Cell Range Expansion with Geometric Information of Pico-Cell in Heterogeneous Networks

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Abstract—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 a higher sum rate than conventional schemes while maintaining balanced load.

I. INTRODUCTION

Consisting of macro-cells overlaid by smaller cells, heterogeneous networks have been proposed for an efficient deployment of base stations (BSs) in space and spectrum [1]. One of the advantages of heterogeneous networks is the reduced burden of macro-cell base stations (MBSs), leading to a highly efficient network design. Apparently, various aspects of heterogeneous networks have been investigated including cell assignment strategy [2], [3], stochastic geometry model [4], and cell range expansion [5].

In a heterogeneous network, the variety of levels of power for various BSs should be taken into account. 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 [5] 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 of a heterogeneous network, CRE users (users offloaded to a pico-cell) suffer from high inter-cell interference (ICI) from the MBS. To prevent the overall sum rate of the system from decreasing due to high ICI, the MBS normally employs inter-cell interference coordination (ICIC) with the CRE [5], [6]. In [7], a practical CRE user association method is proposed which leads to the maximization of downlink system throughput, and various user association methods in heterogeneous networks are discussed in [8]. The capacity and fairness of system is analyzed in [9] when the ICIC is applied, and a user association method is proposed in [10] by focusing on the outage probability of cell users. The Q-learning algorithm, in which each user determines the CRE bias value to minimize the outage probability, is addressed in [11].

In this paper, we propose a CRE scheme by taking the positions of PBSs into account in the determination of the CRE bias. The CRE bias in the proposed CRE scheme is determined, as a function of the PBS location, to maximize the overall sum rate of the system. Through simulation results, we have shown that the proposed CRE scheme with the ICIC has better performance and more balanced load among BSs than the conventional CRE schemes.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Consider the downlink heterogeneous network of a multi-input multi-output multi-user (MIMO-MU) system composed of one macro-cell overlaid by \( C_P \) pico-cells, where the MBS and each of the PBSs are equipped with \( N_M \) and \( N_P \) antennas, respectively, with \( N_M > N_P \).

Assume that the users, each equipped with a single antenna, are uniformly distributed over the cell. Let the transmit power of the MBS and each PBS be \( P_M \) and \( P_P \), respectively, with \( P_M > P_P \). We denote the pathloss exponents in the macro- and pico-cells by \( \alpha_M \) and \( \alpha_P \), respectively. Assuming a simplified pathloss model, the RSRP from the MBS and a PBS can be expressed as \( P_M d_M^{-\alpha_M} \) and \( P_P d_P^{-\alpha_P} \), respectively, where \( d_M \) and \( d_P \) are the distances between a user and the MBS and a PBS, respectively.

A. Expansion of pico-cell range in heterogeneous network

The serving BS 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

\[
k(i) = \arg \max_j \text{RSRP}_{i,j}
\]

is satisfied, where

\[
\text{RSRP}_{i,j} = \begin{cases} P_P d_{i,j}^{-\alpha_P}, & \text{if BS } j \text{ is a PBS}, \\ P_M d_{i,j}^{-\alpha_M}, & \text{if BS } j \text{ is the MBS} \end{cases}
\]

denotes the RSRP of the \( i \)-th user from the \( j \)-th BS with \( d_{i,j} \), the distance between the \( i \)-th user and the \( j \)-th BS.

Let us consider the CRE in which the serving BS of the \( i \)-th user is determined by

\[
k(i) = \arg \max_j \{ b_j \text{RSRP}_{i,j} \},
\]

where

\[
b_j = \frac{P_P d_{i,j}^{-\alpha_P}}{P_M d_{i,j}^{-\alpha_M}}
\]
where
\[
b_j = \begin{cases} 
0, & \text{if BS } j \text{ is a PBS,} \\
1, & \text{if BS } j \text{ is the MBS}
\end{cases}
\]
is the bias with \(b \geq 1\).

We will denote the BS of the \(k\)th cell and the \(i\)th user in the
\(j\)th cell by BS-\(k\) and User-\((i, j)\), respectively. 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. Without loss of generality, we assume that the zero-th cell is the macro-cell and the first, second, \(\cdots\), \(C_P\)-th cells are pico-cells.

Once the serving BS for every user is determined, the received signals \(y_{i,0,S}\) and \(y_{i,j,S}\) of users in the macro- and pico-cells, respectively, under situation \(S\) can be expressed as
\[
y_{i,0,S} = \sqrt{\frac{P_M}{U_M}} d_{i,0,0}^{-\alpha_M} \left\{ h_{i,0,0}^* f_{i,0,S} x_{i,0} + \sum_{m=1, m \neq i}^{U_M} h_{i,m,0}^* f_{m,0,S} x_{m,0} \right\} + \sum_{k=1}^{C_P} \sum_{p=1}^{U_P} \sqrt{\frac{P_P}{U_P}} d_{i,k,0}^{-\alpha_P} h_{i,k,0}^* f_{p,k,S} x_{p,k} + z_{i,0}
\]
and
\[
y_{i,j,S} = \sqrt{\frac{P_P}{U_P}} d_{i,j,j}^{-\alpha_P} \left\{ h_{i,j,j}^* f_{i,j,S} x_{i,j} + \sum_{p=1}^{U_P} h_{i,j,j}^* f_{p,j,S} x_{p,j} \right\} + \sum_{m=1}^{U_M} \sqrt{\frac{P_M}{U_M}} d_{i,j,0}^{-\alpha_M} h_{i,j,0}^* f_{m,0,S} x_{m,0} + \sum_{k=1}^{C_P} \sum_{p=1}^{U_P} \sqrt{\frac{P_P}{U_P}} d_{i,j,k}^{-\alpha_P} h_{i,j,k}^* f_{p,k,S} x_{p,k}
\]
\[
+ z_{i,j}
\]
for \(j = 1, 2, \cdots, C_P\), where \(S \in \{A, B\}\) is the set of the two situations we consider; \(U_M\) and \(U_P\) for \(k = 1, 2, \cdots, C_P\) are the numbers of the macro- and \(k\)-th pico-cells, respectively; \(d_{i,j,k}\) is the distance between User-\((i, j)\) and BS-\(k\); the precoder \(f_{i,j,S}\) of User-\((i, j)\) under situation \(S\) is of size \(N_M \times 1\) when \(S = 0\) and \(N_P \times 1\) when \(S = 1\); the channel constant \(h_{i,j,k}\) between User-\((i, j)\) and BS-\(k\) denotes the zero-mean uncorrelated fading 

with unit variance and Rayleigh-distributed envelope and is of size \(N_M \times 1\) for \(k = 0\) and \(N_P \times 1\) for \(k = 1, 2, \cdots, C_P\); \(x_{i,j}\) is the desired signal for User-\((i, j)\) with power constraint \(E[|x_{i,j}|^2] = 1\); and \(z_{i,j}\) is the complex Gaussian noise for User-\((i, j)\).

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
\[
f_{i,0,A} = h_{i,0,0} \left\| h_{i,0,0} \right\|
\]
for \(i = 1, 2, \cdots, U_M\) and
\[
f_{i,j,A} = h_{i,j,j} \left\| h_{i,j,j} \right\|
\]
for \(i = 1, 2, \cdots, U_P\) and \(j = 1, 2, \cdots, C_P\) under Situation A, and
\[
f_{i,0,B} = \left\{ I_{NM} - H (H^* H)^{-1} H^* \right\} h_{i,0,0} \left\| \left\{ I_{NM} - H (H^* H)^{-1} H^* \right\} h_{i,0,0} \right\|
\]
for \(i = 1, 2, \cdots, U_M\) and
\[
f_{i,j,B} = f_{i,j,A}
\]
for \(i = 1, 2, \cdots, U_P\) and \(j = 1, 2, \cdots, C_P\) under Situation B. Here, \(\| \| \), \(I_n\), and the superscript * denote the Euclidean norm, \(n \times n\) identity matrix, and complex conjugate transpose, respectively, and the matrix
\[
H = \begin{bmatrix} H_1 & H_2 & \cdots & H_{C_P} \end{bmatrix}
\]
onf of the channel constants is of size \(N_M \times U_P\) with \(H_j = [h_{1,j,0} \ h_{2,j,0} \ \cdots \ h_{U_P,j,0}]\) and \(U_P = \sum_{k=1}^{C_P} U_P\) the total number of users in the 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 [12] while the PBSs still exploit eigen-beamforming.

The signal to interference plus noise ratio (SINR) can now be expressed as
\[
\text{SINR}_{i,0,S} = \frac{P_M d_{i,0,0}^{-\alpha_M} \left\| h_{i,0,0}^* f_{i,0,S} \right\|^2}{U_M (N_0 W + I_{i,0,S})}
\]
for macro-cell users and
\[
\text{SINR}_{i,j,S} = \frac{P_P d_{i,j,j}^{-\alpha_P} \left\| h_{i,j,j}^* f_{i,j,S} \right\|^2}{U_P (N_0 W + I_{i,j,S})}
\]
for pico-cell users, where $W$ is the system bandwidth, $N_0$ is the noise power per unit bandwidth, and

$$I_{i,0,S} = \sum_{m=1, m \neq i}^{M} \frac{P_M}{U_M} d_{i,0,0}^{-\alpha_M} |h^*_{i,0,0} f_{m,0,S}|^2$$

$$+ \sum_{k=1}^{CP} \sum_{p=1}^{UP} \frac{P_P}{U_P} d_{i,0,k}^{-\alpha_P} |h^*_{i,0,k} f_{p,k,S}|^2$$

(14)

and

$$I_{i,j,S} = \sum_{m=1}^{M} \frac{P_M}{U_M} d_{i,j,0}^{-\alpha_M} |h^*_{i,j,0} f_{m,0,S}|^2$$

$$+ \frac{U_P}{P_P} \sum_{p=1, p \neq j}^{UP} \frac{P_P}{U_P} d_{i,j,p}^{-\alpha_P} |h^*_{i,j,p} f_{p,j,S}|^2$$

$$+ \sum_{k=1, k \neq j}^{CP} \sum_{p=1}^{UP} \frac{P_P}{U_P} d_{i,j,k}^{-\alpha_P} |h^*_{i,j,k} f_{p,k,S}|^2$$

(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

$$b^* = \arg \max_b \sum_j \sum_i W \log_2 (1 + \text{SINR}_{i,j,S})$$

(16)

for which the sum rate of overall system is maximized.

B. Two examples of heterogeneous network

One PBS (1-PBS) model The simplest case of the heterogeneous network with one macro-cell and one pico-cell ($CP = 1$) is shown in Figure 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 pico-cells as we have already observed in, for example, (6) and (15).

III. NUMERICAL RESULTS AND ANALYSIS

In the 1-PBS model, let us now consider some simulation results, for which the simulation parameters are shown in Table I. Here, the transmit power of the MBS and PBS and the pathloss exponents of the macro- and pico-cells are adopted from [13].

For simplicity, we assume that the total number of users serviced simultaneously in the heterogeneous network is 8 since the number is upper-limited by the number of antennas of the MBS. 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.

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.

A. Bias and sum rate

Figure 3 shows the sum rate with the proposed CRE as a function of the distance between the MBS and PBS at several values of the CRE bias. It is 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 Figure 3. 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 less than 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
TABLE I: Values of parameters used in simulation

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

the optimum bias is around 160 Mbps. In essence, the increase in the sum rate with the ICIC is around 50 Mbps.

Figure 4 shows 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.

B. Coverage area

Figure 5 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 area of the PBS less dependent on the distance of the PBS from the MBS.

Figure 6 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 Figures 4 and 6.

C. Offloading performance

Figure 7 shows the offloading performance of the proposed CRE scheme with an optimum bias. It is clearly observed that the number of users in the pico-cell increases when the proposed CRE scheme is applied. In addition, it is confirmed that the ICIC in the proposed CRE scheme provides more balanced 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.

IV. CONCLUSION

In heterogeneous networks, we have addressed a novel cell range expansion scheme, in which the positions of pico base stations are taken into account in the determination of the bias. The proposed cell range expansion scheme is shown to perform better when it is employed together with an inter-cell interference coordination scheme.

Although we have not yet included in this paper, some results in the 3-PBS model are currently being obtained: We hope to be able to present some of the results at the conference later this year. It is expected that the observations in the 3-PBS model are similar to those in the 1-PBS model. We believe that finding a sub-optimal value of the bias via a simpler method would be an interesting topic to pursue.

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Fig. 4: Optimum CRE bias value versus the distance between the MBS and PBS in the 1-PBS model

Fig. 5: 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. 6: Ratio of the coverage area with the proposed CRE to the coverage area without CRE in the 1-PBS model

Fig. 7: Offloading performance of the proposed CRE scheme with optimum bias in the 1-PBS model


