Expansion of Cell Range with Geometric Information of Pico-Cell for Maximum Sum Rate in Heterogeneous Networks

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Abstract. *In this paper, taking the positions of pico-cell base stations (PBSs) into consideration, a scheme of cell range expansion (CRE) for maximum sum rate is addressed in heterogeneous multi-input multi-output multi-user wireless networks. The optimal CRE bias obtained numerically by the proposed CRE scheme with inter-cell interference coordination (ICIC) allows us to maximize the sum rate while successfully maintaining the load balance between the macro-cell base station and PBSs. Numerical results confirm that the proposed CRE scheme with ICIC can provide higher sum rate than conventional schemes and balanced load.*

Keywords

Cell range expansion (CRE), heterogeneous network, interference coordination, multi-input multi-output multi-user (MIMO-MU) system

1. Introduction

Consisting of macro-cells overlaid by smaller cells such as micro-cells, femto-cells, and pico-cells, heterogeneous networks have been proposed as a breakthrough for an efficient deployment of base stations (BSs) in space and spectrum [1], [2]. One of the advantages of heterogeneous networks is the reduced burden of macro-cell base stations (MBSs) with the smaller cells incorporated, leading to a highly efficient network design. On the other hand, since various types of BSs are incorporated, the network planning, resource allocation design, and interference management may become more complicated. Apparently, various aspects of the heterogeneous networks have been investigated including cell assignment strategy [3], [4], power control schemes [5], coverage area [6–8], stochastic geometry models [9], [10], and cell range expansion [11].

Unlike in homogeneous networks, in which the BS that provides the highest downlink signal power is selected as the serving BS, the variety of level of power for various BSs should be taken into account in heterogeneous networks. Specifically, since the transmission power of a pico-cell BS (PBS) is lower than that of the MBS, most users would choose the MBS instead of a PBS as the serving BS, which naturally leads to load unbalance among the BSs. Addressing this problem, the scheme proposed in [11] expands the cell range by imposing a bias to the reference signal received power (RSRP) from the PBS, consequently making some macro-cell users be offloaded to a pico-cell.

Although the cell range expansion (CRE) improves the performance (i.e., overall sum rate) of the heterogeneous network, CRE users (that is, users offloaded to pico-cells) suffer from high inter-cell interference (ICI) from the MBS. To avoid the decrease in the overall sum rate of the system resulting from the high ICI, the MBS normally employs inter-cell interference coordination (ICIC) with the CRE [11], [12]. Among the typical research on CRE are capacity and fairness analysis [13], resource partitioning [14], adaptive CRE bias control [15], cell association [16], and offloading performance [17]. In addition, an algorithm that allows each user to determine CRE bias value to lower the number of outage users is proposed in [18]. The CRE method in [19] optimizes the parameters by evaluating the average throughput of the cell-edge users as well as the other users. The optimal CRE bias value for various density of small cell clusters in the coverage area of the macro-cell has been analyzed in [20]. Adaptive CRE schemes have also been proposed taking into account varying load among the MBS and PBSs [21] and overall capacity [22].

In this paper, we propose a CRE scheme in which the positions of PBSs are taken into account for the determination of the CRE bias, which have not been considered in other research of the CRE. In the proposed CRE scheme, the CRE bias, as a function of the PBS location, is determined to max-

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imize the overall sum rate of the system. Through simulation results, we have shown that the proposed CRE scheme with ICIC has better overall performance and more balanced load among BSs than the conventional schemes.

The rest of this paper is organized as follows. After a description of the system model assumed in this paper, the problem is formulated in Sec. 2. Section 3 provides some results from numerical simulations and performance analysis. Section 4 concludes this paper.

2. System Model and Problem Formulation

Consider the downlink of a heterogeneous network in a multi-input multi-output multi-user (MIMO-MU) system. We assume that the heterogeneous network is composed of one macro-cell overlaid by C_{P} pico-cells, where the MBS and each of the C_{P} PBSs are equipped with N_{M} and N_{P} antennas, respectively, with $N_{\mathrm{M}} > N_{\mathrm{P}}$. It is also assumed that the users, each equipped with a single antenna, are uniformly distributed over the cell.

Let the transmit power of the MBS and each of the C_{P} PBSs be P_{M} and P_{P}, respectively, with $P_{\mathrm{M}} > P_{\mathrm{P}}$, and denote by α_{M} and α_{P} the pathloss exponents of the macro-cells and pico-cells, respectively. Assuming simplified pathloss model, the RSRP from the MBS and a PBS can be expressed as $P_{\mathrm{M}}\tilde{d}_{\mathrm{M}}^{-\alpha_{\mathrm{M}}}$ and $P_{\mathrm{P}}\tilde{d}_{\mathrm{P}}^{-\alpha_{\mathrm{P}}}$, respectively, where $\tilde{d}_{\mathrm{M}}$ and $\tilde{d}_{\mathrm{P}}$ are the distances between a user and the MBS and PBS, respectively.

2.1 Expansion of Pico-Cell Range in Heterogeneous Network

We will denote the BS of the kth cell and the ith user in the jth cell by BS-k and User-(i, j), respectively: Here, without loss of generality, we assume that the zero-th cell is the macro-cell and the first, second, $\ldots$, C_{P}-th cells are pico-cells. In addition, by Situations A and B, we denote the cases in which the MBS does not and does, respectively, incorporate ICIC via zero-forcing for users in pico-cells: In any of the two situations, no PBS performs ICIC.

The serving BS, to which a user reports the channel state information (CSI) and through which the user transmits and receives the information signal, of a user is determined by comparing the RSRP from BSs. Specifically, without CRE, the serving BS of user i will be BS-$k(i)$ when

$$k(i) = \arg\max_{j} \ \mathrm{RSRP}_{i,j} \tag{1}$$

is satisfied, where

$$\mathrm{RSRP}_{i,j} = \begin{cases} P_{\mathrm{P}}\tilde{d}_{i,j}^{-\alpha_{\mathrm{P}}}, & \text{if BS-}j \text{ is a PBS,} \\ P_{\mathrm{M}}\tilde{d}_{i,j}^{-\alpha_{\mathrm{M}}}, & \text{if BS-}j \text{ is the MBS} \end{cases} \tag{2}$$

denotes the RSRP of the ith user from BS-j with $\tilde{d}_{i,j}$ the distance between the ith user and BS-j.

Now, consider a CRE scheme with which the serving BS of the i-th user is determined by

$$k(i) = \arg\max_{j} \left\{ b_j \, \mathrm{RSRP}_{i,j} \right\}, \tag{3}$$

where

$$b_j = \begin{cases} b, & \text{if BS } j \text{ is a PBS,} \\ 1, & \text{if BS } j \text{ is the MBS} \end{cases} \tag{4}$$

is the bias with $b \geq 1$. Equation (3) basically implies that we have now expanded the cell ranges of pico-cells. Clearly, when the ranges of pico-cells are expanded, some users in the macro-cell will be offloaded to a pico-cell.

Once the serving BS for every user is determined, the received signals $y_{i,0,S}$ and $\left\{y_{i,j,S}\right\}_{j=1}^{C_{\mathrm{P}}}$ of users in the macro- and pico-cells, respectively, under Situation S can be expressed as

$$\begin{aligned} y_{i,0,S} = {} & \sqrt{\frac{P_{\mathrm{M}}}{U_{\mathrm{M}}} d_{i,0,0}^{-\alpha_{\mathrm{M}}}} \\ & \times \left\{ \boldsymbol{h}_{i,0,0}^{*} \boldsymbol{f}_{i,0,S} x_{i,0} + \underbrace{\sum_{m=1,\ m\neq i}^{U_{\mathrm{M}}} \boldsymbol{h}_{i,0,0}^{*} \boldsymbol{f}_{m,0,S} x_{m,0}}_{\text{intra-cell interference}} \right\} \\ & + \underbrace{\sum_{k=1}^{C_{\mathrm{P}}} \sum_{p=1}^{U_{P_k}} \sqrt{\frac{P_{\mathrm{P}}}{U_{P_k}} d_{i,0,k}^{-\alpha_{\mathrm{P}}}} \boldsymbol{h}_{i,0,k}^{*} \boldsymbol{f}_{p,k,S} x_{p,k}}_{\text{inter-cell interference}} + z_{i,0} \end{aligned} \tag{5}$$

and

$$\begin{aligned} y_{i,j,S} = {} & \sqrt{\frac{P_{\mathrm{P}}}{U_{P_j}} d_{i,j,j}^{-\alpha_{\mathrm{P}}}} \\ & \times \left\{ \boldsymbol{h}_{i,j,j}^{*} \boldsymbol{f}_{i,j,S} x_{i,j} + \underbrace{\sum_{p=1,\ p\neq i}^{U_{\mathrm{P}_j}} \boldsymbol{h}_{i,j,j}^{*} \boldsymbol{f}_{p,j,S} x_{p,j}}_{\text{intra-cell interference}} \right\} \\ & + \underbrace{\sum_{m=1}^{U_{\mathrm{M}}} \sqrt{\frac{P_{\mathrm{M}}}{U_{\mathrm{M}}} d_{i,j,0}^{-\alpha_{\mathrm{M}}}} \boldsymbol{h}_{i,j,0}^{*} \boldsymbol{f}_{m,0,S} x_{m,0} + \sum_{k=1,\ k\neq j}^{C_{\mathrm{P}}} \sum_{p=1}^{U_{\mathrm{P}k}} \sqrt{\frac{P_{\mathrm{P}}}{U_{\mathrm{P}k}} d_{i,j,k}^{-\alpha_{\mathrm{M}}}} \boldsymbol{h}_{i,j,k}^{*} \boldsymbol{f}_{p,k,S} x_{p,k}}_{\text{inter-cell interference}} \\ & + z_{i,j} \end{aligned} \tag{6}$$

for $j = 1, 2, \ldots, C_{\mathrm{P}}$, where $S \in \{\mathrm{A}, \mathrm{B}\}$ is the set of the two situations we consider; U_{M} and U_{P_k} for $k = 1, 2, \ldots, C_{\mathrm{P}}$ are the numbers of users in the macro- and k-th pico-cells, respectively; $d_{i,j,k}$ is the distance between User-(i, j) and BS-k; $\boldsymbol{f}_{i,j,S}$ is the precoder of User-(i, j) under Situation S; $\boldsymbol{h}_{i,j,k}$ is the channel constant between User-(i, j) and BS-k and is modeled as a zero-mean uncorrelated fading with unit variance and Rayleigh-distributed envelope; $x_{i,j}$ is the desired signal for User-(i, j) with power constraint $E\left[\left|x_{i,j}\right|^2\right] = 1$; and $z_{i,j}$ is the complex Gaussian noise for User-(i, j). In passing, let us note that the precoder $\boldsymbol{f}_{i,j,S}$ is of size $N_\mathrm{M} \times 1$ when $j = 0$ and $N_\mathrm{P} \times 1$ when $j = 1, 2, \ldots, C_\mathrm{P}$ with $\left\|\boldsymbol{f}_{i,j,S}\right\|^2 = 1$ and that the channel constant $\boldsymbol{h}_{i,j,k}$ is of size $N_\mathrm{M} \times 1$ for $k = 0$ and $N_\mathrm{P} \times 1$ for $k = 1, 2, \ldots, C_\mathrm{P}$. It should be noted that the received signals $y_{i,0,S}$ and $\left\{y_{i,j,S}\right\}_{j=1}^{C_\mathrm{P}}$ are functions of the bias b although we have not shown the dependence explicitly for a brevity reason.

Clearly, macro-cell users would suffer intra-cell interference from the MBS and ICI from the PBSs. Similarly, pico-cell users would suffer intra-cell interference from the serving PBS and ICI from the MBS and other PBSs. Now, since the transmit power of the MBS is normally much higher than that of the PBSs, pico-cell users, especially the CRE users, suffer high ICI from the MBS. To alleviate the influence of such interference, we employ precoders at the BSs. Specifically, the precoders used in the BSs can be expressed as

$$\boldsymbol{f}_{i,0,\mathrm{A}} = \frac{\boldsymbol{h}_{i,0,0}}{\left\|\boldsymbol{h}_{i,0,0}\right\|} \tag{7}$$

for $i = 1, 2, \ldots, U_\mathrm{M}$ and

$$\boldsymbol{f}_{i,j,\mathrm{A}} = \frac{\boldsymbol{h}_{i,j,j}}{\left\|\boldsymbol{h}_{i,j,j}\right\|} \tag{8}$$

for $i = 1, 2, \ldots, U_{\mathrm{P}_j}$ and $j = 1, 2, \ldots, C_\mathrm{P}$ under Situation A, and

$$\boldsymbol{f}_{i,0,\mathrm{B}} = \frac{\left\{\boldsymbol{I}_{N_\mathrm{M}} - \boldsymbol{H}\left(\boldsymbol{H}^*\boldsymbol{H}\right)^{-1}\boldsymbol{H}^*\right\}\boldsymbol{h}_{i,0,0}}{\left\|\left\{\boldsymbol{I}_{N_\mathrm{M}} - \boldsymbol{H}\left(\boldsymbol{H}^*\boldsymbol{H}\right)^{-1}\boldsymbol{H}^*\right\}\boldsymbol{h}_{i,0,0}\right\|} \tag{9}$$

for $i = 1, 2, \ldots, U_\mathrm{M}$ and

$$\boldsymbol{f}_{i,j,\mathrm{B}} = \boldsymbol{f}_{i,j,\mathrm{A}} \tag{10}$$

for $i = 1, 2, \ldots, U_{\mathrm{P}_j}$ and $j = 1, 2, \ldots, C_\mathrm{P}$ under Situation B. Here, $\|\ \|$, $\boldsymbol{I}_n$, and the superscript * denote the Euclidean norm, $n \times n$ identity matrix, and complex conjugate transpose, respectively, and the matrix

$$\boldsymbol{H} = \left[\boldsymbol{H}_1\ \boldsymbol{H}_2\ \ldots\ \boldsymbol{H}_{C_\mathrm{P}}\right] \tag{11}$$

of the channel constants is of size $N_\mathrm{M} \times U_\mathrm{P}$ with $\boldsymbol{H}_j = \left[\boldsymbol{h}_{1,j,0}\ \boldsymbol{h}_{2,j,0}\ \ldots\ \boldsymbol{h}_{U_{\mathrm{P}_j},j,0}\right]$ and $U_\mathrm{P} = \sum_{k=1}^{C_\mathrm{P}} U_{\mathrm{P}_k}$ the total number of users in the C_P pico-cells.

Equations (7) and (8) indicate that the MBS and PBSs both employ eigen-beamforming for their own users with no ICIC in Situation A. In Situation B on the other hand, as implied in (9) and (10), the MBS employs zero-forcing in order to reduce the interference toward the users in the pico-cells [23] while the PBSs still exploit eigen-beamforming. Here, the MBS normally exploits many antennas and high transmission power and thus the performance degradation of the macro-cell users due to the ICIC via zero-forcing would be, if not negligible, small while the ICIC would allow significant performance enhancement for pico-cell users. On the other hand, as the PBS has less antennas and lower transmission power, performance degradation of the pico-cell users would be severe if the PBS performed ICIC via zero-forcing. This is why only MBS performs ICIC and the PBS exploits eigen-beamforming regardless of the situation.

The signal to interference plus noise ratio (SINR) can now be expressed as

$$\mathrm{SINR}_{i,0,S} = \frac{P_\mathrm{M} d_{i,0,0}^{-\alpha_\mathrm{M}} \left|\boldsymbol{h}_{i,0,0}^* \boldsymbol{f}_{i,0,S}\right|^2}{U_\mathrm{M}\left(N_0 W + I_{i,0,S}\right)} \tag{12}$$

for macro-cell users and

$$\mathrm{SINR}_{i,j,S} = \frac{P_\mathrm{P} d_{i,j,j}^{-\alpha_\mathrm{P}} \left|\boldsymbol{h}_{i,j,j}^* \boldsymbol{f}_{i,j,S}\right|^2}{U_{\mathrm{P}_j}\left(N_0 W + I_{i,j,S}\right)} \tag{13}$$

for pico-cell users, where W is the system bandwidth, N_0 is the noise power per unit bandwidth, and

$$\begin{aligned} I_{i,0,S} = & \sum_{m=1,\ m\neq i}^{U_\mathrm{M}} \frac{P_\mathrm{M}}{U_\mathrm{M}} d_{i,0,0}^{-\alpha_\mathrm{M}} \left|\boldsymbol{h}_{i,0,0}^* \boldsymbol{f}_{m,0,S}\right|^2 \\ & + \sum_{k=1}^{C_\mathrm{P}} \sum_{p=1}^{U_{\mathrm{P}k}} \frac{P_\mathrm{P}}{U_{\mathrm{P}k}} d_{i,0,k}^{-\alpha_\mathrm{P}} \left|\boldsymbol{h}_{i,0,k}^* \boldsymbol{f}_{p,k,S}\right|^2 \end{aligned} \tag{14}$$

and

$$\begin{aligned} I_{i,j,S} = & \sum_{m=1}^{U_\mathrm{M}} \frac{P_\mathrm{M}}{U_\mathrm{M}} d_{i,j,0}^{-\alpha_\mathrm{M}} \left|\boldsymbol{h}_{i,j,0}^* \boldsymbol{f}_{m,0,S}\right|^2 \\ & + \sum_{p=1,\ p\neq i}^{U_\mathrm{P}} \frac{P_\mathrm{P}}{U_\mathrm{P}} d_{i,j,j}^{-\alpha_\mathrm{P}} \left|\boldsymbol{h}_{i,j,j}^* \boldsymbol{f}_{p,j,S}\right|^2 \\ & + \sum_{k=1,\ k\neq j}^{C_\mathrm{P}} \sum_{p=1}^{U_{\mathrm{P}k}} \frac{P_\mathrm{P}}{U_{\mathrm{P}k}} d_{i,j,k}^{-\alpha_\mathrm{P}} \left|\boldsymbol{h}_{i,j,k}^* \boldsymbol{f}_{p,k,S}\right|^2 \end{aligned} \tag{15}$$

denote the total interference in the macro- and pico-cells, respectively. When the MBS incorporates the ICIC, the ICI term (that is, the first term in the right-hand side) of (15) will vanish. Note that, when we have only one PBS, the last term of (15) will be zero.

Eventually, we try to find the optimal CRE bias value

$$b^* = \arg\max_b \sum_j \sum_i \mathrm{Rate}_{i,j,S} \tag{16}$$

for which the sum rate of overall system is maximized, where

$$\mathrm{Rate}_{i,j,S} = W \log_2\left(1 + \mathrm{SINR}_{i,j,S}\right) \tag{17}$$

is the achievable rate for User-(i, j) under Situation S. As we shall see shortly, the overall sum rate first increases and then decreases as the value b of the CRE bias increases.

2.2 Two Examples of Heterogeneous Networks

One PBS (1-PBS) model: The simplest case of heterogeneous networks with one macro-cell and one pico-cell ($C_P = 1$) is shown in Fig. 1. The two small circles of solid and dash-dot lines indicate the ranges of the pico-cell without and with the CRE, respectively. The solid and dotted arrows indicate desired (information data) signal and ICI, respectively, with the CRE. The user between the two small circles is the CRE user, offloaded to the PBS, and would suffer high ICI from the MBS.

Three PBS (3-PBS) model: Figure 2 shows the heterogeneous network with one macro-cell and three pico-cells. It is easy to see that the ICI will be higher with more PBSs as we have already observed in, for example, (6) and (15).

3. Numerical Results and Analysis

Let us now consider some simulation results, for which the simulation parameters in the 1-PBS model are shown in Tab. 1. Here, the values of the transmit power of the BSs and the pathloss exponents of the macro- and pico-cells are adopted from those employed in [24]. It is assumed that the transmit power of a BS is equally distributed to its users: Thus, the power received by each user is determined by the type of its serving BS and the number of users dwelling in the same cell. The maximum value of the CRE bias is set to 12 dB, at which the coverage area of a pico-cell becomes almost the same as that of the macro-cell. For the 3-PBS model, we have in addition assumed the minimum distance between two PBSs to be 100 m.

Since the number of users serviced simultaneously is upper-limited by the number of antennas of the MBS, we assume that the total number of users in the heterogeneous network is 8 for simplicity. When the number of users in a pico-cell reaches the number 4 of antennas of the PBS, no additional macro-cell user will be offloaded even when the pico-cell range is expanded with the CRE. Note that the minimum and maximum distances between BSs are considered to avoid the cases in which the PBS is too close to the MBS or to the boundary of the macro-cell: In both cases, the coverage area of the PBS would become too small.

Without loss of generality, we assume that the MBS and PBS are located at $(0,0)$ and $(x_P, 0)$, respectively, on the x-axis in the 1-PBS model, with two additional PBSs at $\left(x_P \cos\frac{2\pi}{3},\ \pm x_P \sin\frac{2\pi}{3}\right)$ in the 3-PBS model on a two-dimensional plane.

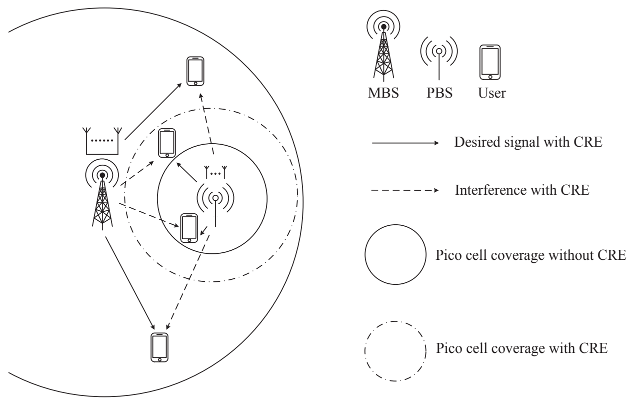

Fig. 1. Heterogeneous network: 1-PBS model.

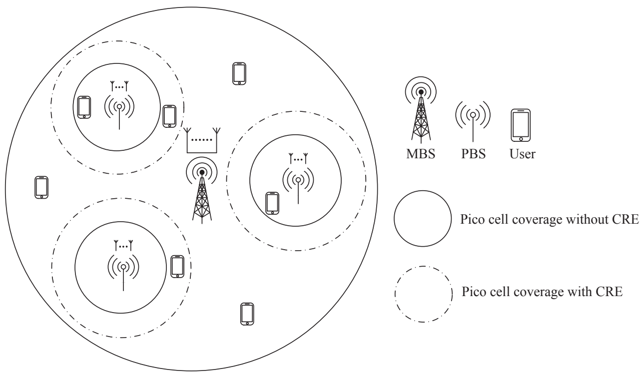

Fig. 2. Heterogeneous network: 3-PBS model.

	Macro-cell	Pico-cell
Number of antennas	$N_M = 8$	$N_P = 4$
Transmit power	$P_M = 46$ dBm	$P_P = 30$ dBm
Pathloss exponent	$\alpha_M = 3.76$	$\alpha_P = 3.67$
Total number of users	8	
Macro-cell radius	1000 m	
Minimum distance between MBS and PBS	200 m	
Maximum distance between MBS and PBS	800 m	
CRE bias range	$0 \sim 12$ dB	
Noise power per bandwidth	$N_0 = -174$ dBm/Hz	
System bandwidth	$W = 10$ MHz	

Tab. 1. Values of parameters used in simulation.

3.1 Bias and Sum Rate

Figures 3 and 4 show the sum rate as a function of the bias of the proposed CRE scheme in the 1-PBS and 3-PBS models, respectively, when the distance between the MBS and PBS is 200, 500, and 800 m. Clearly, it is confirmed that the proposed CRE scheme increases the overall sum rate of the system when the ICIC is applied: Such increase of overall sum rate has been observed, for example, in [25], [26] also. It is observed that, as the PBS is located closer to the MBS, the sum rate varies more with the CRE bias. It should be noted that, at each location of the PBS, there exists an optimal value of the CRE bias maximizing the sum rate and that the optimal value is dependent on the distance between the MBS and PBS.

Figures 5 and 6 show the sum rate with the proposed CRE scheme as a function of the distance between the MBS and PBS at several values of the CRE bias.

It is again observed that the ICIC increases the sum rate at any value of the CRE bias irrespective of the PBS position. It is also observed that the increase of the sum rate with the optimum CRE bias is more considerable with the ICIC. For example, consider the sum rate when the PBS is 200 m from the MBS in Fig. 5. The sum rate with the CRE bias of 0 dB is slightly over 95 Mbps and that with the optimum bias is less than 100 Mbps, implying that the optimum CRE provides us with an increase of about 5 Mbps in the sum rate. On the other hand, with the ICIC applied, the sum rate with the CRE bias of 0 dB is around 110 Mbps and that with the optimum bias is around 160 Mbps. In essence, the increase in the sum rate with the ICIC is around 50 Mbps.

From the comparison of the results in Figs. 5 and 6, we may conclude that the sum rate in the 3-PBS model is generally higher than that in the 1-PBS model. We believe this is due to the fact that, although the interference would also be increased, more PBSs in a fixed space imply more antennas and higher transmit power in addition to decreased average distance between the user and BS, resulting in increased average received power for users.

Figures 7 and 8 show the optimal CRE bias that induces the maximum sum rate as a function of the distance between the MBS and PBS. The optimal CRE bias tends to decreases when the distance between the MBS and PBS increases. This is due to the increase of the coverage area of the PBS.

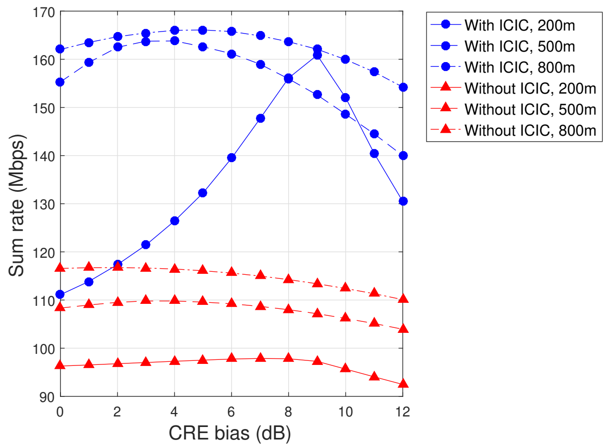

Fig. 3. Sum rate when the distance between the MBS and PBS is 200, 500, and 800 m in the 1-PBS model.

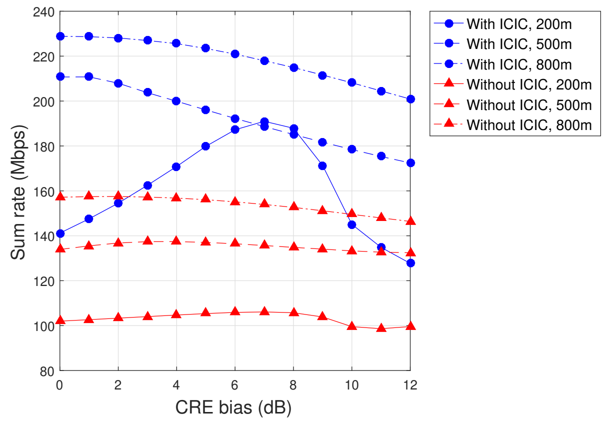

Fig. 4. Sum rate when the distance between the MBS and a PBS is 200, 500, and 800 m in the 3-PBS model.

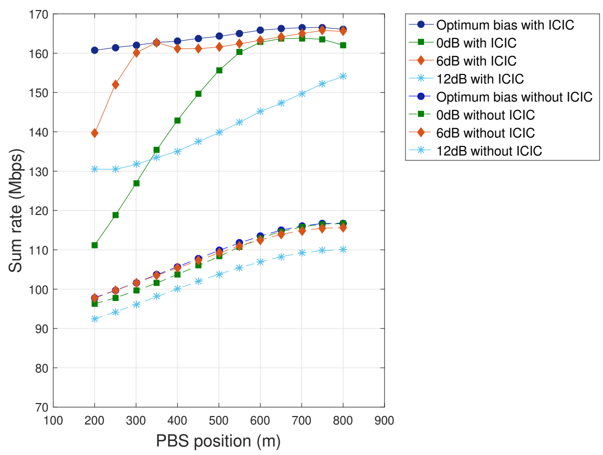

Fig. 5. Sum rate when the distance between the MBS and PBS varies from 200 to 800 m in the 1-PBS model.

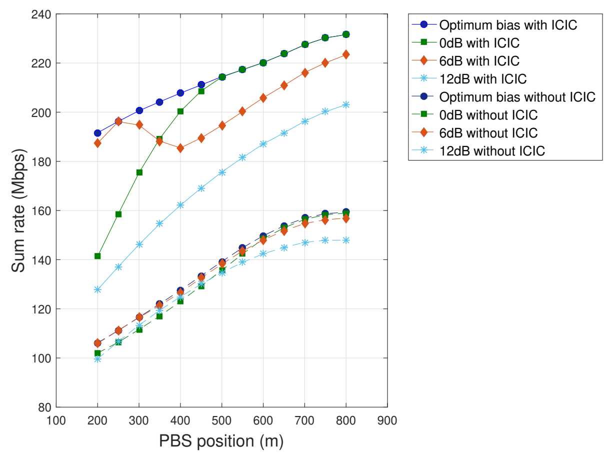

Fig. 6. Sum rate when the distance between the MBS and PBS varies from 200 to 800 m in the 3-PBS model.

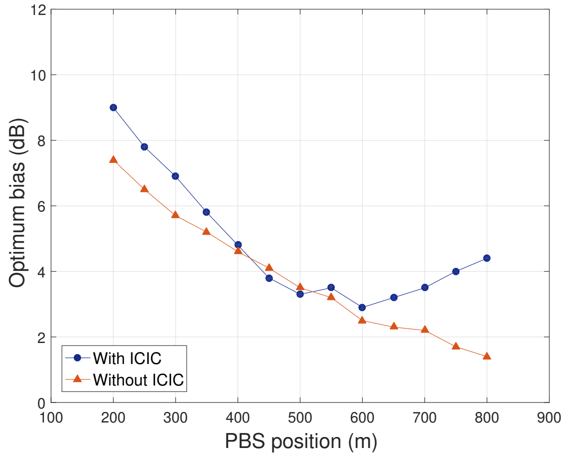

Fig. 7. Optimum CRE bias value versus the distance between the MBS and PBS in the 1-PBS model.

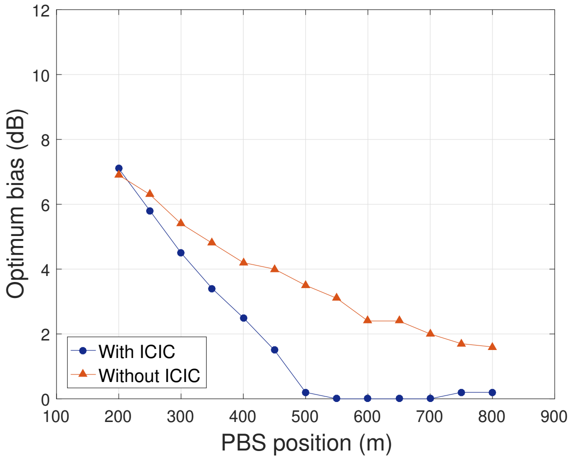

Fig. 8. Optimum CRE bias value versus the distance between the MBS and a PBS in the 3-PBS model.

3.2 Coverage Area

The boundary of the pico-cell can be expressed as

$$P_{\mathrm{M}}\left(x^2+y^2\right)^{-\frac{\alpha_{\mathrm{M}}}{2}} = P_{\mathrm{P}}\left\{(x-x_{\mathrm{P}})^2+y^2\right\}^{-\frac{\alpha_{\mathrm{P}}}{2}}, \tag{18}$$

or equivalently as

$$\left\{(x-x_{\mathrm{P}})^2+y^2\right\}^{\alpha_{\mathrm{P}}} - \left(\frac{P_{\mathrm{P}}}{P_{\mathrm{M}}}\right)^2\left(x^2+y^2\right)^{\alpha_{\mathrm{M}}} = 0, \tag{19}$$

which can eventually be approximated as an ellipse under the assumption that the coverage area of the macro-cell is unbounded [7]: Some examples are shown in Figs. 9–11 for the 1-PBS model. In these figures, a user located at the positions of black and red dots represents a macro- and a pico-cell users, respectively.

Figure 12 shows the coverage areas of the PBS without any CRE, with the proposed CRE scheme only, and with the proposed CRE scheme plus ICIC, where 'proposed scheme' denotes the proposed CRE scheme with an optimum bias value. It is observed that the coverage area of the PBS increases with the proposed CRE scheme, and that the ICIC makes the coverage of PBS less dependent on the distance between the PBS and MBS.

Figure 13 shows the ratio of the coverage area with the proposed CRE scheme to that without a CRE scheme in decibel scale. Clearly, when the ICIC is employed with the proposed scheme, the ratio (denoted by blue circles) decreases and then increases slightly after a certain point as the PBS is located farther from the MBS. On the other hand, when the ICIC is not employed with the proposed scheme, the ratio (denoted by red triangles) decreases monotonically. It is interesting to note the resemblance between Figs. 7 and 13.

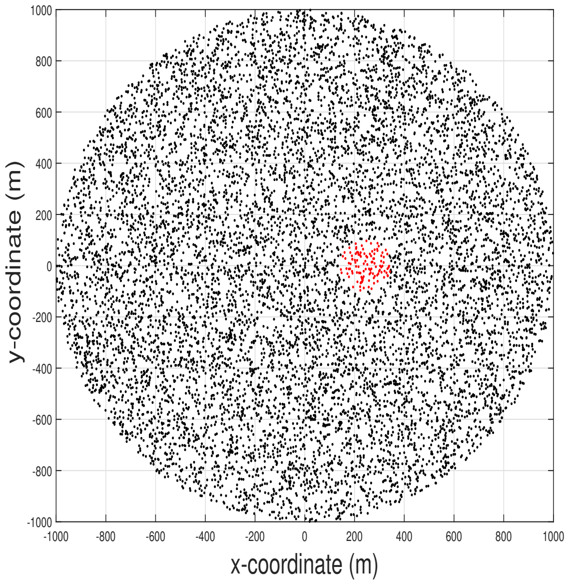

Fig. 9. Coverage areas of the MBS and PBS when the MBS and PBS are located at (0, 0) and (200, 0), respectively.

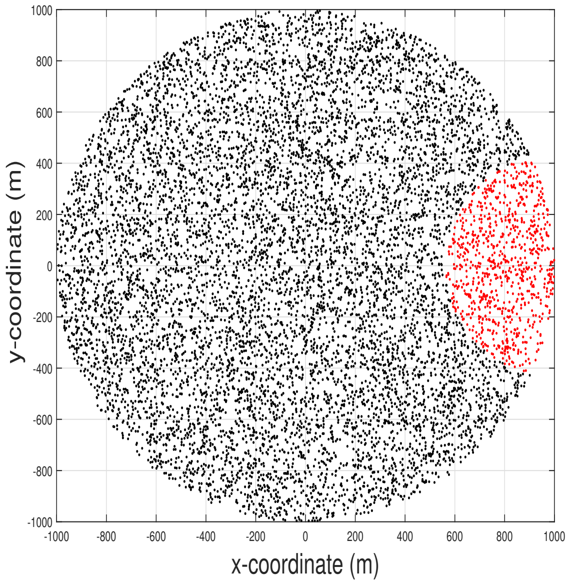

Fig. 10. Coverage areas of the MBS and PBS when the MBS and PBS are located at (0, 0) and (800, 0), respectively.

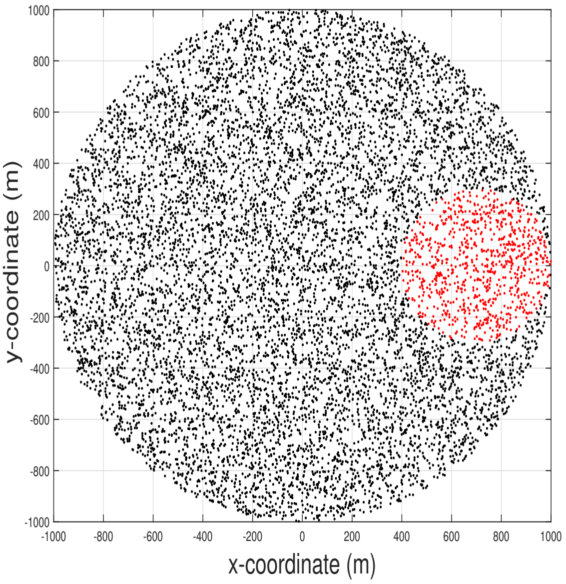

Fig. 11. Coverage areas of the MBS and PBS when the MBS and PBS are located at (0, 0) and (566, 0), respectively.

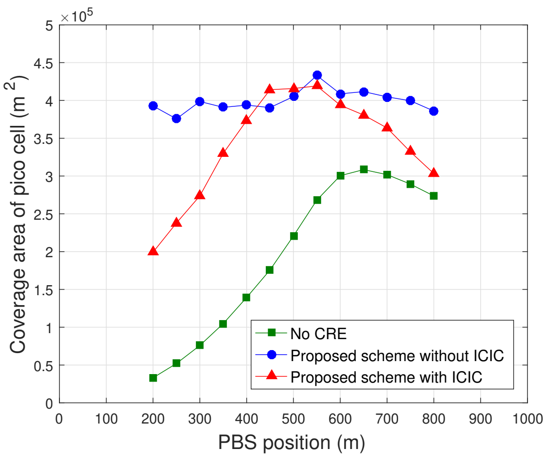

Fig. 12. Coverage area of the PBS with no CRE, with the proposed CRE only, and with the proposed CRE plus ICIC in the 1-PBS model.

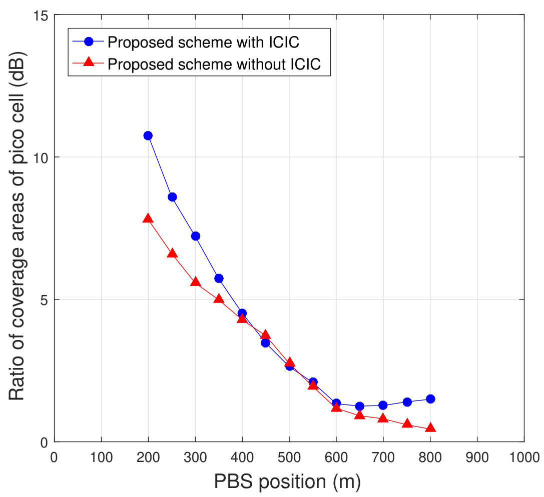

Fig. 13. Ratio of the coverage area with the proposed CRE to the coverage area without CRE in the 1-PBS model.

3.3 Offloading Performance

Figures 14 and 15 show the offloading performance of the proposed CRE scheme with optimum bias. It is clearly observed that the number of users in the pico-cell increases when the proposed CRE scheme is applied. Note also that the offloading performance (in terms of the ratio of the number of users in the pico-cell to the total number of users) with the proposed CRE scheme plus the ICIC is less sensitive to the distance between the MBS and PBS: 2 %–10 % versus 12 %–14 % and 3 %–29 % versus 17 %–29 %, in the 1- and 3-PBS models, respectively. In addition, it is confirmed that the ICIC in the proposed CRE scheme provides more balance in the loading performance: A possible observation is that the ICIC in the proposed CRE scheme reduces the influence of the distance between the MBS and PBS on the number of users in the pico-cell.

Figures 16 and 17 show the average rates of users in the 1- and 3-PBS models, respectively. Here, ‘Macro’ and ‘Pico’ in the legends represents average rate of a user in the macro- and pico-cells, respectively. From the results shown in these two figures we can make the following observations: (A) The average rates of users in the macro-cell do not change considerably with the proposed CRE scheme. (B) The variation, as the distance between the MBS and PBS changes, of the average rates of users in the pico-cell with the proposed CRE scheme is smaller than that without the proposed CRE scheme. (C) If the ICIC is employed in addition to the proposed CRE scheme, the average rates of users in the pico-cell increase significantly. In passing, let us note that, since the average rate of pico-cell users is much higher than that of macro-cell users, macro-cell users may complain about such unfairness: Finding a fairer CRE scheme would be an interesting research topic.

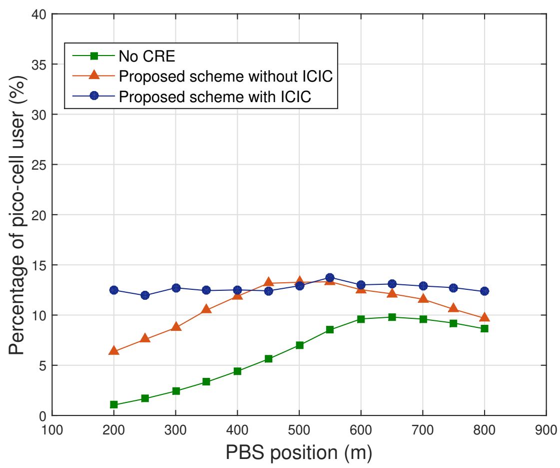

Fig. 14. Offloading performance of the proposed CRE scheme with optimum bias in the 1-PBS model.

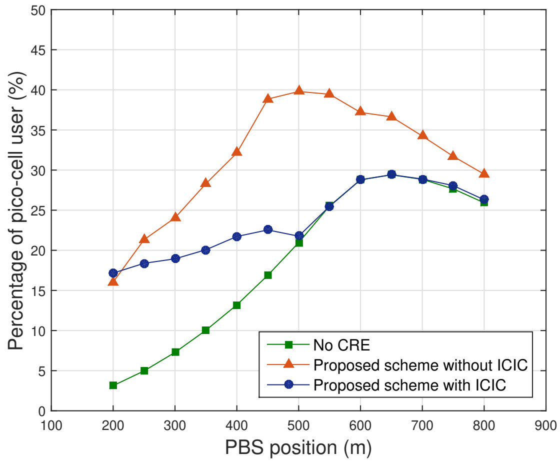

Fig. 15. Offloading performance of the proposed CRE scheme with optimum bias in the 3-PBS model.

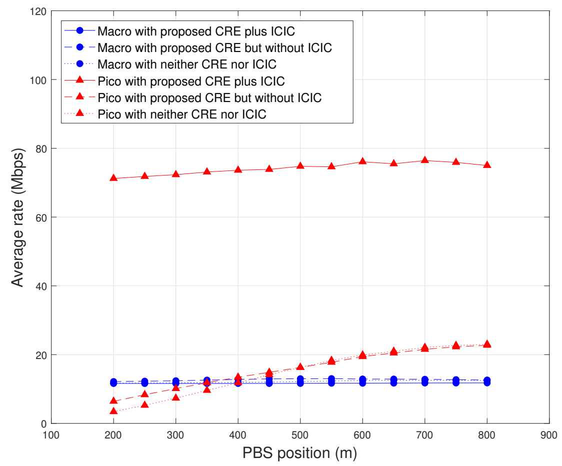

Fig. 16. Average rate of users in the 1-PBS model.

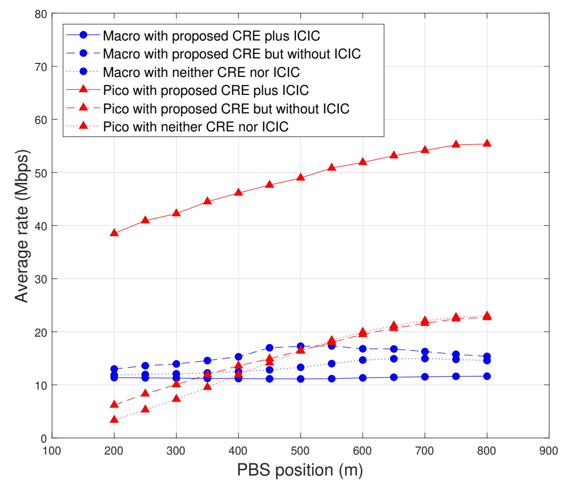

Fig. 17. Average rate of users in the 3-PBS model.

We would like to mention that the goal in this paper is to maximize the overall sum rate in the macro- and pico-cells, because of which the basic purpose (providing balance in the loading of the MBS and PBS while requiring some users intentionally to operate at lower SINR, or equivalently, increasing the capacity of the system) of CRE may be achieved only partially. It should also be noted that, while some users (those in the macro-cell after the CRE) can enjoy more favorable environment with the proposed CRE scheme, some of the other users (especially those originally in the pico-cell) may have to operate at lower SINR after the proposed CRE scheme is employed since the number of users in the pico-cell will tend to be larger than that before the CRE scheme is employed. This is common to all CRE schemes.

4. Concluding Remark

Heterogeneous networks have recently been proposed as an attractive solution to overcome the deficiency of invaluable spectrum resource. The scheme of CRE has been reported to be successful in overcoming the drawback of heterogeneous network and intensifying the merit of heterogeneous network. In heterogeneous networks, we have addressed in this paper a novel CRE scheme, in which the positions of pico base stations are taken into account for the determination of the bias. The proposed CRE scheme is shown to perform better when it is employed together with an inter-cell interference coordination scheme.

The optimal bias of the proposed CRE scheme is observed to depend on the relative position of PBSs to the MBS. We have presented simulation results in one-PBS and three-PBS models and confirmed that the sum rate is increased with the proposed CRE scheme. It is noteworthy that the optimal bias tends to decrease when PBSs are located farther from the MBS. In addition, the proposed CRE scheme with the optimal bias is shown to provide higher sum rate and more balanced load among base stations. Finding a sub-optimal value of the bias via a simpler method would be an interesting topic to pursue.

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