of-service (QoS), and the demand to minimize the interference to other cells as well as to save energy of mobile terminals. Various power control mechanisms have been proposed for interference coordination in heterogeneous networks. Generally, the transmitting power of each UE is configured according to the downlink pathloss and power control coefficient α, resulting in different transmitting power of each UE and also different interference power. It is obvious that the interference from the UE causing largest received power at eNB should be eliminated at the highest priority.

Our proposed interference coordination algorithm for multiple picocells scenario takes the received interference power into consideration. Detail steps are as follows.

(a) MeNB detects the interfering UEs in picocells and the received power $P_{\mathrm{inter}}^{(k)}$ of each interfering UE.

(b) Compare the received power of interfering UE, and find the UE corresponding to the maximum received power, which is denoted as

$$k^* = \underset{k=1,2,\ldots,K}{\arg} \max P_{\mathrm{inter}}^{(k)}. \tag{16}$$

(c) Calculate the receiver coding matrix by IC-FC or IC-PC with SVD proposed in Section 3, in which the corresponding channel matrix $\mathbf{H}_P^{(1)}\mathbf{W}_P^{(1)}$ of interference PUE is replaced with $\mathbf{H}_P^{(k^*)}\mathbf{W}_P^{(k^*)}$ of UE k^* in (6) and (12). Eliminate the interference from UE k^* and then the SINR after receiver coding can be expressed as

$$\gamma_m = \frac{P_M\left|\mathbf{g}_m\mathbf{H}_M\mathbf{w}_m\right|^2}{\left|\mathbf{g}_m\mathbf{n}_M\right|^2 + \sum_{j=1, j\neq k^*}^{K}\sum_{n=1}^{r} P_P^{(j)}\left|\mathbf{g}_m\mathbf{H}_P^{(j)}\mathbf{w}_n^{(j)}\right|^2}. \tag{17}$$

It is obvious that the application of receiver coding matrix in single picocell scenario can be regarded as a special case of that in multiple picocells scenario, where the interfering UE with maximum received power is the only interfering UE and step of comparing the received power can be omitted.

5. Simulation Results

The link level and system level simulations are both employed to evaluate the performance of our proposed interference coordination schemes in this section. As the link level simulation does not take into consideration the effect of downlink pathloss, the performance of multiple picocells scenario is evaluated by system level simulation.

The heterogeneous deployment of LTE system is considered here for simulation, where K picocells are randomly placed over the coverage of a macrocell layout. The LTE single-carrier frequency division multiple access (SC-FDMA) uplink provides orthogonal transmission of different

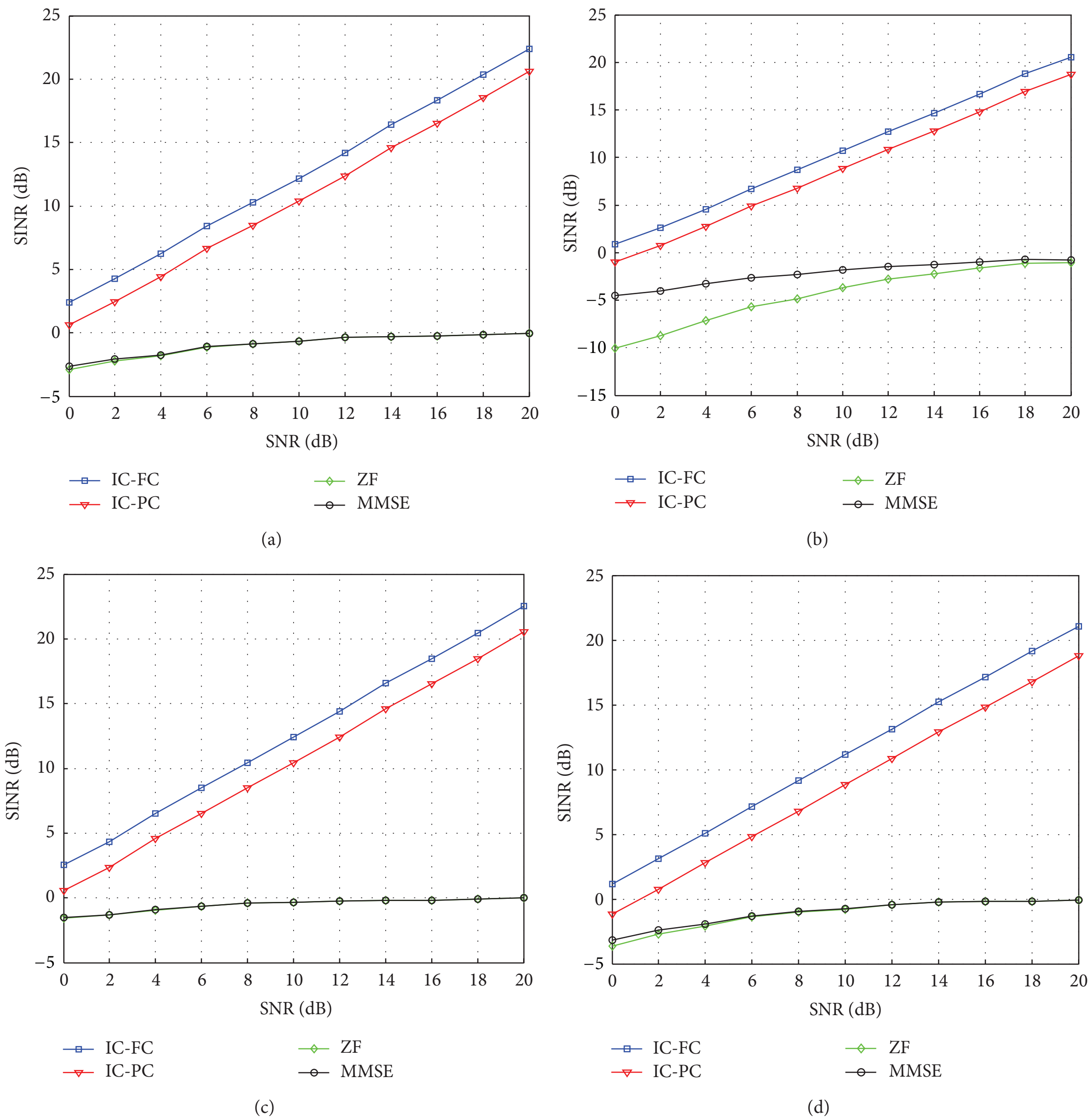

Figure 2: Link level results of receive SINR for single picocell scenario, for four cases: (a) $n_M = 4$, $r = 1$; (b) $n_M = 4$, $r = 2$; (c) $n_M = 8$, $r = 1$; (d) $n_M = 8$, $r = 2$.

UEs in the same cell, so intra-cell interference can be canceled. With uplink power control, the UE transmit power is given as

$$P = \min\{P_{\max}, P_0 + \alpha \cdot PL\}\ [\text{dBm}], \tag{18}$$

where P_0 and α are power control parameters set on the basis of different cell types, and PL represents the downlink pathloss estimated through downlink reference signal in dB. The maximum transmit power of UE $P_{\max}$ indicates the transmit capacity of UE, which is fixed as in Table 1. The pathloss models are different for PUE and MUE, because of different transmit power of PeNB and MeNB and also different propagation environment. Detail simulation parameters are listed in Table 1.

In order to validate our proposed interference coordination schemes, IC-PC and IC-FC methods are simulated as well as traditional receiver schemes, ZF and MMSE.

Figure 2 shows the link level simulation results of the receive SINR curves for different receiver schemes as a function of the transmit SNR for single picocell scenario when $n_P = 4$, for four cases: (a) $n_M = 4$, $r = 1$; (b) $n_M = 4$, $r = 2$; (c) $n_M = 8$, $r = 1$; (d) $n_M = 8$, $r = 2$. We can see the receive SINR with IC-FC and IC-FC increases

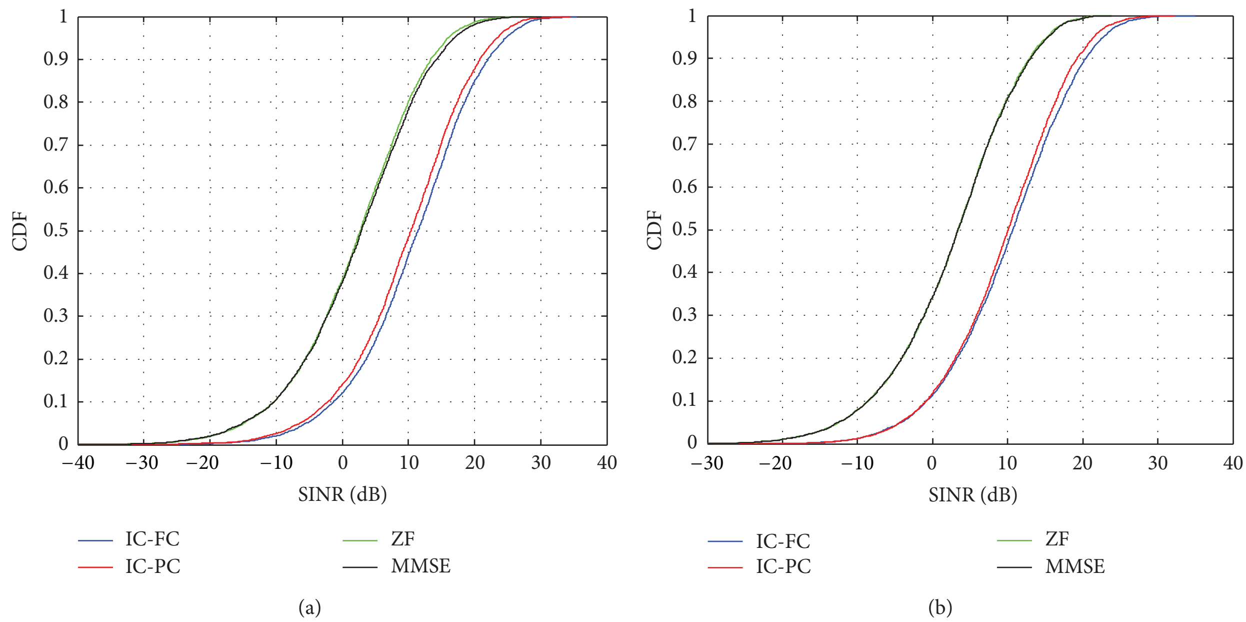

Figure 3: System level results of receive SINR CDF for multiple picocells scenario, for two cases: (a) $n_M = 4$, $K = 4$, $r = 1$; (b) $n_M = 4$, $K = 4$, $r = 2$.

Table 1: Simulation parameters.

Parameter	Assumption
Cellular layout	1 macrocell with K picocells
System bandwidth	10 MHz
Number of Picocells (K)	1, 2, 4, 8
Cell radius	
Macro	1 km
Pico	300 m
Antenna number (MeNB, PeNB, UE)	(4, 4, 2), (8, 4, 2)
UE noise figure	9 dB
Minimum distance	
Macro to Pico	>75 m
Macro to UE	>35 m
Pico to Pico	>40 m
Pico to UE	>10 m
Maximum UE Tx power ($P_{\max}$)	23 dBm
Pathloss Model (R in km)	
Macro to UE	$L = 128.1 + 37.6\log_{10}(R)$
Pico to UE	$L = 140.7 + 36.7\log_{10}(R)$
Power control	
Macro	$\alpha = 1.0$, $P_0 = -106$ dB m
Pico	$\alpha = 0.8$, $P_0 = -90$ dB m

almost linearly with the transmitter SNR as the CCI is totally canceled, while ZF and MMSE receiver hardly improve the MeNB performance due to the severe intercell interference. Compared with IC-PC, IC-FC scheme outperforms by about 1 dB at receive SINR for each case. It is also indicated that as the number of receiver antennas becomes larger, the receive SINR of IC-FC and IC-PC increases, which is due to the larger array gain. Another observation is that the SINR performance in cases $r = 2$ is a little beyond to the cases $r = 1$, because the transmit power of each stream decreases with respect to the limitation of total power.

The system level results of receive SINR CDF for multiple picocells scenario is shown in Figure 3 where $n_M = 4$, $K = 4$, $r = 1$ and 2. Similarly, it is demonstrated that IC-FC and IC-PC schemes outperform ZF and MMSE schemes obviously in receive SINR for the CCI from PUE can be canceled by IC-PC and IC-FC. The most severe interfering picocell can be mitigated by the interference coordination schemes of IC-FC and IC-PC, but interference from other picocells still leads to performance loss, resulting in little performance gap between IC-FC and IC-PC.

Figure 4 shows the receive SINR CDF curves of IC-PC and IC-FC when $n_M = 4$, $r = 2$, and different numbers of picocells are applied. It can be indicated that as the number of picocells increases, the receive SINR of each method decreases, because the interference from picocells increases which reduces the performance of the interference coordination schemes. It can also be observed that the performance gap between IC-FC and IC-PC turns smaller with more picocells deployed, because IC-FC and IC-PC schemes can only cancel the most severely interfering picocell, while the performance improvement may not be obvious with respect to the remaining CCI from other picocells.

6. Conclusion

The CCI coordination for uplink HetNets is took into consideration in this paper, where a receiver coding matrix is utilized to perform interference coordination at the receiver side. Two schemes, IC-PC and IC-FC, are proposed, by which

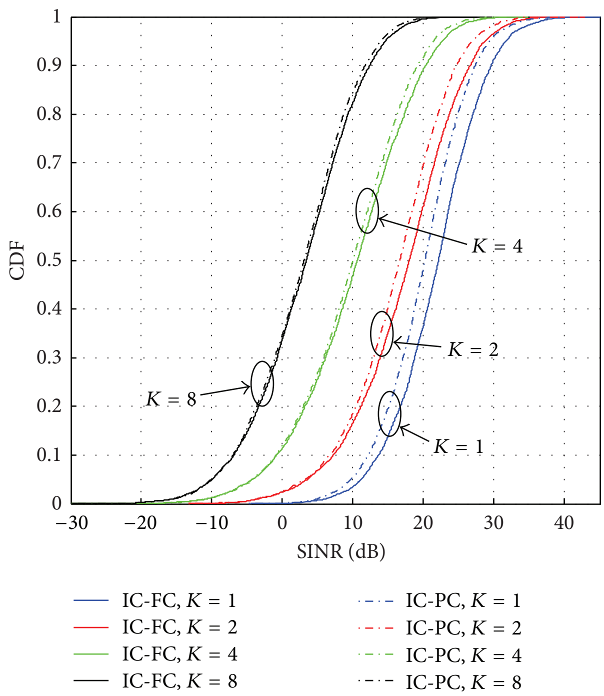

Figure 4: System level results of receive SINR CDF for multiple picocells scenario.

the CCI can be totally eliminated in single picocell scenario, and an algorithm is presented to mitigate the most severely interfering picocell for multiple picocells scenario. It is shown by simulations that significant improvement is achieved by our proposed schemes over the traditional ZF and MMSE schemes.

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