

# Regionalized Interference Alignment in Two-Tiered Cognitive Heterogeneous Networks

Jingwen Yang, Li Li\*, and Xiaoping Zhou

College of Information, Mechanical and Electrical Engineering, Shanghai Normal University, Shanghai 200235, China  
Email: m13681627221@163.com; {lilyxuan, zhoup}@shnu.edu.cn

**Abstract**—Interference alignment in cognitive networks is an efficient way to achieve the cognitive system throughput gain without degrading the throughput of the primary system. In this paper a novel interference management strategy is presented to use interference alignment in cognitive heterogeneous networks flexibly. Characteristics of interference distribution in two-tiered networks are considered to divide the cell deployed by this structure into two regions. Cognitive radio system determines which region the primary users locate in based on channel state information, and suppresses interference by designing their precoders to achieve interference alignment, hence is termed regionalized interference alignment. Thereby, it can manage interference in different situations effectively. Numerical results are given for the uplink average rates of primary user and second users, which shows that regionalized interference alignment ensures the performance of the cognitive heterogeneous networks.

**Index Terms**—Heterogeneous networks, cognitive radio, interference alignment, regionalization

## I. INTRODUCTION

Femtocell is a type of small cell usually deployed by residential users [1]. It provides better coverage and high speed data service for indoor users via internet backhaul and shares the same frequency band with the existing macrocell network [2]. As frequency is a scarce resource, utilizing femtocell and interference management will become a developing trend for next generation wireless cellular networks.

Cognitive radio (CR) can sense or capture information interested from its transmission environment, and change its parameters to meet the demands of the communication network. Second users (SU) opportunistically access the idle frequency band licensed to primary users (PU), improving spectrum efficiency of whole network [3]. In some cognitive scenarios, SUs have chance to communication only when they detect a spectrum hole unused by primary users which have the licensed rights to the spectrum. However, there are also some types of CR paradigms, like underlay, which allow the coexistence of PU transmission and SU transmission by adjusting their transmission power so that the interference received by PU is under a certain threshold [4]. CR technique can be a valid way to enhance the ability of measuring, sensing and adapting on both femtocell network and macrocell

network. This paper applies CR to heterogeneous two-tiered (femtocell/macrocell) networks. Femtocells reduce the load on macrocell network in order to ensure the quality of service (QoS) of macrocell user (MU), so we consider the MU as the primary user. The femtocell user (FU) is regarded correspondingly as the second user (SU).

As femtocell networks and existing macrocell network share spectrum, it will cause inevitably high level interference when FU and MU communicate over the same bandwidth. Interference alignment (IA) [5] is an interference management method that can effectively decrease the interference in the same band. IA overlaps interference in the same one signal space at receiving terminal by precoding so as to thoroughly eliminate the influence of interference on expected signals, thus making K-user interference channel achieve the maximum degree of freedom (DoF) at multiple receivers simultaneously [5]-[6]. A number of practical IA schemes in single-tiered system have been developed to date, including maximizing signal to interference plus noise ratio (SINR) [7], minimizing the leakage interference [7], [8], and minimizing mean square error (MSE) [9]. All of these algorithms are developed for single-tiered K-user interference channels, where each receiver has an expected transmitter, and other transmitters are considered as interference sources to that receiver. For example, minimizing the leakage interference algorithm proposed in [7] utilizes the channel reciprocity and iterates between the precoders of transmitters and receivers repetitively until the leaked interference minimizes.

Recently, IA has become an important tool to study interference management on two-tiered heterogeneous networks [10]-[20]. Like the single-tiered network, those IA algorithms also can be used in the two-tiered model. However, unlike the signal-tiered system, the scheme in two-tiered system should deal with both femtocell and macrocell interference together. Ref. [10] introduces an IA scheme that allows the coexistence of an orthogonal frequency division multiplexing (OFDM) macrocell and a cognitive smallcell. The optimal linear precoders maximize the spectral efficiency of the cognitive link as well as preserve the DoF of the macrocell transmission. A partial interference alignment in heterogeneous networks is presented in [11]. It requires only partial channel knowledge and simple computation. The proposed scheme in [11] provides interference-free communications for macrocell users which suffer from

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\*Corresponding author email: lilyxuan@shnu.edu.cn

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strong interference. Ref. [12] proposed an interference management termed selective IA. It judiciously chooses the set of users to be aligned at each receiver as a subset of the cross-tier interferers, which could eliminate the destructive uplink macrocell interference at the femtocell base station so as to enhance the QoS of FU. A transceiver beamforming design strategy in MIMO femtocell networks was discussed in [13]. IA algorithms are used to mitigate the interference at macrocell users caused by femtocell base stations. The transceiver design algorithms proposed in [13] achieve a large femtocell throughput gain with only a small sacrifice of macrocell user throughput.

By and large, all these above algorithms regard single-tiered IA schemes as the foundation, and try to make various degrees of optimization so as to meet the demands of solving both femtocell and macrocell interference in the same time. For example, [12] exploits minimizing MSE algorithm, and the schemes in [13] is very similar to maximizing SINR algorithm. Similar with the above references, single-tiered IA schemes are also applied in this paper, differently from previous works, we present a new interference management strategy called regionalized IA. Characteristics of interference distribution in two-tiered networks are considered, and the macrocell is divided into two regions. MU is the true mobile user which appears in region I or region II randomly. Cognitive system determines the active primary user in which region based on channel state information (CSI). IA scheme is used in both macrocell network and femtocell network to eliminate their interferences. We analysis the uplink rates of MU and FU to show the advantage of IA. The average uplink rate of MU in the whole cell is also given to reflect the performance gain by regionalized IA.

The remainder of the paper is organized as follows: the system model is introduced in Section II. In Section III, the position of PU is estimated. Regionalized IA is used to suppress interference in different regions. Numerical simulation results of average uplink are given in section IV. Conclusions are discussed in Section V.

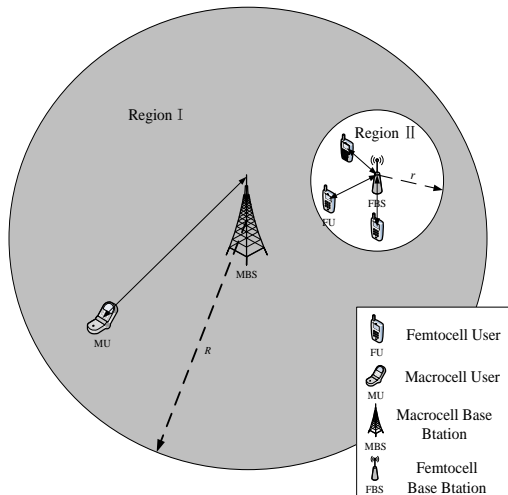


Fig. 1. A cell employed two-tiered networks

## II. SYSTEM MODEL

Fig. 1 is a cell scenario of two-tiered cognitive heterogeneous networks with three FUs and one MU. As shown in Fig. 1, the coverage radius of macrocell base station is  $R$ , i.e., the whole macrocell has radius  $R$  and there are region I and region II in it. The radius of region II is  $r$ , which reflects the coverage of femtocell base station (FBS). MU moves in region I or region II randomly. FUs are confined to region II relatively. When MU moves in region I and communicates with MBS (uplink transmission), FBS will be interfered because of the coverage of MBS is the whole cell. However, the communication between FU and FBS will generate little interference on MBS at this moment because of the limited coverage of FBS. Thus the interference of FU to MBS can be viewed as background noise. When MU moves into region II, the SINR of MU decreases rapidly, the cross interference between FU and MU exists as well, i.e., FBS will receive the interference from MU and MBS will also receive the interferences from FUs. Specific system models are as follows.

### A. Case 1: MU in Region I

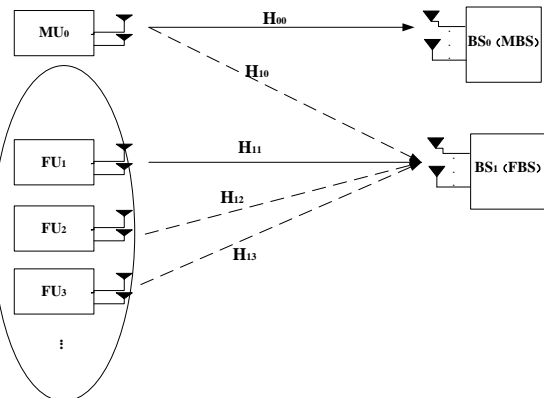


Fig. 2. Uplink transmission model for case 1

Fig. 2 is an uplink transmission model for case1 with one MU and several FUs. MU communicates with MBS and FU communicate with FBS. In the case 1 scenario, the number of FU is denoted by  $M$ , and each mobile user has  $N_t$  transmitting antennas. There are  $N_f$  receive antennas in both MBS and FBS. Assuming the communication between FU and FBS has no interference to MBS because of the short coverage of the FBS, but the communication between MU and MBS will have interference on FBS. The received signal at MBS are given as Eq.(1).

$$\mathbf{y}_M = \mathbf{H}_{00} \mathbf{V}_0 \mathbf{s}_0 + \mathbf{n}_0 \quad (1)$$

The received signal at FBS is shown as Eq.(2),

$$\mathbf{y}_F = \mathbf{H}_{11} \mathbf{V}_1 \mathbf{s}_1 + \mathbf{H}_{10} \mathbf{V}_0 \mathbf{s}_0 + \sum_{i=2}^M \mathbf{H}_{1i} \mathbf{V}_i \mathbf{s}_i + \mathbf{n}_1 \quad (2)$$

where  $\mathbf{H}_{ij}$  is the matrix with  $N_t$  rows and  $N_f$  columns, which represent the channel matrix from the  $j^{th}$  user

( $j \in \{1, 2, \dots, M\}$ ) to the  $i^{\text{th}}$  base station ( $i \in \{0, 1\}$ ) as shown in Fig. 2. We assume that system has got a perfect CSI.  $\mathbf{s}_i \in \mathbb{C}^{d \times 1}$  denotes the transmission signal of the  $i^{\text{th}}$  user, the number of message bits transmitted from each mobile user is denoted by  $d$ , should satisfy  $d \leq \min(N_t, N_f)$ .  $\mathbf{V}_i \in \mathbb{C}^{N_f \times d}$  represents the precoding matrix of the  $i^{\text{th}}$  user. The noise vector at the base station is denoted by  $\mathbf{n}_i \in \mathbb{C}^{N_i \times d}$ , which consists of independent zero mean Gaussian random variables with  $E(\mathbf{n}_i \mathbf{n}_i^H) = \sigma^2 \mathbf{I}_{N_i}$ .  $\mathbf{I}_d$  is the  $d \times d$  identity matrix.  $E(\cdot)$  stands for the expectation operator and  $(\cdot)^H$  refers to the Hermitian transpose.  $\mathbf{H}_{i0} \mathbf{V}_i \mathbf{s}_i$  is the desired signal of receiver, i. e., transmitters and receivers are connected by solid line in Fig. 2.  $\mathbf{H}_{10} \mathbf{V}_0 \mathbf{s}_0$  represents the interference received from MU by FBS, i.e., cross-tier interference.  $\mathbf{H}_{1i} \mathbf{V}_i \mathbf{s}_i$  is the interference received from other FUs by FBS, i.e., inner-tier interference.

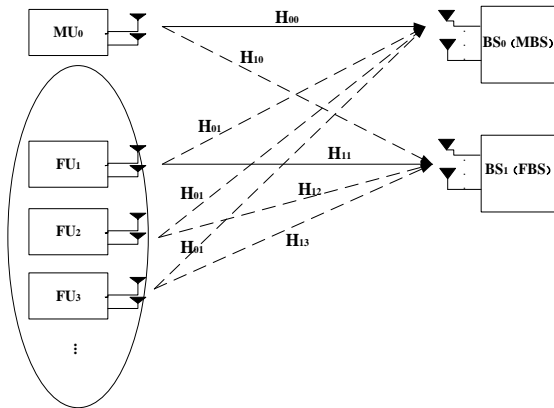


Fig. 3. Uplink transmission model for case 2

**B. Case 2: MU in Region II**

Uplink transmission model for case 2 with one MU and several FUs is depicted in Fig. 3. As MU communicates in region II, SINR of MU decreases sharply for case 2. The cross interference between FU and MU exists as well. Since the distance among FUs is very short compared with the distance from FUs to MBS, the channels between FUs to MBS can be simply viewed as the same. The received signal at FBS is the same as in case1 which has been denoted by Eq. (2). The received signal at MBS shown in Fig. 3, given as Eq. (3).

$$\mathbf{y}'_{M_0} = \mathbf{H}_{00} \mathbf{V}_0 \mathbf{s}_0 + \sum_{i=1}^M \mathbf{H}_{0i} \mathbf{V}_i \mathbf{s}_i + \mathbf{n}_0 \quad (3)$$

Like case 1,  $\mathbf{H}_{00} \mathbf{V}_0 \mathbf{s}_0$  represents the desired signal and  $\mathbf{H}_{0i} \mathbf{V}_i \mathbf{s}_i$  is the interference received from FUs. In section III, IA technique is used to suppress the interference at base stations both in case 1 and case 2.

**III. REGIONALIZED INTERFERENCE ALIGNMENT**

**A. Estimate the Position of MU**

First we describe how to estimate which region the MU locates in. System model considers cognitive networks have the ability to sense and monitor the MU

nearby. Assuming that system has got a perfect CSI, we define a threshold value  $S$  to reflect the channel environment of region II, where

$$S = \text{tr}((\mathbf{H}_{11})^H (\mathbf{H}_{11})) \quad (4)$$

$\text{tr}(\cdot)$  is the trace of matrix.  $S_{MU}$  is referred as the channel environment between MU to FBS,  $S_{MU}$  can be expressed as Eq.(5)

$$S_{MU} = \text{tr}((\mathbf{H}_{10})^H (\mathbf{H}_{10})) \quad (5)$$

If  $S_{MU} \geq \gamma S$ , where  $\gamma \in (0, 1]$  is a constant which is determined by the specific transmitting power of FBS, reflects the coverage of FBS, then the MU is referred to causing higher interference at FBS, which reflect that FU is closed to FBS, so that MU is considered in region II.

If  $S_{MU} < \gamma S$ , the MU is thought as in region I accordingly.

**B. IA in Case 1**

Since the interference of FUs to MBS can be viewed as background noise in region I, we just consider the interference alignment in FBS,  $\mathbf{V}_i$  is used to align the interference in the same subspace at FBS receiver,  $\mathbf{V}_i$  should satisfy the constraint as Eq.(6)

$$\mathbf{H}_{1i} \mathbf{V}_i = \mathbf{H}_{1j} \mathbf{V}_j \quad (6)$$

where  $i, j = 2, 3, \dots, M$ , and  $i \neq j$ .

$\mathbf{U}_1 \in \mathbb{C}^{N_f \times d}$  is designed to eliminate the interference at FBS receiver,  $\mathbf{U}_1$  should satisfy the constraint shown as Eq.(7).

$$\begin{aligned} \mathbf{U}_1^H (\sum_{i=0, i \neq 1}^M \mathbf{H}_{1i} \mathbf{V}_i) &= 0 \\ \text{rank}(\mathbf{U}_1^H \mathbf{H}_{11} \mathbf{V}_1) &= d \end{aligned} \quad (7)$$

where  $\text{rank}(\cdot)$  denotes the rank of matrix. After the interference alignment, the received signal at FBS in case 1 can be written as Eq.(8)

$$\begin{aligned} \tilde{\mathbf{y}}_F &= \mathbf{U}_1^H \mathbf{y}_F = \mathbf{U}_1^H \mathbf{H}_{11} \mathbf{V}_1 \mathbf{s}_1 + \mathbf{U}_1^H \mathbf{H}_{10} \mathbf{V}_0 \mathbf{s}_0 \\ &+ \mathbf{U}_1^H \sum_{i=2}^M \mathbf{H}_{1i} \mathbf{V}_i \mathbf{s}_i + \mathbf{U}_1^H \mathbf{n}_1 \end{aligned} \quad (8)$$

In order to verify what benefits the IA technique really brings to both MU and FU, we introduce the uplink transmission rate in [21] to describe the system performance. The uplink transmission rate of MU in case 1 is referred to  $R_p$  and described by Eq.(9),

$$R_p = \log_2 |\mathbf{I} + (p_0 \mathbf{H}_{00} \mathbf{V}_0 (\mathbf{H}_{00} \mathbf{V}_0)^H) (\mathbf{n}_0 \mathbf{n}_0^H)^{-1}| \quad (9)$$

and the uplink transmission rate of FU is defined as  $R_s$ , shown as Eq.(10),

$$R_s = \log_2 |\mathbf{I} + \mathbf{U}_1^H \mathbf{Q}_1 \mathbf{U}_1 (\mathbf{U}_1^H (\mathbf{n}_0 \mathbf{n}_0^H + \mathbf{Q}_{11}) \mathbf{U}_1)^{-1}| \quad (10)$$

where  $(\cdot)^{-1}$  represent the inverse of matrix and  $|\cdot|$  means the determinant of a matrix.  $\mathbf{Q}_1$  represents the power of desired signal at the FBS receiver, is described as Eq.(11)

$$\mathbf{Q}_1 = p_1 \mathbf{H}_{11} \mathbf{V}_1 (\mathbf{H}_{11} \mathbf{V}_1)^H \quad (11)$$

$\mathbf{Q}_{11}$  represents the power of interference and noise at the FBS receiver, shown as Eq.(12)

$$\mathbf{Q}_{11} = \sum_{i=0, i \neq 1}^M p_i \mathbf{H}_{1i} \mathbf{V}_i (\mathbf{H}_{1i} \mathbf{V}_i)^H \quad (12)$$

where  $p_0$  is the transmitting power of MU and  $p_i$  is the transmitting power of the  $i^{th}$  FU ( $i \in \{1, \dots, M\}$ ).

Fig. 4 and Fig. 5 are the simulations of uplink rate in case 1 with 1 MU and 3 FUs. In Fig. 4, MU does not change transmitting power and FUs rise their power with the same slope. We could see that with the increasing power of FU, the uplink transmission rate of FU is increasing yet the uplink transmission rate of MU stay the same. In Fig. 5, the power of FUs are fixed and MU rise its transmitting power, the uplink transmission rate of FU is constant while the uplink transmission rate of MU is increasing. From Fig. 4 and Fig. 5 we could see neither MU nor FU is influenced by the increasing power of the other when we employ IA, the simulation results demonstrate that IA successfully removes the interferences on MBS and FBS in case 1.

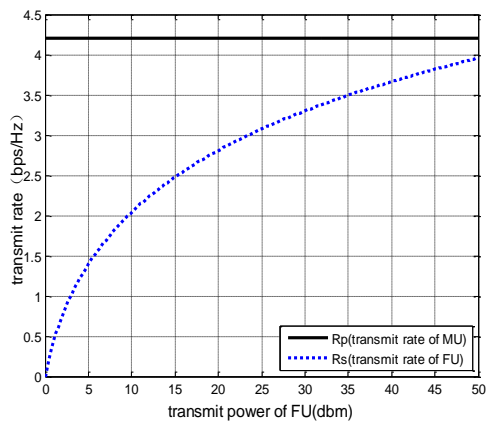


Fig. 4. Increase power of FU in case 1

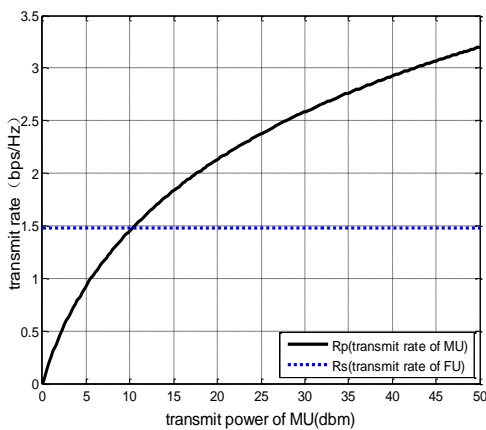


Fig. 5. Increase power of MU in case 1

### C. IA in Case 2

The SINR of MU decreases rapidly when MU is in region II. The cross interference between FU and MU

will generate in this scenario as stated in section II. The interference generated by FUs on MBS should be considered.  $\mathbf{U}_0 \in \mathbb{C}^{N_i \times d}$  is designed to eliminate the interference at MBS,  $\mathbf{U}_0$  should satisfy the constraints as Eq.(13).

$$\begin{aligned} \mathbf{U}_0^H \left( \sum_{i=1}^M \mathbf{H}_{0i} \mathbf{V}_i \right) &= \mathbf{U}_0^H \mathbf{H}_{01} \left( \sum_{i=1}^M \mathbf{V}_i \right) = 0 \\ \text{rank}(\mathbf{U}_0^H \mathbf{H}_{00} \mathbf{V}_0) &= d \end{aligned} \quad (13)$$

After the interference alignment, the received signal at MBS in case 2 can be written as Eq.(14)

$$\begin{aligned} \tilde{\mathbf{y}}_{M0} &= \mathbf{U}_0^H \mathbf{y}'_{M0} = \mathbf{U}_0^H \mathbf{H}_{00} \mathbf{V}_0 \mathbf{s}_0 \\ &+ \mathbf{U}_0^H \sum_{i=1}^M \mathbf{H}_{0i} \mathbf{V}_i \mathbf{s}_i + \mathbf{U}_0^H \mathbf{n}_0 \end{aligned} \quad (14)$$

the uplink transmission rate of MU [21] in case 2 is

$$R'_p = \log_2 |\mathbf{I} + \mathbf{U}_0^H \mathbf{Q}_0 \mathbf{U}_0 (\mathbf{U}_0^H (\mathbf{n}_0 \mathbf{n}_0^H + \mathbf{Q}_{00}) \mathbf{U}_0)^{-1}| \quad (15)$$

$\mathbf{Q}_0$  represents the power of desired signal at the FBS receiver, is described as Eq.(16)

$$\mathbf{Q}_0 = p_0 \mathbf{H}_{00} \mathbf{V}_0 (\mathbf{H}_{00} \mathbf{V}_0)^H \quad (16)$$

where  $\mathbf{Q}_{00}$  represents the power of interference and noise at the FBS receiver, can be written as Eq.(17)

$$\mathbf{Q}_{00} = \sum_{i=1}^M p_i \mathbf{H}_{0i} \mathbf{V}_i (\mathbf{H}_{0i} \mathbf{V}_i)^H \quad (17)$$

where  $p_0$  is the transmitting power of MU and  $p_i$  is the transmitting power of the  $i^{th}$  FU ( $i \in \{1, \dots, M\}$ ).

The uplink transmission rate of FU in case 2 is the same as it in case 1. We also do a simulation with 1 MU and 3 FUs like case1,  $p_1, p_2, p_3$  is increasing while  $p_0$  is constant in Fig. 6 and  $p_0$  is increasing while  $p_1, p_2, p_3$  is fixed in Fig. 7.

Comparing Fig. 4, Fig. 5, Fig. 6 and Fig. 7, the rate of FU and MU is stable and neither FUs nor MU could interfere each other receivers. All the results show that IA technique has a good effect on interference management both in case 1 and case 2.

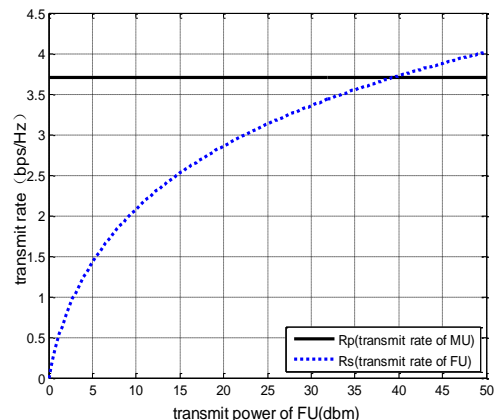


Fig. 6. Increase power of FU in case 2

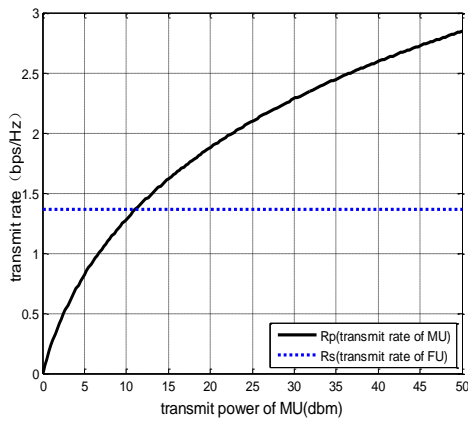


Fig. 7. Increase power of MU in case 2

#### IV. AVERAGE TRANSMITTING RATE

Simulations in section III reveal that IA technique creates a zero interference circumstance for users in both case 1 and case 2. In this section, we put efforts on the improvement of system performance by applying regionalized IA. Fig. 8 and Fig. 9 show the changes of uplink transmission rates with the growth of SNR in case 1 and case 2 respectively. It is obvious that the rates of both FU and MU increase as the SNR increases, which reflects IA guarantees the performance in case 1 and case 2.

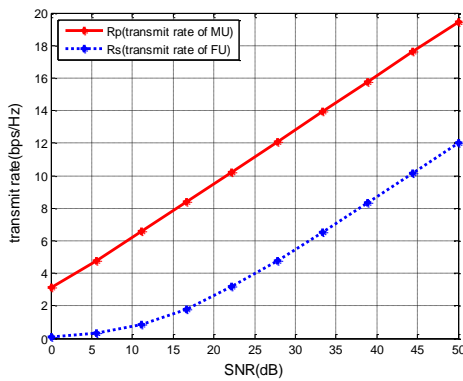


Fig. 8. Transmit rate increases as SNR increases in case 1

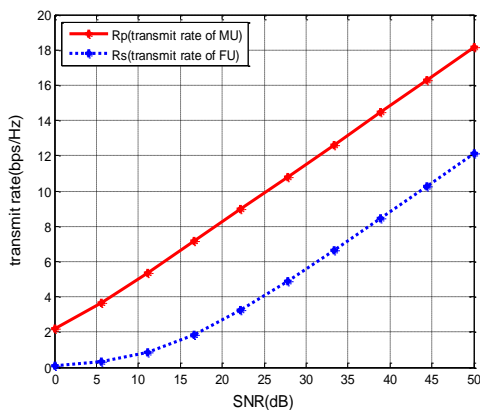


Fig. 9. Transmit rate increases as SNR increases in case 2

In order to verify the performance enhanced on the whole network system more directly when regionalized

IA is employed, the average rates of MU and FU in the whole cell has been discussed. As the rate of FU is the same in case 1 and case 2, the average rate of FU is equal to  $R_s$  in Eq.(10), then only the average rate of MU should be concerned about.

Combining the uplink transmission rate of MU in case 1 and case 2, average uplink transmission rate of MU in the whole cell is defined in this paper as Eq.(18).

$$\begin{aligned} \bar{R}_p &= P_1 R_p + P_2 R_p' \\ &= P_1 \times \log_2 |\mathbf{I} + \mathbf{U}_1^H \mathbf{Q}_1 \mathbf{U}_1 (\mathbf{U}_1^H (\mathbf{n}_0 \mathbf{n}_0^H + \mathbf{Q}_{11}) \mathbf{U}_1)^{-1}| \\ &\quad + P_2 \times \log_2 |\mathbf{I} + \mathbf{U}_0^H \mathbf{Q}_0 \mathbf{U}_0 (\mathbf{U}_0^H (\mathbf{n}_0 \mathbf{n}_0^H + \mathbf{Q}_{00}) \mathbf{U}_0)^{-1}| \end{aligned} \quad (18)$$

where  $P_1$  denotes the probability of MU in region I, is described as Eq.(19)

$$P_1 = \frac{R^2 - r^2}{R^2} \quad (19)$$

$R$  is the coverage radius of MBS,  $r$  is the coverage radius of FBS.  $P_2$  represents the probability of MU in region II, can be written as Eq.(20)

$$P_2 = \frac{r^2}{R^2} \quad (20)$$

First we simulate the Scenario with one MU and three FUs in the whole cell. In Fig.10 we compare the average transmission rate of MU and FU with different case, including regionalized IA proposed in this paper, IA algorithm proposed in [13] and algorithm without IA. The FU's average transmission rate employing regionalized IA and IA are almost unanimous when SNR is smaller than 20 dB. When SNR is more than 20dB, it can be seen that the FU's average transmission rate employing regionalized IA is higher than that of IA. Comparing the average transmission rate of MU, regionalized IA provides about 1bps/Hz benefits over IA. As expected, both the average transmission rate of MU and FU employing regionalized IA and IA have significant advantages over that of without IA. From Fig.10 we can see that the proposed regionalized IA technique really guarantees the transmitting performance of both FU and MU.

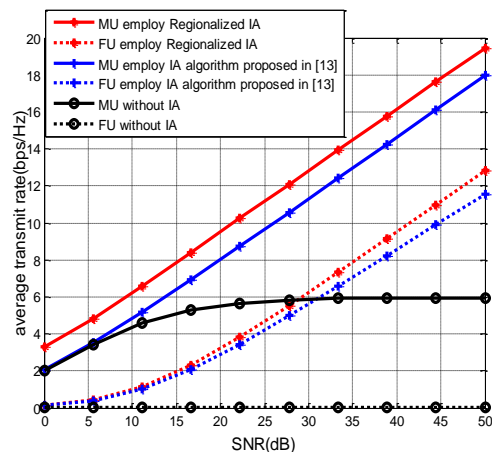


Fig. 10. Average rates of both FU and MU

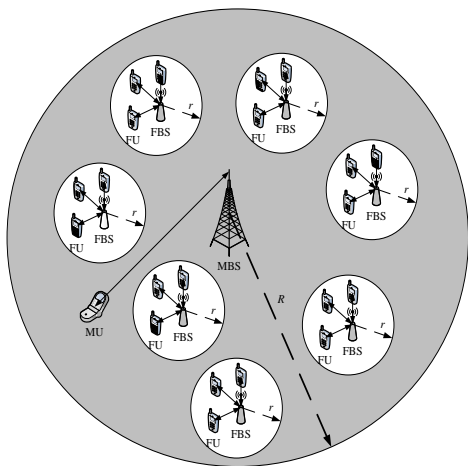


Fig. 11. A macrocell coexisting with several femtocells

Next, we simulate the MU's average transmission rate change with the number of femtocells. Fig. 11 shows a macrocell coexisting with several femtocells. The paper assume that all these femtocells keep from each others in a reasonable distance, so we ignore the interference between these femtocells. There are still three FUs in every femtocell in our simulation scenario.

Fig. 12 reflects the impact of femtocell's number change on the average rate of MU. When the number of femtocell increase from 1 to 20, the rate of MU failed by just under 0.1bps/Hz in Fig. 12, which indicated regionalized IA has an excellent effect on interference management again.

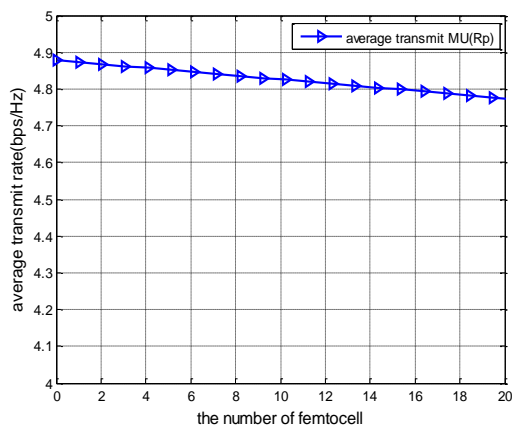


Fig. 12. MU's average rate changed by the number of femtocell

## V. CONCLUSION

In this paper, we have developed a regionalized IA that is applicable to two-tiered heterogeneous cognitive networks in which femtocell and macrocell coexist. The macrocell is divided into two regions based on the characteristics of its interference distribution. We employ IA technique to suppress the interference at receivers both in MBS and FBS. The simulations show that the proposed interference management strategy ensures the performance of both MU and FU. Future work includes considering more MUs. With the number of femtocells

increases in the macrocell, the interference between femtocells will also be considered. How to optimize the average rate and allocate the power of FUs in a reasonable way is also the next phase in our study.

## ACKNOWLEDGMENT

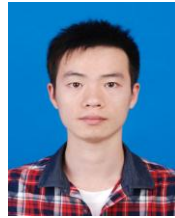
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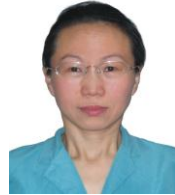
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**Jingwen Yang** obtained the Bachelor of Science degree in 2013 and is currently pursuing M.S. degree program in Shanghai Normal University. His research interest is currently at interference alignment algorithms in heterogeneous cognitive radio network.



**Li Li** received the B.S.EE. degree from Tsinghua University in 1985, the M.S.EE. degree from China Research Institute of Radiowave Propagation in 1988, and Ph.D. degree in science from Peking University in 1997. Prof. Li's research interest is currently at the wideband spectrum sensing, spectrum allocation and interference alignment algorithms in heterogeneous cognitive radio network.



**Xiaoping Zhou** received the Ph.D. degree from Shanghai University in 2011. He is an associate professor in Shanghai Normal University. His research interest is mainly broadband wireless communications.