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Area-classified interference coordination for heterogeneous cellular network

Yongming Huang[1,2*], Shiwen He[1], Shi Jin[1], Luxi Yang[1], Lei Jiang[3] and Ming Lei[3]

Abstract

In this paper, we aim to address the cross-layer interference in the heterogenous cellular network (HetNet). In order to exploit the overlapping characteristics of the HetNet coverage and achieve a good trade-off between the interference coordination gain and the cost, an area-classified interference coordination strategy is first proposed. The basic idea is that coverage of the HetNet is classified into four different areas such that area-specific interference coordination can be used to increase the cross-layer cooperation efficiency. A new steepest slope method based on relative cooperation gain is proposed to realize efficient area classification. Then, a coordinated beamforming scheme based on area-specific limited feedback is proposed to examine the effectiveness of this new strategy. It is shown that the proposed scheme could increase the success rate of user pairing and thus improve the throughput performance, with reduced feedback overhead in contrast to existing schemes. Its effectiveness is finally verified via numerical simulations.

Keywords: Heterogenous cellular network (HetNet); Cross-layer interference; Coordinated beamforming; Limited feedback

1 Introduction

Driven by the development of new wireless user equipments (UEs) and the proliferation of bandwidth-intensive applications, traffic load in cellular networks will increase in an explosive manner. The use of conventional cellular network framework is difficult to meet the new demands. To solve this issue, recently, a new framework called heterogeneous network (HetNet) has emerged as a flexible and cost-effective solution [1-4]. It is realized by overlaying lower-power access points such as relay node, picocell base station (BS), femtocell BS, and remote radio head (RRH) in the coverage of macrocell [5-7]. It is shown in [8] that the integration of the cross-layered macrocells and femtocells promises to significantly improve the area spectral efficiency of cellular network. Recently, the distribution of the achievable signal-to-interference-noise ratio (SINR) of the HetNet is derived in [9], and the achievable throughput of the HetNet is also analyzed in [10], both revealing that the HetNet has a potential of greatly improving the system performance in contrast to the conventional homogeneous cellular network.

In order to fully exploit the benefit of the lower-power nodes in the HetNet, a method of cell range expansion is developed. It is realized by adding a positive bias value to the lower-power node in the cell selection process; by this, it means that more users can associate to the lower-power node cell even if the lower-power node is not of the strongest signal. This method is useful for the load balancing and the exploitation of spatial reuse, and it also helps to mitigate the uplink (UL) inter-cell interference by reducing the UL transmit power [11-14]. However, in the downlink phase, the UEs in the range expansion area will suffer severe cross-layer interference from the macrocell base station (MBS). Therefore, it is important to develop new interference coordination technology for the HetNet.

In the 3GPP long-term evolution (LTE) R10 standard specification, a specific subframe called almost blank subframe (ABS) is adopted to partially address this problem. Since the MBS is kept silent within ABSs, the users in the lower-power node cell can be allocated without suffering strong macrocell interference within ABSs. However, the effective use of ABSs requires the lower-power nodes to have perfect knowledge of the ABS patterns such that they can make a proper user scheduling [11-14]. Besides

*Correspondence: huangym@seu.edu.cn
[1]School of Information Science and Engineering, Southeast University, Nanjing 210096, China
[2]Key Laboratory of Broadband Wireless Communication and Sensor Network Technology (Nanjing University of Posts and Telecommunications), Ministry of Education, Nanjing 210003, China
Full list of author information is available at the end of the article

this approach, interference control (IC) based on limited feedback of channel information, such as the best companion cluster (BCC) technology [15,16], recently has also been intensively studied and applied in the HetNet [17-20]. In [17], an adaptive strategy is proposed which uses joint beamforming to address the inter-cell interference between scheduled users only when the interference is significant. In [18], a prioritized selection (PS)-based IC scheme is developed. Furthermore, the performance of low-complexity random beamforming transmission with user scheduling in the same scenarios is analyzed in [19]. Later, a joint selection (JS)-based IC is presented to achieve more balanced performances between the macrocell users and the RRH cell users [20], which is efficient especially when the number of users is sufficiently large. However, it should be noted that this scheme requires that each user feeds back the preferred matrix index (PMI) and the best companion cluster index in a predetermined codebook, causing increased feedback overhead and limiting the freedom degree for user pairing. More recently, an efficient IC scheme based on heterogenous limited feedback is proposed, which fully exploits the inherent heterogeneous structure of user density and large-scale channel effects [21]. Furthermore, a distributed scheduling policy based on the cumulative distribution function of the channel quality indicator is designed and analyzed for the HetNet [22]. Also, new interference alignment approaches are proposed to solve the inter-cell interference of the HetNet [23,24]. In addition, radio resource allocation is also an important issue for the HetNet, which has attracted much attention. In [25], the authors propose a radio resource allocation framework for the HetNet and derive a resource allocation strategy that is asymptotically optimal on the proportional fairness metric.

In contrast to the homogeneous network, the ratios of the interference level to the desired signal strength for the users randomly distributed in a HetNet vary in a much broader range. This is due to the fact that the lower-power nodes are overlaid in the macrocell. As a result, direct application of conventional interference coordination approaches in a HetNet usually has low efficiency. In this paper, different from previous works which focus on specific interference coordination scheme design based on a fixed or simple cooperative region, we study a new interference coordination strategy by exploiting an adaptive cooperation region. We propose to first classify the coverage of HetNet into a couple of areas based on coordination efficiency. Users located in different areas have different coordination requests and feedback different channel information so as to improve the coordination efficiency. A new method is then proposed to realize an efficient area classification, and as a particular application, an area-classified spatial interference coordination scheme based on limited feedback is further developed, which has a much increased success rate of user pairing and thus improves the throughput performance. Simulation results finally show that the proposed scheme outperforms the conventional schemes even with reduced feedback overhead.

2 System model

Consider a HetNet consisting of one MBS and several overlaid lower-power nodes (henceforth, we use RRHs as example). Assume that the MBS is equipped with N_t^m antennas; each RRH BS is equipped with N_t^r antennas and each user is equipped with a single antenna, as shown in Figure 1. In general, each BS serves its own users in an orthogonal way via orthogonal frequency-division multiple access (OFDMA) or time division multiple access (TDMA). Assume that the RRH BSs are well deployed such that their coverage has no obvious overlapping, therefore the interference between the RRH cells can be ignored. However, there exists severe cross-layer interference between the macrocell and the RRH cells due to coverage overlapping. To address this issue, the MBS and the RRH BS are designed to perform coordinated transmission on the same time-frequency resource such as a single subcarrier or a couple of neighboring subcarriers in the OFDMA system, where the MBS and the RRH BS each serves a single user and design their transmit beamforming vectors cooperatively. Without loss of generality, we assume that the macrocell user i and RRH cell user i in the HetNet are simultaneously active on the same time-frequency resource, with their received signal y_i^m and y_i^r are written respectively as

$$y_i^m = \sqrt{P_m \alpha_{i,m}^m} \left(\boldsymbol{h}_{i,m}^m\right)^H \boldsymbol{w}_i^m x_i^m + \sqrt{P_r \alpha_{i,m}^r} \left(\boldsymbol{h}_{i,m}^r\right)^H \boldsymbol{w}_i^r x_i^r + n_i^m \tag{1}$$

$$y_i^r = \sqrt{P_r \alpha_{i,r}^r} \left(\boldsymbol{h}_{i,r}^r\right)^H \boldsymbol{w}_i^r x_i^r + \sqrt{P_m \alpha_{i,r}^m} \left(\boldsymbol{h}_{i,r}^m\right)^H \boldsymbol{w}_i^m x_i^m + n_i^r \tag{2}$$

where P_m and P_r denote respectively the transmit power of the MBS and the RRH BS, $\alpha_{i,m}^r$ and $\alpha_{i,r}^m$ denote respectively the large-scale fading coefficients from the RRH BS to macrocell user i and from the MBS to RRH cell user i, $\boldsymbol{h}_{i,m}^r$ and $\boldsymbol{h}_{i,r}^m$ denote respectively the small-scale flat Rayleigh fading channels from the RRH BS to macrocell user i and from the MBS to RRH cell user i, $\boldsymbol{w}_i^m$ and $\boldsymbol{w}_i^r$ denote respectively the beamforming vectors employed by the MBS and the RRH BS, x_i^m and x_i^r denote respectively the information symbols intended for macrocell user i and RRH cell user i, and n_i^m and n_i^r denote respectively the additive Gaussian white noise at the macrocell user and the RRH cell user, both with zero mean and variance σ^2.

The main concern for the above system is to mitigate the severe cross-layer interference between the macrocell and the RRH cell. An efficient way to address this issue

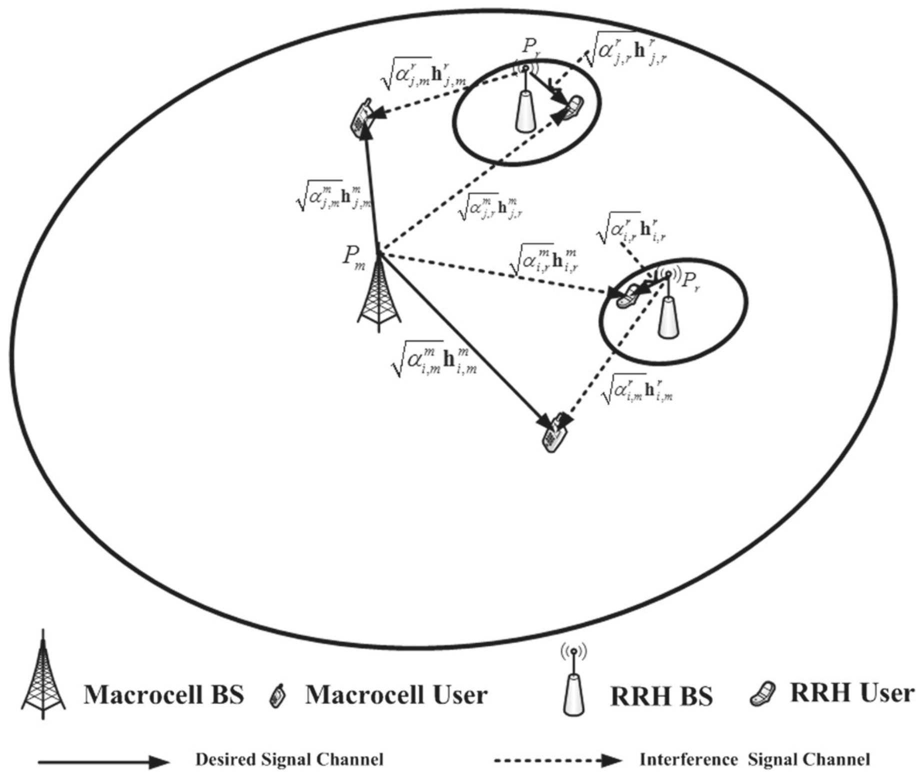

Figure 1 Illustration of the heterogenous network.

is by cooperatively designing the beamforming vectors $\{\boldsymbol{w}_i^r, \boldsymbol{w}_i^m\}$ and allocating the transmit powers [26-28]. This requires the exchange of channel state information (CSI) of the users between the MBS and the RRH BS. In frequency division duplex (FDD) systems, the CSI should be fed back from the users using the methods such as [29,30] and then shared between the BSs, causing a large overhead. Though this problem has been intensively studied for the homogeneous network in the literature, the wide range of the SINR distribution resulting from heterogenous deployment has not been well exploited to reach a good trade-off between the coordination gain and the overhead.

3 Area-classified interference coordination

Due to the fact that RRH cells are overlaid in the macrocell, in general, all the RRH cell users suffer interference from the MBS. However, the users in different areas usually have significantly distinct orders of signal-to-interference ratios (SIRs). Therefore, it is not efficient to employ a uniform interference coordination over all areas. In particular, performing interference coordination on the users with high SIRs usually brings marginal gain but requires additional cost such as the feedback of interference channels. The same issue exists in the macrocell. To improve the coordination efficiency, we propose to classify both the macrocell coverage and RRH cell coverage into two types of areas, i.e., the cooperative area and non-cooperative area. The interference coordination is only used for the users located in the cooperative area.

To mathematically illustrate this idea, let $\mathcal{A}^m$ and $\mathcal{A}^r$ denote the cooperative areas of the macrocell and the RRH cell, respectively. Let $R_{\rm IC}^m$ and $R_{\rm IC}^r$ denote respectively the rates of the macrocell user and the RRH cell user in the cooperative area achieved using interference coordination such as the zero-forcing beamforming, and $R_{\rm WIC}^m$ and $R_{\rm WIC}^r$ denote the rates achieved without using interference coordination, where the MBS and the RRH BS design their transmit beamforming vectors independently based on local CSI. Then, the relative cooperation gains (RCG) of the macrocell user and the RRH cell user are defined respectively as

$$\mathcal{G}_c^m = \frac{R_{\rm IC}^m - R_{\rm WIC}^m}{R_{\rm WIC}^m}, \quad (3)$$

$$\mathcal{G}_c^r = \frac{R_{\rm IC}^r - R_{\rm WIC}^r}{R_{\rm WIC}^r}. \quad (4)$$

Note that the cooperation gain comes at the cost of additional overhead, including the increased CSI feedback and inter-cell communication burden. In order to improve the coordination efficiency, the area classification is determined by solving the following optimization problem:

$$\max_{\{\mathcal{A}^m,\mathcal{A}^r\}} f_s(\mathcal{A}^m)+f_s(\mathcal{A}^r)$$
$$\text{s.t. } \mathbb{E}_{\mathcal{A}^m}\left(\mathcal{G}_c^m\right)\geq g_{\text{th}}^m,\ \mathbb{E}_{\mathcal{A}^r}\left(\mathcal{G}_c^r\right)\geq g_{\text{th}}^r \quad (5)$$

where $f_s(\cdot)$ denotes the size of the cooperative area, $\mathbb{E}_{\mathcal{A}}(\cdot)$ denotes the expectation operator over the cooperative area, and g_{th}^m and g_{th}^r denote the minimum GCR requirements of the macro and RRH cooperative areas, respectively.

It is difficult to directly solve the above optimization problem due to the fact that the closed-form expression of the average relative cooperation gain is hard to achieve. Alternatively, we propose to classify the cell coverage according to the reference signal receiving power (RSRP), where the RSRP is defined as the received power at the user terminal measured from the cell-specific reference signal within the considered frequency bandwidth. By this means, the cooperative area can be represented by a couple of parameters and has fewer drawbacks to determine. Before introducing the detailed method, we first provide some numerical results to illustrate some useful observations.

Figure 2 illustrates the values of the macrocell RSRP and the RRH cell RSRP of a user varying its position within the distances 30 $\sim$ 190 m to the macro BS, where the distance between the macro BS and the RRH is 200 m.

It is seen that the difference between the macrocell RSRP and the RRH cell RSRP is less than 5 dB only when the user has a distance of 160 $\sim$ 180 m to the macro BS, where the cross-layer interference is severe and the coordinated beamforming is necessary. In other cases, a cooperation between the macro and RRH BSs may not promise a large gain.

Figure 3 shows the variation of the relative cooperation gain of a user who moves from the macrocell center to the RRH cell center as shown in Figure 4. It can be seen that the relative cooperative gain monotonically decreases when the user moves from the macro (RRH) cell edge to the center, with a reduced decreasing rate. This implies that the cell central area has a much smaller coordination efficiency.

3.1 Area classification strategy

Motivated by the above observations, we propose the following area classification scheme to achieve a good coordination efficiency. The location of each user i is classified into one of four classes according to the relationship between its macrocell RSRP denoted as RSRP_i^m and its RRH cell RSRP denoted as RSRP_i^r, as shown in Figure 5, where β denotes the range expansion bias to increase the offload capacity of the RRH cell [12,13], θ is defined as the RRH cell user coordination bias with $\theta \leq \beta$, and α is defined as the macrocell user coordination bias with $\alpha > \beta$. Correspondingly, four area classes are formulated as follows and illustrated in Figure 6.

- *RRH non-central area.* This area is the edge region of the RRH cell. A user i belongs to the RRH non-central area if its RSRPs satisfy the following condition:

$$\text{RSRP}_i^r+\theta \leq \text{RSRP}_i^m < \text{RSRP}_i^r+\beta \quad (6)$$

  In Figure 6, it is illustrated as the light red grid area tagged with number ①. A user located in this area usually requires a cooperation between the RRH and the macro BS to suppress the cross-layer interference. It is easily seen that the estimated minimum value of θ can be calculated according to the large-scale fading of the channels, given by

$$\theta_{\min}=P_{\text{dB}}^m-(128.1+37.6\times\log_{10}(R_m)) -(P_{\text{dB}}^r-(140.7+36.7\times\log_{10}(D_{\min}^r))) \quad (7)$$

  where $D_{\min}^r$ denotes the minimum distance between the RRH cell user and the RRH BS in km, R_m denotes the macrocell service radius in km, P_{dB}^r and P_{dB}^m denote the transmit power of the RRH node and the macro BS in dB, respectively.
- *RRH central area.* This area is the interior region of the RRH cell. A user i belongs to the RRH central area if its RSRPs satisfy the following condition:

$$\text{RSRP}_i^m < \text{RSRP}_i^r+\theta \quad (8)$$

  In Figure 6, it is illustrated as the pastel striped areas tagged with number ②. A user located in the RRH central area usually does not require a cooperation between the macro BS and the RRH due to the fact that the strength of the interference is much less than that of the effective signal.
- *Macro non-central area.* This area is the edge region of the macrocell with the RRH cell. A user i belongs to the macrocell non-central area if its RSRPs satisfy the following condition:

$$\text{RSRP}_i^r+\beta \leq \text{RSRP}_i^m < \text{RSRP}_i^r+\alpha \quad (9)$$

  In Figure 6, it is illustrated as the orange grid areas tagged with number ③. A user located in this area usually also requires a cooperation between the RRH and the macro BS to suppress the cross-layer interference. Similarly, the estimated maximum value of α can be calculated according to the large-scale fading of the channels, i.e.,

$$\alpha_{\max}=P_{\text{dB}}^m-(128.1+37.6\times\log_{10}(D_{\min}^m)) -(P_{\text{dB}}^r-(140.7+36.7\times\log_{10}(D_{m\_r}+R_m))) \quad (10)$$

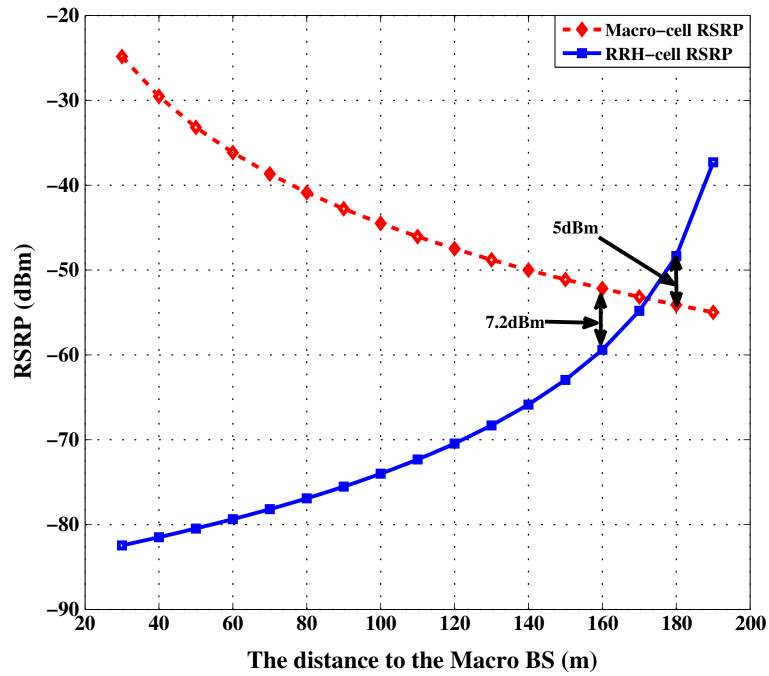

Figure 2 Comparison of macrocell and RRH cell RSRPs. MBS Tx power = 46 dBm and RRH Tx power = 30 dBm.

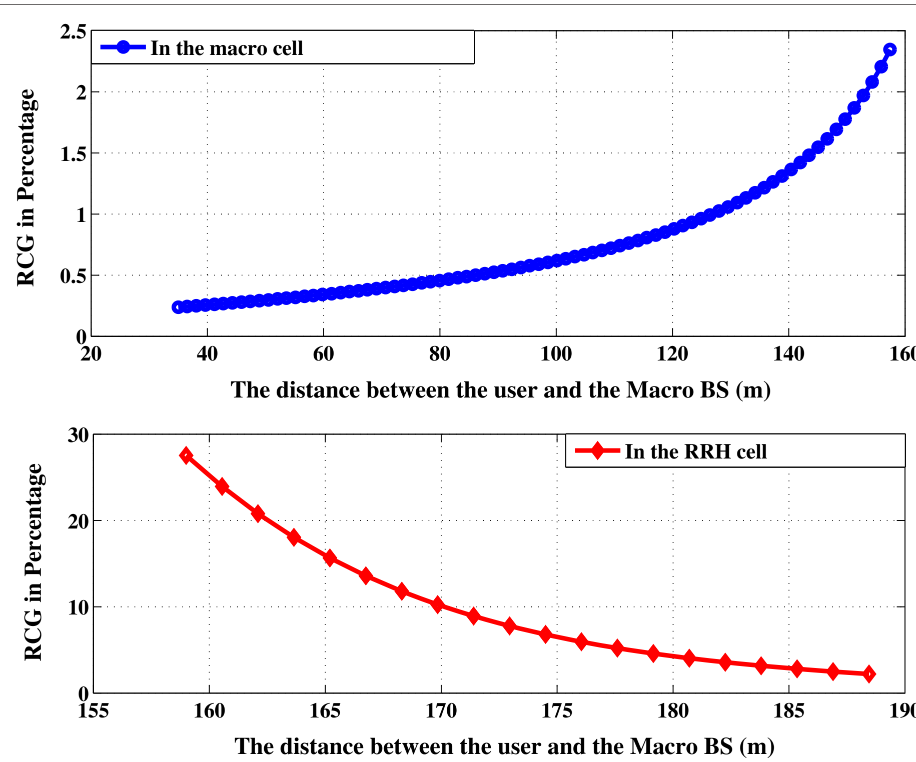

Figure 3 Variation of relative cooperation gain for a user who moves according to the trajectory shown in Figure 4. $N_t^m = N_t^r = 4$.

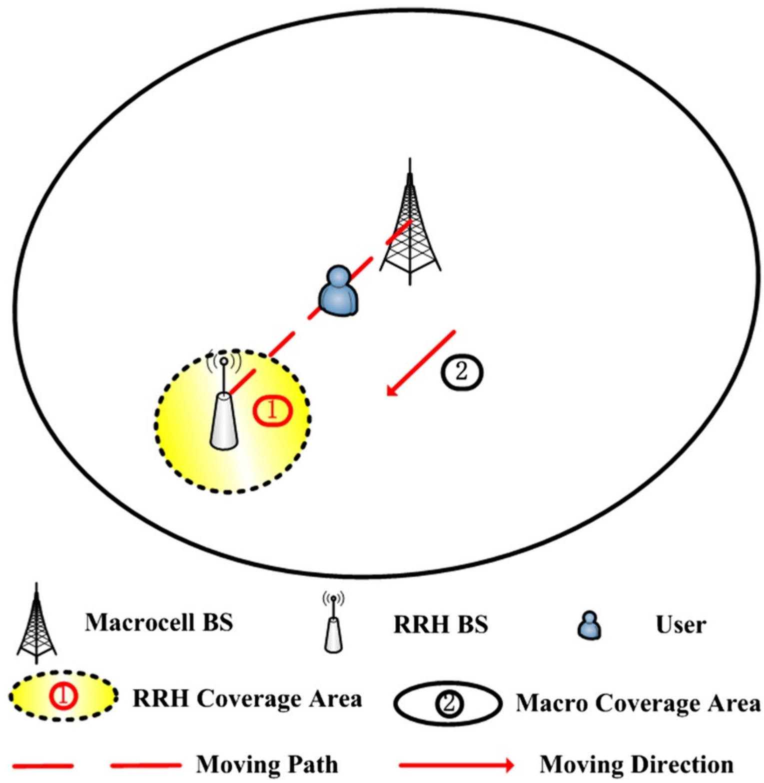

Figure 4 The trajectory of a user moving from the macrocell center to the RRH cell center.

where $D^m_{\min}$ denotes the minimum distance between the macrocell user and the macro BS in kilometers, and D_{m_r} denotes the distance between the RRH and the macro BS in kilometers.

- *Macro central area.* This area is the interior region of the macrocell. A user i belongs to macrocell central area if its RSRPs satisfy the following condition:

$$\mathrm{RSRP}_i^r + \alpha \le \mathrm{RSRP}_i^m \tag{11}$$

In Figure 6, it is illustrated as the shaded areas tagged with number ④. Similar to the RRH central area, a user located in this area usually does not require a cooperation between the macro BS and the RRH.

It is worth mentioning that from Theorem 1 in the literature [13], we know that the above-mentioned first three areas are in the shape of an ellipse. Based on the area classification, the user can request different levels of coordination according to its location in different areas, by feeding back different amounts of channel information. By this means, a better trade-off between the coordination gain and the feedback overhead than the conventional approach can be achieved.

3.2 Classification criterion

One can see that the parameters $\{\beta, \theta, \alpha\}$ need to determine in carrying out the above area-specific user classification. Note that the RPB parameter β can be given by the range expansion mechanism, so it is essential to determine the remaining parameters, θ and α. We propose to determine these two parameters based on the measure of relative cooperation gain. To proceed, assume that a RRH cell user i belongs to the RRH non-central area given by

$$① = \left\{ i : \mathrm{RSRP}_i^r + \theta \le \mathrm{RSRP}_i^m < \mathrm{RSRP}_i^r + \beta \right\}. \tag{12}$$

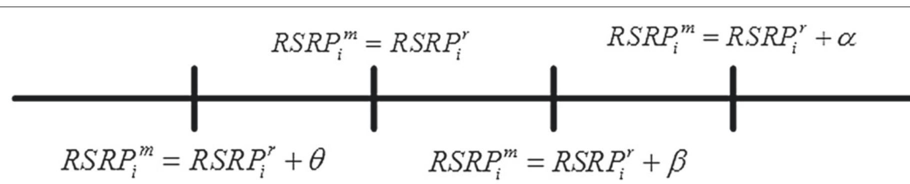

Figure 5 Illustration of RSRP division for area classification.

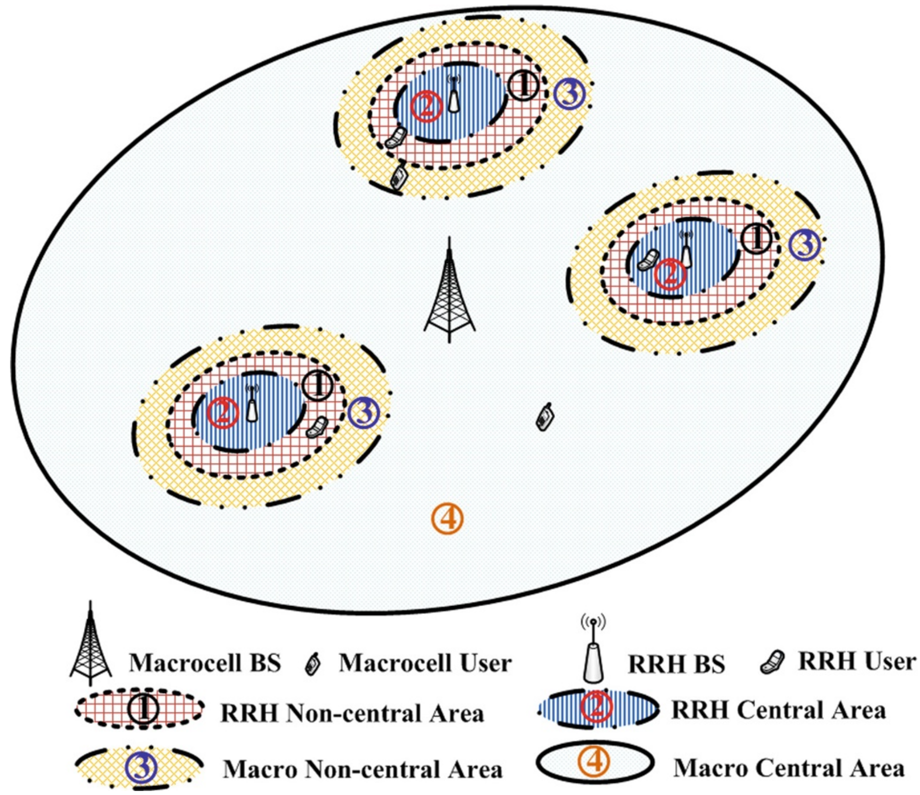

Figure 6 The area classification of the heterogenous network based on the RSRP criterion.

If no coordinated beamforming is used, the rate achieved by the user is written as

$$R_{\mathrm{WIC}}^{\theta} = \log_2\left(1 + \frac{P_r\alpha_{i,r}^{r}\left\|\left(\boldsymbol{h}_{i,r}^{r}\right)^{H}\boldsymbol{w}_i^{r}\right\|^2}{\sigma^2 + P_m\alpha_{i,r}^{m}\mathbb{E}\left\{\|\boldsymbol{h}_{i,r}^{m}\|^2\right\}}\right) = \log_2\left(1 + \frac{P_r\alpha_{i,r}^{r}\left\|\left(\boldsymbol{h}_{i,r}^{r}\right)^{H}\boldsymbol{w}_i^{r}\right\|^2}{\sigma^2 + 2N_t^{m}P_m\alpha_{i,r}^{m}}\right), \tag{13}$$

where $\boldsymbol{w}_i^{r}$ is the beamforming vector of the RRH for the RRH cell user i. While if a coordinated beamforming strategy between the macro BS and the RRH is employed, the user's achievable rate R_{IC}^{θ} is calculated as

$$R_{\mathrm{IC}}^{\theta} = \log_2\left(1 + \frac{P_r\alpha_{i,r}^{r}\left\|\left(\boldsymbol{h}_{i,r}^{r}\right)^{H}\boldsymbol{w}_i^{r}\right\|^2}{\sigma^2 + P_m\alpha_{i,r}^{m}\|\left(\boldsymbol{h}_{i,r}^{m}\right)^{H}\boldsymbol{w}_{i,r}^{m}\|^2}\right) \tag{14}$$

where $\boldsymbol{w}_{i,r}^{m}$ is the beamforming vector of the macro BS which is cooperatively designed such that the caused interference $\|\left(\boldsymbol{h}_{i,r}^{m}\right)^{H}\boldsymbol{w}_{i,r}^{m}\|^2$ is minimized. Compared with $R_{\mathrm{WIC}}^{\theta}$, it achieves a certain gain due to the fact that the cross-layer cross-layer interference is suppressed. To evaluate the gain, we define the average relative gain for the RRH non-central area as follows:

$$G_R(\theta) = \mathbb{E}_{①}\left\{\frac{R_{IC}^{\theta} - R_{\mathrm{WIC}}^{\theta}}{R_{\mathrm{WIC}}^{\theta}}\right\}. \tag{15}$$

It is easy to verify that a smaller θ gives a lower cooperation gain due to the fact that the ratio of the interference strength to the effective signal strength decreases with θ decreasing. While on the other hand, a smaller θ produces an enlarged RRH non-central area, resulting in increased cooperation overhead.

To achieve a good trade-off between the cooperation gain and the overhead, we propose to determine the area classification parameter θ using the following criteria:

$$\theta^* = \max_{\theta}\{\theta : G_R(\theta) \le \xi\} \tag{16}$$

where ξ is a threshold representing the desired relative cooperation gain for the RRH user. Note that the choice of θ obtains the boundary between the cooperative RRH non-central area and the non-cooperative RRH central area. The above criterion suggests that the boundary is determined by minimizing the size of the RRH cooperative area (maximizing θ) subject to a given maximum performance loss caused by the non-cooperation of the RRH central area.

Similarly, the other parameter α is determined using the following criteria:

$$\alpha^* = \min_{\alpha} \left\{ \alpha : G_M(\alpha) = \mathbb{E}_{③} \left\{ \frac{R_{\text{IC}}^{\alpha} - R_{\text{WIC}}^{\alpha}}{R_{\text{WIC}}^{\alpha}} \right\} \leq \zeta \right\} \quad (17)$$

where ζ is a threshold representing the desired relative cooperation gain for the macro user, the set ③ denotes the macro non-central area given by

$$③ = \left\{ i : \text{RSRP}_i^r + \beta \leq \text{RSRP}_i^m < \text{RSRP}_i^r + \alpha \right\}, \quad (18)$$

R_{IC}^{α} denotes the rate of the macrocell user i belonging to ③ achieved with coordinated beamforming, given by

$$R_{\text{IC}}^{\alpha} = \log_2 \left(1 + \frac{P_m \alpha_{i,m}^m \left\| \left(\boldsymbol{h}_{i,m}^m \right)^H \boldsymbol{w}_i^m \right\|^2}{\sigma^2 + P_r \alpha_{i,m}^r \| \left(\boldsymbol{h}_{i,m}^r \right)^H \boldsymbol{w}_{i,m}^r \|^2} \right) \quad (19)$$

where $\boldsymbol{w}_i^m$ is the beamforming vector for the macrocell user i, and $\boldsymbol{w}_{i,m}^r$ is the beamforming vector of the RRH which is cooperatively designed such that the interference to the macrocell user is minimized. R_{WIC}^{α} denotes the rate achieved by the user without performing coordinated beamforming, calculated as

$$\begin{aligned} R_{\text{WIC}}^{\alpha} &= \log_2 \left(1 + \frac{P_m \alpha_{i,m}^m \left\| \left(\boldsymbol{h}_{i,m}^m \right)^H \boldsymbol{w}_i^m \right\|^2}{\sigma^2 + P_r \alpha_{i,m}^r \mathbb{E} \left\{ \| \boldsymbol{h}_{i,m}^r \|^2 \right\}} \right) \\ &= \log_2 \left(1 + \frac{P_m \alpha_{i,m}^m \left\| \left(\boldsymbol{h}_{i,m}^m \right)^H \boldsymbol{w}_i^m \right\|^2}{\sigma^2 + 2 N_t^r P_r \alpha_{i,m}^r} \right). \end{aligned} \quad (20)$$

We note that based on the above criteria (16) and (17), it is still difficult to obtain closed-form solutions of the area classification parameters θ and α. However, provided the detailed coordinated beamforming optimization approach, the optimal values of θ and α can be achieved via one-dimensional numerical search. In particular, as a practically useful approach, θ and α can both be determined using a deepest slope method. As shown in Section 5.1, $G_R(\theta)$ and $G_M(\alpha)$ are non-decreasing and non-increasing functions, respectively, with the slope varying in different intervals. Thus, it is reasonable to choose θ and α to be the ending points of the sharpest slope interval, such that the coordinated transmission strategy is employed only if it brings significant gain.

4 Area-classified coordinated beamforming based on limited feedback

In order to examine the performance of the proposed area-classified inter-cell interference coordination strategy above, as a typical application, in this section, we develop a coordinated beamforming scheme using area-specific limited feedback. It is known in [15,16] that if coordinated transmission strategy is performed based on a codebook, each user needs to feed back not only the index of the preferred precoding matrix or beamforming vector (PMI) and the channel quality indicator (CQI) usually defined as the SINR, but also the index of the company precoding matrix or beamforming vector to be used by the cooperative BS which causes the least interference. With these information, the MBS and the RRH can cooperatively select a pair of users (also called user pairing, each serves one user) to perform coordinated beamforming which imposes minimized interference to each other. To further improve the performance, a cluster-structured codebook is developed by clustering together the codewords with high correlation [31,32]. Based on that, the user feeds back the index of the company cluster instead of the company precoding matrix or beamforming vector. This can significantly improve the success rate of user pairing.

Following the idea of area classification, next we consider a cluster-structured codebook-based coordinated beamforming and design an area-specific limited feedback. To proceed, the MBS codebook $\boldsymbol{B}^m$ and the RRH node codebook $\boldsymbol{B}^r$ are defined as follows:

$$\boldsymbol{B}^m = \left\{ \boldsymbol{B}_1^m, \ldots, \boldsymbol{B}_M^m \right\} \quad (21)$$

and

$$\boldsymbol{B}^r = \left\{ \boldsymbol{B}_1^r, \ldots, \boldsymbol{B}_N^r \right\} \quad (22)$$

where $\boldsymbol{B}_i^m$ and $\boldsymbol{B}_i^r$ denote the ith codeword cluster consisting of a set of correlated codewords, in the MBS and the RRH codebooks, respectively. Denote the number of codewords in the cluster $\boldsymbol{B}_i^m$ and $\boldsymbol{B}_i^r$ as I_i^m and I_i^r, respectively. Then, the total numbers of codewords in the codebook $\boldsymbol{B}^m$ and $\boldsymbol{B}^r$ are $I^m = \sum_{i=1}^{M} I_i^m$ and $I^r = \sum_{i=1}^{N} I_i^r$, respectively. Without loss of generality, we assume that codeword cluster $\boldsymbol{B}_i^m$ consists of the $\left(\sum_{j=1}^{i-1} I_j^m + 1 \right)$th to $\left(\sum_{j=1}^{i} I_j^m \right)$th codewords in the MBS codebook, and codeword cluster $\boldsymbol{B}_i^r$ consists of the $\left(\sum_{j=1}^{i-1} I_j^r + 1 \right)$th to $\left(\sum_{j=1}^{i} I_j^r \right)$th codewords in the RRH codebook.

4.1 Area-specific feedback scheme

Now we focus on the limited feedback design. In our proposed method, each user first determines its belonging area according to the RSRPs and then calculates feedback information correspondingly. If the user judges that it belongs to the central area, i.e., the macro central area or the RRH central area, it feeds back the area tag, the PMI and the SINR. Otherwise, if it belongs to the non-central area, i.e., the macro non-central area and the RRH non-central area, it feeds back the company cluster index along with the area tag, the PMI and the SINR. The details are given as follows:

- The RRH central area user determines the preferred codeword and computes the SINR as

$$\mathrm{PMI}_i^r = \max_{j=1,\ldots,I^r} \left\| \left(\boldsymbol{h}_{i,r}^r\right)^H \boldsymbol{w}_j^r \right\| \tag{23}$$

and

$$\mathrm{SINR}_i^r = \frac{P_r \alpha_{i,r}^r \left\| \left(\boldsymbol{h}_{i,r}^r\right)^H \boldsymbol{w}_{\mathrm{PMI}_i^r}^r \right\|^2}{\sigma^2 + 2N_t^m P_m \alpha_{i,r}^m}. \tag{24}$$

Note that, here, the cross-layer interference is only estimated based on the large-scale fading.

- The RRH non-central area user determines the preferred codeword, the company cluster, and computes the SINR as

$$\mathrm{PMI}_i^r = \max_{j=1,\ldots,I^r} \left\| \left(\boldsymbol{h}_{i,r}^r\right)^H \boldsymbol{w}_j^r \right\| \tag{25}$$

and

$$\mathrm{SINR}_i^r = \min_{j \in \boldsymbol{B}_{P_i^r}^m} \frac{P_r \alpha_{i,r}^r \left\| \left(\boldsymbol{h}_{i,r}^r\right)^H \boldsymbol{w}_{\mathrm{PMI}_i^r}^r \right\|^2}{\sigma^2 + P_m \alpha_{i,r}^m \left\| \left(\boldsymbol{h}_{i,r}^m\right)^H \boldsymbol{w}_j^m \right\|^2} \tag{26}$$

where $\boldsymbol{B}_{P_i^r}^m$ denotes the company cluster which is determined as the least interference codeword cluster. To be specific, we select the codeword with the minimum interference on the non-central area RRH user as follows:

$$\mathrm{C}_i^r = \min_{j=1,\ldots,I^m} \left\| \left(\boldsymbol{h}_{i,r}^m\right)^H \boldsymbol{w}_j^m \right\|, \tag{27}$$

It also means that this minimum interference codeword should belong to $\boldsymbol{B}_{P_i^r}^m$.

- The macro central area user determines the preferred codeword index PMI_i^m and computes SINR_i^m using the method similar to that of the RRH central area user.
- The macro non-central area user determines the preferred codeword index PMI_i^m, the company cluster index P_i^m, and the SINR using the method similar to that of the RRH non-central area user.

4.2 Area-classified interference coordination scheme

Based on the above limited feedback method, we develop an area-classified coordinated beamforming scheme summarized as Algorithm 1.

Algorithm 1 Area-classified coordinated beamforming algorithm

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1: **Area classification:** Determine the area classification parameters α, θ, and β according to the proposed method in Section 3.2, i.e., based on criteria (16) and (17).

2: **Area-specific user feedback:** Each user carries out area-specific channel information feedback based on given MBS and RRH codebooks. Then, the MBS and the RRH exchange their served users' feedback information through the backhaul.

3: **User paring:** The MBS and the RRH cooperatively perform user pairing; a macrocell user and a RRH cell user are paired together if they satisfy one of the following conditions:

  I. They are both central area users.
  II. They are both non-central area users, and each user's preferred codeword is included in the company cluster reported by the other user.
  III. One is a central area user; the other is a non-central area user. The preferred codeword of the central user is included in the company cluster of the non-central user.

4: **User scheduling:** Select the best user pair using the proportional fairness (PF) scheduler, i.e., $k^* = \mathrm{argmax}_{k \in \mathcal{K}} \left(\frac{\log_2\left(1+\mathrm{SINR}_{I(k)}^r(t)\right)}{\bar{R}_{I(k)}^r(t)} + \frac{\log_2\left(1+\mathrm{SINR}_{II(k)}^m(t)\right)}{\bar{R}_{II(k)}^m(t)} \right)$, where $\mathcal{K}$ denotes the set of all the user pairs; $I(k)$ and $II(k)$ denote indices of the RRH cell user and the macrocell user in the kth user pair, respectively; $\mathrm{SINR}_{I(k)}^r(t)$ and $\mathrm{SINR}_{II(k)}^m(t)$ denote the SINRs fed back from the users at time slot t; $\bar{R}_{I(k)}^r(t)$ and $\bar{R}_{II(k)}^m(t)$ denote respectively the average rates achieved by the RRH cell user and the macrocell user of the kth user pair, defined as $\bar{R}_{I(k)}^r(t) = \left(1 - \frac{1}{t_c}\right) \bar{R}_{I(k)}^r (t-1) + t_c \log_2\left(1 + \mathrm{SINR}_{I(k)}^r(t)\right)$ and $\bar{R}_{II(k)}^m(t) = \left(1 - \frac{1}{t_c}\right) \bar{R}_{II(k)}^m(t-1) + t_c \log_2\left(1 + \mathrm{SINR}_{II(k)}^m(t)\right)$, using $t_c > 1$ as the smoothing factor.

5: **Coordinated beamforming:** The MBS and the RRH simultaneously transmit signal to the scheduled user pair, each with the precoding matrix or beamforming vector recommended by its user.

Remark 1. Compared with the conventional codebook-based coordinated beamforming algorithms such as [18,20], the proposed algorithm significantly increases the success rate of user pairing[a] and thus improves the rate performance. On the other hand, the feedback burden is also reduced by the proposed area-specific feedback method. Note that in the proposed algorithm, central users with non-coordinated transmission may suffer a certain performance loss, but such a loss is controlled to be below the given threshold via the area classification. Therefore, the throughput improvement benefiting from increased user pairing rate usually dominates the overall performance, as verified by the numerical results provided in the following section.

5 Numerical results

In this section, the performance of the proposed area-classified coordinated beamforming scheme is investigated by numerical results. Consider a HetNet consisting of one macro BS and one RRH node, with multiple users uniformly distributed in its coverage. The macro BS and the RRH node are both equipped with $M = 4$ antennas, and all the users are with a single antenna. For simplicity, in our simulations, we evaluate the coordinated beamforming on a single carrier of the OFDM system with 10-MHz bandwidth. The channels are generated based on the 3GPP spatial channel model [33]. We assume uniform noise figure in all users, and it is set to be 9 dB. More detailed simulation parameters and assumptions are listed in Table 1. The throughput of each cell is calculated as the sum rate of all its served users averaged on the number of time slots used.

For comparison, two relevant coordinated beamforming schemes, i.e., the prioritized selection (PS)-based IC scheme (PS-IC) in [18] and the joint selection-based interference coordination scheme (JS-IC) in [20] are simulated, too. In addition, the performance of the conventional zero-forcing (ZF) coordinated beamforming scheme and the TDMA interference coordination with maximum ratio transmitter (MRT) are simulated, too, both based on limited feedback CSI. Note that for the fairness, the comparing schemes and the proposed scheme all employ the same codebook, i.e., the cluster-structured discrete fourier transformation (DFT) codebook which is generated in [20].

Table 1 Simulation parameters

Parameters	Setting
Bandwidth	10 MHz
Number of subcarriers	2,048
Thermal noise density	−174 dBm/Hz
Number of macro BSs	1
Mobile users within macro range	$6 \sim 30$
Number of RRH BSs	1
Mobile users within RRH range	$6 \sim 30$
MBS transmit power	46 dBm
MUE distribution radius	289 m
RRH node transmit power	30 dBm
Codebook size	32, 64
Codebook cluster size	4, 8
Macro path loss model	$128.1+37.6\log_{10}(R)$ dB (R in km)
RRH path loss model	$140.7+36.7\log_{10}(R)$ dB (R in km)
Distance MBS-RRH node	200 m
Minimum distance MBS-macro user	35 m
Minimum distance RRH node-RRH user	10 m
Scheduler	Proportional fairness

5.1 Relative cooperation gain performance

It is useful to first investigate the behavior of the newly defined relative cooperation gain, as it is quite relevant to the area classification criterion. In the simulations, we employ codebook-based coordinated beamforming. Figures 7, 8, 9 and 10 show the average relative cooperation gain varying with the values of θ and α under different scenarios. The sizes of the codebooks for Figures 7A and 8A and Figures 7B and 8B are 32 and 64, respectively. While in Figures 9 and 10, the size of the codebook is 32. The REB β is set to 8. The other simulation parameters and assumptions are given in Table 1.

Simulation results show that, in general, the average relative cooperation gain decreases with the value of θ decreasing or with the value of α increasing. This is due to the fact that the decreased θ and the increased α produce an enlarged RRH non-central area and macro non-central area, respectively. As a result, the difference between the RSRPs from the macro BS and the RRH node in these non-central areas is increased, which degrades the interference coordination efficiency. This behavior of the average relative gain suggests that expanding the cooperation area cannot always bring significant gain.

The results also illustrate that the slope of the average relative cooperation gain with respect to α or θ is varying interval by interval. In particular, the sharpest slope only appears in a small interval, meaning that only in this interval did the interference coordination brought significant gain and was the most efficient. Based on this observation, it is reasonable to determine jointly the factors (ξ, θ) and (ζ, α) as the points that end the sharpest slope interval so as to achieve a good trade-off between the cooperation gain and the cost. Such a method is called 'the steepest slope method'. For example, in Figure 7A, we can determine the value of the θ based on the turn point that ends

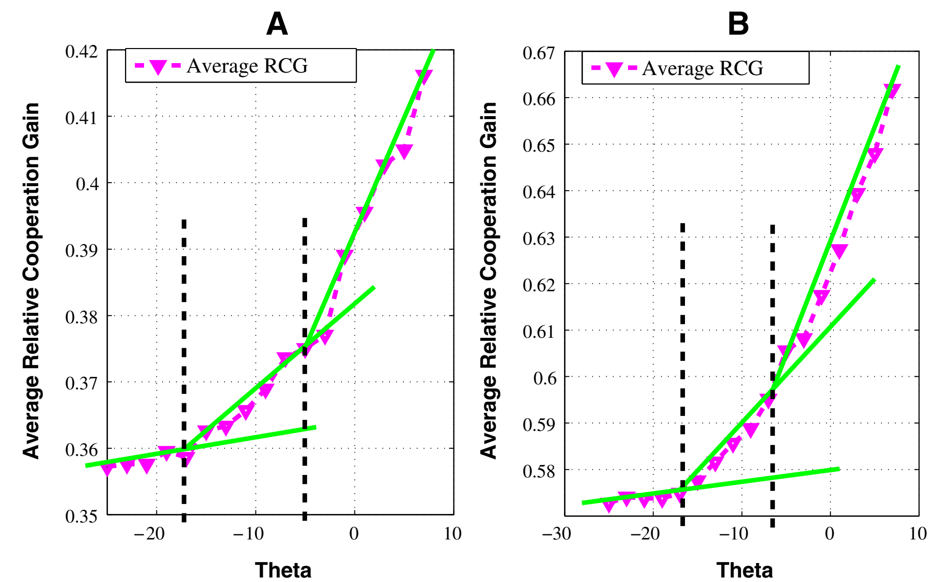

Figure 7 The behavior of $G_R(\theta)$, $N_t^m = N_t^r = 4$, $D_{m\_r} = 200$ m. (A) Codebook size is 32. **(B)** Codebook size is 64.

the right-most slope, i.e., the relative cooperation gain is 0.375 and the value of θ is -6.

5.2 Throughput performance

The throughput performance of the proposed scheme and the comparing schemes are illustrated in Figures 11, 12 and 13 with $\xi = 0.375$, $\theta = -6$, $\zeta = 0.18$, and $\alpha = 29$, which are determined by the steepest slope method and $\beta = 8$. As shown in Figure 11, in terms of the total throughput of two cells, the proposed scheme significantly outperforms all other schemes. In particular, compared with the PS-IC scheme, the ZF scheme and the TDMA scheme, a gain of over 5bit/s/Hz is observed in a wide range. It is also shown that our scheme achieves a better multi-user diversity, and thus, the achieved gain increases with the number of users. Compared with the JS-IC scheme, our scheme exhibits obvious advantage especially when the number of users is small, but the gain shrinks with the number of users increasing. This is due to the fact that the degree of freedom of user pairing is limited by the number of users for the JS-IC scheme, while the proposed area-classified interference coordination scheme improves the

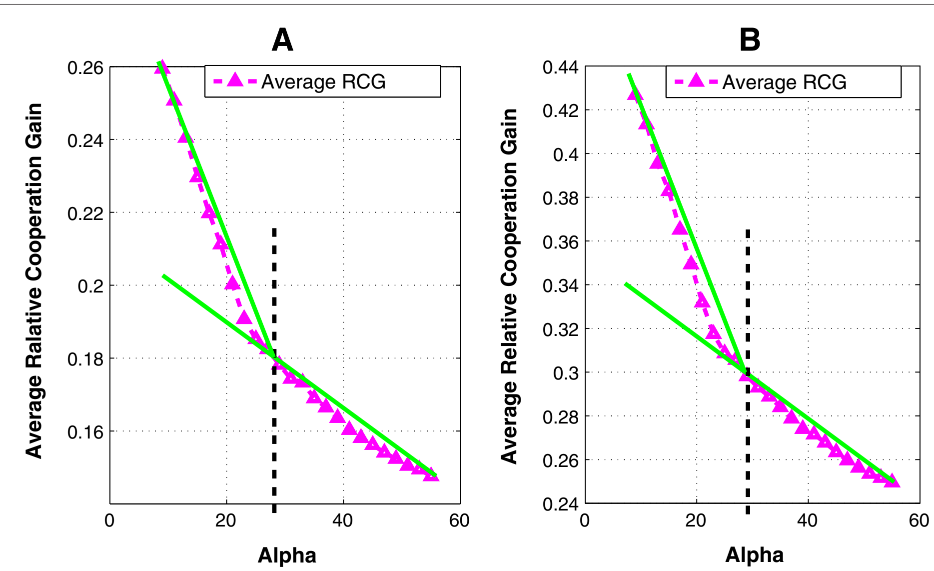

Figure 8 The behavior of $G_M(\alpha)$, $N_t^m = N_t^r = 4$, $D_{m\_r} = 200$ m. (A) Codebook size is 32. **(B)** Codebook size is 64.

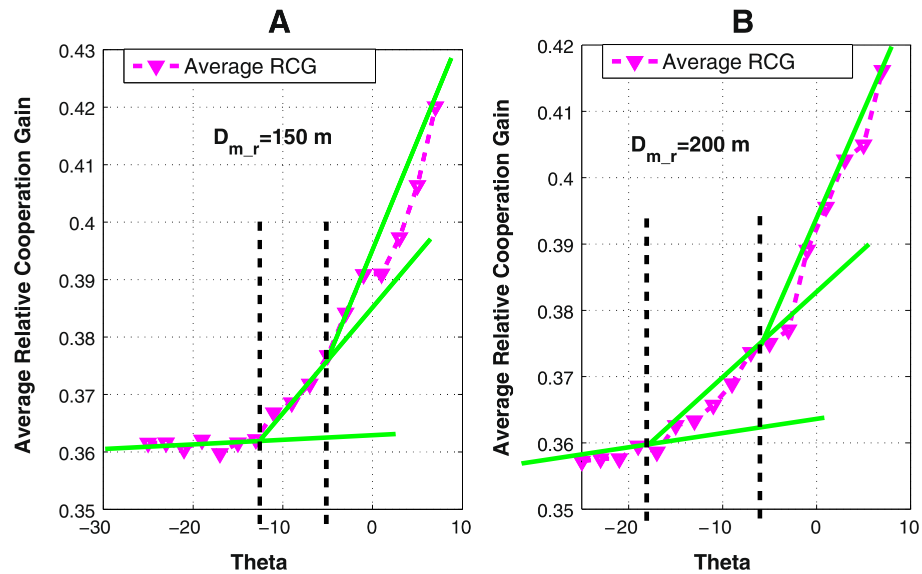

Figure 9 The behavior of $G_R(\theta)$, $N_t^m = N_t^r = 4$. (A) $D_{m\_r} = 150$ m. **(B)** $D_{m\_r} = 200$ m.

success rate of user pairing. Similar results are observed in the throughput performance of the macrocell. It is shown in Figure 12 that the proposed scheme also achieves the best performance in terms of macrocell throughput. It is interesting to point out that the performance comparison results are slightly different for the throughput of the RRH cell. As shown in Figure 13, in this metric, the proposed scheme is superior over the PS-IC scheme, the ZF scheme, and the TDMA scheme, but it is slightly poorer than the TDMA scheme. This reveals that the time division interference avoiding scheme usually benefits the small cell of the HetNet, but its overall achievable throughput of the HetNet is not optimal.

Figure 14 illustrates the macrocell throughput of the proposed scheme and the comparing schemes varying with the number of RRH users, under configurations $\xi = 0.375$, $\theta = -6$, $\zeta = 0.18$, $\alpha = 29$, and $\beta = 8$. We consider two macrocell scenarios, i.e., the number of the macrocell users is fixed to be 10 or 20. It can be seen that in our proposed scheme, increasing the number of RRH cell users has little impact on the rate performance of the macrocell, while the macrocell throughput of the JS-IC scheme

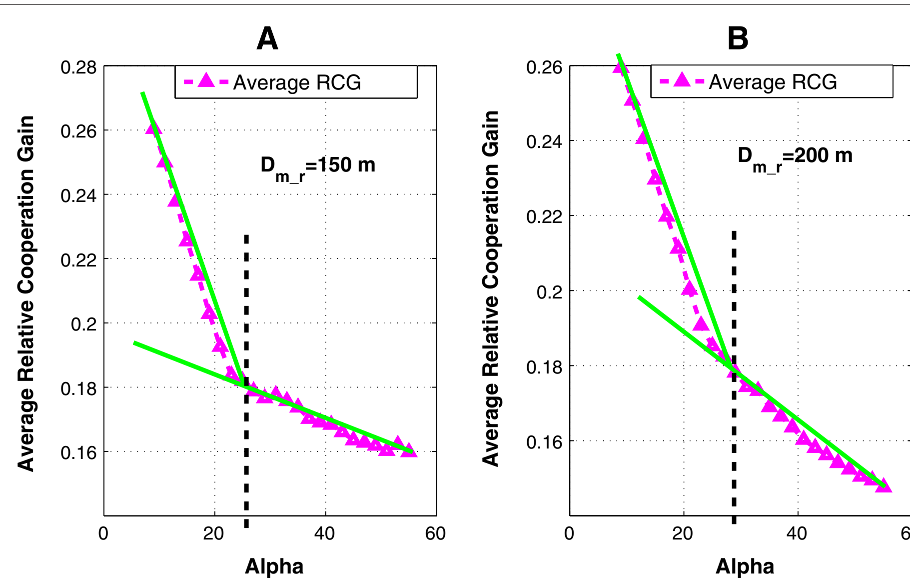

Figure 10 The behavior of $G_M(\alpha)$, $N_t^m = N_t^r = 4$. (A) $D_{m\_r} = 150$ m. **(B)** $D_{m\_r} = 200$ m.

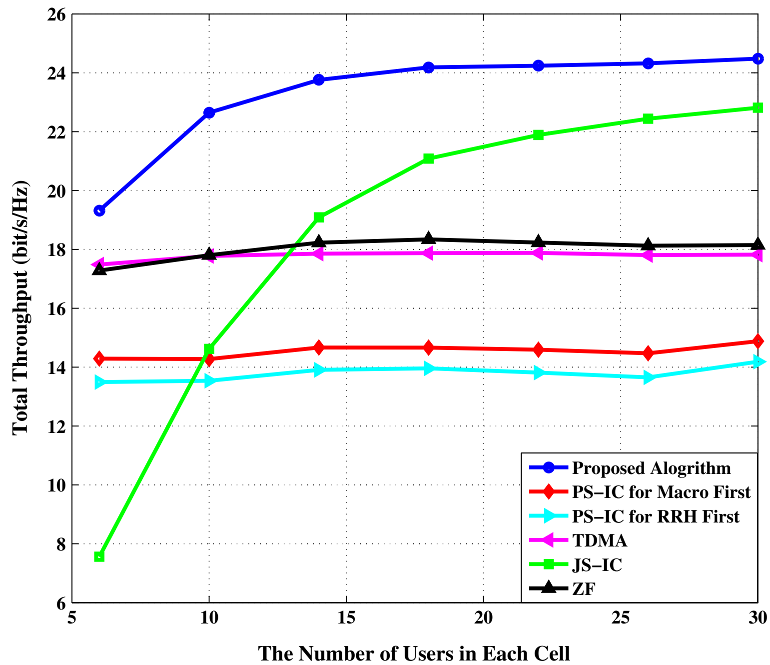

Figure 11 **Total throughput performance of the interference coordination schemes, $N_t^m = N_t^r = 4$.**

suffers a performance loss when the number of RRH users is not large. This is due to the fact that our proposed area-classified interference coordination scheme improves the success rate of user pairing.

Finally, the feedback overhead of the proposed area-classified IC scheme is evaluated and compared with the existing JS-IC scheme. The amount of feedback bits and the number of the matched user pairs are calculated for these two schemes. The simulation results are obtained using 1, 000 Monte Carlo runs and are given in Table 2, where the number of users in each cell is configured with 50, and independent channel realizations are generated in

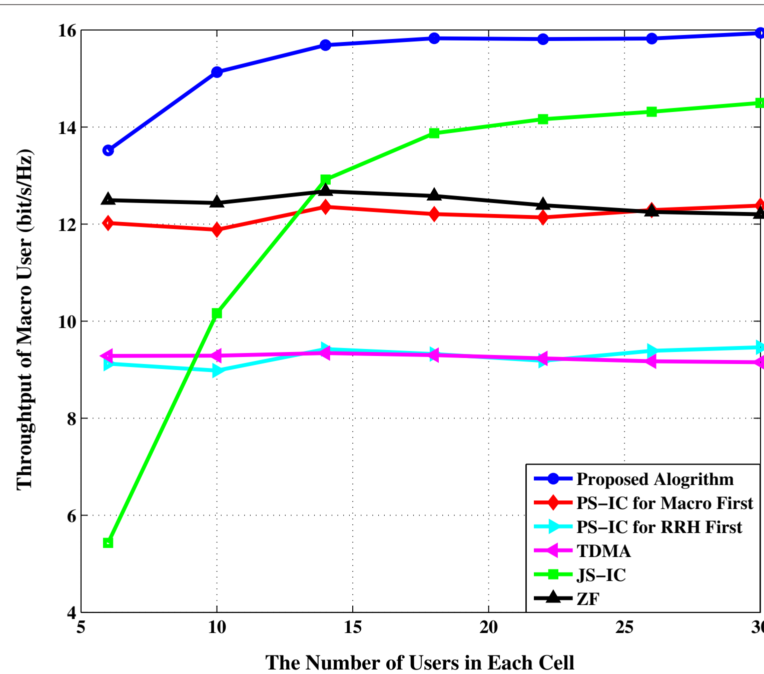

Figure 12 **Throughput performance achieved by the macrocell in the interference coordination schemes, $N_t^m = N_t^r = 4$.**

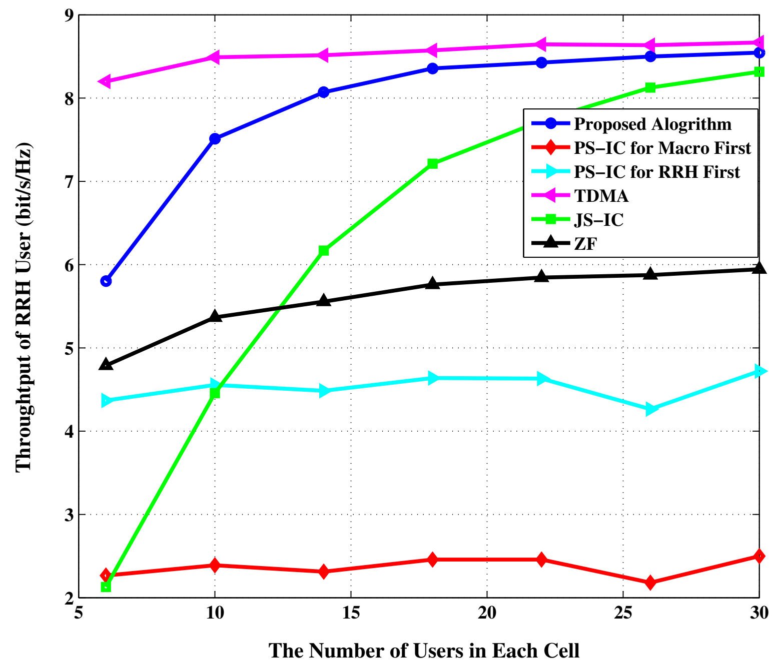

Figure 13 Throughput performance achieved by the RRH cell in the interference coordination schemes, $N_t^m = N_t^r = 4$.

each run. The size of the codebook is 32. One can see that the proposed scheme saves considerable number of feedback bits and significantly increases the success rate of the user paring. That is why our scheme achieves a much better performance than the existing schemes. In other words, the proposed scheme outperforms the JS-IC scheme in terms of the number of successful user pairs, i.e., the proposed scheme has more degrees of freedom of user pairing, and has a reduced feedback overhead.

6 Conclusions

In this paper, an area-classified interference coordination strategy was first proposed for heterogeneous cellular networks. The basic principle was to classify the cell

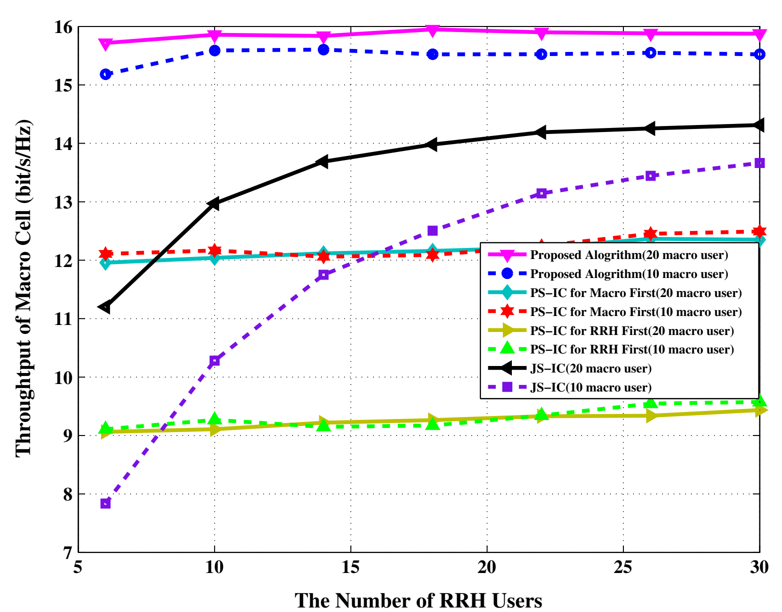

Figure 14 Macrocell throughput performance of the interference coordination schemes, $N_t^m = N_t^r = 4$.

Table 2 Feedback overhead comparison

Parameters	JS-IC	Proposed scheme (0.375, 0.18)
(θ, α)		$(-6, 29)$
The number of feedback bits	300	225
The number of matched user pairs	39	260

coverage into different areas and further perform area-specific interference coordination. A new steepest slope method based on relative cooperation gain was provided to realize efficient area classification. Following this idea, an area-classified coordinated beamforming scheme with limited feedback was further proposed for the HetNet. In this scheme, the proposed area-specific limited feedback scheme could increase the success rate of user pairing and thus improve the throughput performance, and with reduced feedback overhead in contrast to existing schemes. The effectiveness of the proposed method was finally verified with simulation results.

Endnote

[a]It is seen that in our scheme, two users are paired if any one of three conditions is satisfied, while in [20], the user pairing succeeds only if condition II is satisfied.

Competing interests
The authors declare that they have no competing interests.

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Author details
[1]School of Information Science and Engineering, Southeast University, Nanjing 210096, China. [2]Key Laboratory of Broadband Wireless Communication and Sensor Network Technology (Nanjing University of Posts and Telecommunications), Ministry of Education, Nanjing 210003, China. [3]NEC Laboratories China, Beijing 100084, China.

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References
1. V Chandrasekhar, J Andrews, A Gatherer, Femtocell networks: a survey. IEEE Commun. Mag. **46**(9), 59–67 (2008)
2. M Yavuz, F Meshkati, S Nanda, Interference management and performance analysis of UMTS/HSPA+ femtocells. IEEE Commun. Mag. **47**(9), 102–109 (2009)
3. SM Cheng, SY Lien, FS Chu, On exploiting cognitive radio to mitigate interference in macro/femto heterogeneous networks. IEEE Wireless Commun. **18**(3), 40–47 (2011)
4. A Damnjanovic, J Montojo, Y Wei, T Ji, T Luo, M Vajapeyam, T Yoo, O Song, D Malladi, A survey on 3GPP heterogeneous networks. IEEE Wireless Commun. **18**(3), 10–21 (2011)
5. D López-Pérez, I Güvenç, G Roche, M Kountouris, T Quek, J Zhang, Enhanced intercell interference coordination challenges in heterogeneous networks. IEEE Wireless Commun. **18**(3), 22–30 (2011)
6. J Sangiamwong, Y Saito, N Miki, T Abe, S Nagata, Y Okumura, Investigation on cell selection methods associated with inter-cell interference coordination in heterogeneous networks for LTE-advanced downlink, in *11th European Wireless Conference 2011 - Sustainable Wireless Technologies (European Wireless),* Vienna, 27–29 April 2011 (IEEE Piscataway, 2011), pp. 1–6
7. R Madanand, J Borran, A Sampath, N Bhushan, A Khandekar, TF Ji, Cell association and interference coordination in heterogeneous LTE-A cellular networks. IEEE J. Sel. Areas Commun. **28**(9), 1479–1489 (2010)
8. M Shakir, M Alouini, On the area spectral efficiency improvement of heterogeneous network by exploiting the integration of macro-femto cellular networks, in *IEEE International Conference on Communications (ICC),* Ottawa, 10–15 June 2012 (IEEE Piscataway, 2012), pp. 5695–5700
9. S Mukherjee, Distribution of downlink SINR in heterogeneous cellular networks. Selec. Areas Commun. IEEE J. **30**(3), 575–585 (2012)
10. P Li, Y Fang, On the throughput capacity of heterogeneous wireless networks. IEEE Trans. Mob. Comp. **11**(12), 2073–2086 (2012)
11. M Shirakabe, A Morimoto, N Miki, Performance evaluation of inter-cell interference coordination and cell range expansion in heterogeneous networks for LTE-Advanced downlink, in *International Symposium on Wireless Communication Systems,* Aachen, 6–9 Nov 2011 (IEEE Piscataway, 2011), pp. 844–848
12. I Güvenç, M Jeong, I Demirdogen, B Kecicioglu, F Watanabe, Range expansion and inter-cell interference coordination (ICIC) for picocell networks, in *IEEE Vehicular Technology Conference (VTC Fall),* San Francisco, 5–8 Sept 2011 (IEEE Piscataway, 2011), pp. 1–6
13. D López-Pérez, X Chu, I Güvenç, On the expanded region of picocells in heterogeneous networks. IEEE J. Sel. Sig. Proc. **6**(3), 281–294 (2012)
14. A Barbieri, A Damnjanovic, T Ji, J Montojo, Y Wei, D Malladi, O Song, G Horn, LTE femtocells: system design and performance analysis. IEEE J. Sel. Areas Commun. **30**(3), 586–594 (2012)
15. Y Huang, L Yang, J Liu, A limited feedback SDMA for downlink of multiuser MIMO communication system. EURASIP J. Adv. Signal Process. **2008**, 1–13 (2008)
16. Y Du, J Tong, J Zhang, S Liu, Evaluation of PMI feedback schemes for MU-MIMO pairing. IEEE Syst. J. **4**(4), 505–510 (2010)
17. J Zhang, JG Andrews, Adaptive spatial intercell interference cancellation in multicell wireless networks. IEEE J Sel Areas Commun. **28**(9), 1455–1468 (2010)
18. J Zhu, H Yang, Interference control with beamforming coordination for two-tier femtocell networks and its performance analysis, in *IEEE International Conference on Communications (ICC),* Kyoto, 5–9 June 2011, (2011), pp. 1–5
19. J Zhu, H Yang, Performance analysis of low-complexity dual-cell random beamforming transmission with user scheduling. EURASIP J. Wireless Commun. Netw. **2011**, 191 (2011)
20. Y Dai, S Jin, L Jiang, X Gao, M Lei, A PMI feedback scheme for downlink multi-user MIMO based on dual-codebook of LTE-advanced, in *IEEE Vehicular Technology Conference (VTC Fall),* Quebec City, 3–6 Sept 2012 (IEEE Piscataway, 2012), pp. 1–5
21. Y Huang, B Rao, An analytical framework for heterogeneous partial feedback design in heterogeneous multicell OFDMA networks. IEEE Trans. Sig. Proc. **61**(3), 753–769 (2013)
22. Y Huang, B Rao, Performance analysis of heterogeneous feedback design in an OFDMA downlink with partial and imperfect feedback. IEEE Trans. Sig. Proc. **61**(4), 1033–1046 (2013)
23. M Maso, M Debbah, L Vangelista, Cognitive interference alignment for OFDM two-tiered networks, in *International Workshop on Signal Processing Advances in Wireless Communications,* Cesme, 17–20 June 2012 (IEEE Piscataway, 2012), pp. 244–248
24. SK Sharma, S Chatzinotas, B Ottersten, Interference alignment for spectral coexistence of heterogeneous networks. EURASIP J. Wireless Commun. Netw. **2013**, 46 (2013)
25. Q Li, G Wu, Intracell cooperation and resource allocation in a heterogeneous network with relays. IEEE Trans. Veh. Tech. **62**(4), 1770–1784 (2013)
26. Y Huang, G Zheng, M Bengtsson, K-K Wong, L Yang, B Ottersten, Distributed multicell beamforming design approaching pareto boundary with max-min fairness. IEEE Trans. Wireless Commun. **11**(8), 2921–2933 (2012)

27. S He, Y Huang, L Yang, A Nallanathan, P Liu, A Multi-cell beamforming design by uplink-downlink max-min SINR duality. IEEE Trans. Wireless Commun. **11**(8), 2858–2867 (2012)
28. Y Huang, G Zheng, M Bengtsson, K-K Wong, L Yang, B Ottersten, Distributed multicell beamforming design with limited intercell coordination. IEEE Trans. Sig. Proc. **59**(2), 728–738 (2011)
29. D Xu, Y Huang, L Yang, Feedback of downlink channel state information based on superimposed coding. IEEE Commun. Lett. **11**(3), 240–242 (2007)
30. Y Huang, L Yang, M Bengtsson, B Ottersten, Exploiting long-term channel correlation in limited feedback SDMA through channel phase codebook. IEEE Trans Signal Process. **59**(3), 1217–1228 (2011)
31. 3GPP R1-083759, R1-084141, R1-090051, R1-090777, UE PMI feedback signalling for user pairing coordination. 3GPP TSG RAN WG1 56, (Alcatel-Lucent, 2009) http://www.3gpp.org/ftp/tsg_ran/wg1_rl1/TSGR1_54b/Docs/. Accessed 16 May 2010
32. 3GPP R1-090926, R1-091307, R1-092031, R1-092546, R1-093333, Best companion reporting for improved single-cell MU-MIMO pairing. 3GPP TSG RAN WG1 56, (Alcatel-Lucent, 2009) http://www.3gpp.org/ftp/tsg_ran/wg1_rl1/TSGR1_54b/Docs/. Accessed 16 May 2010
33. 3GPP TR25.996 v.8.0.0 Release 8, Spatial channel model for multiple input multiple output (MIMO) simulations. (3GPP Technical report, 2009). http://www.3gpp.org/ftp/tsg_ran/wg1_rl1/TSGR1_54b/Docs/. Accessed 16 May 2010

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