Clustering small cells in heterogeneous networks with interference alignment

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Abstract: In this letter, we consider heterogeneous networks (HetNets) where interference alignment (IA), which is one of the promising interference management techniques, is applied. Using IA in HetNet has an issue that as the number of small-cells increases, small base stations (BSs) become more costly in terms of the number of antennas, because they require more spatial degrees of freedom (DoF) to align the inter-small-cell interference. To overcome this issue, we conduct clustering small-cells and aligning inter-small-cell interference only within each cluster, which reduces the number of required spatial DoF at each small BS. The effects of clustering small-cells are evaluated through the simulations and it is found that the achievable rate per transmit antenna increases by clustering small-cells.

Keywords: heterogeneous networks, interference alignment, cell clustering

Classification: Wireless Communication Technologies

References


1 Introduction

Wireless networks are utilized in more and more diverse fields. Although wireless networks have been dedicated to only the voice service or Internet-access service, Internet of Things (IoT) [1] is connecting many kinds of things (e.x., vehicles, electric appliances, etc.) via wireless access points (APs), which is expected to create additional values in our lives. This technology innovation, on the other hand, induces the explosion of wireless traffic and the massive increase of wireless devices (resulting in severer interference), which should be immediately resolved. To solve the problems, we focus on two technologies, i.e., heterogeneous networks (HetNets) [2], where small-cells are deployed in the macro-cell area so as to improve the network capacity, and interference alignment (IA) [3], which constraints the interference signals into a certain space so as to utilize communication resources more efficiently. In particular, combining these techniques is predicted to bring the synergistic effect for the aforementioned issues [4]. The authors in [4] consider a downlink heterogeneous network where inter-small-cell interference is aligned to the strongest interference from macro base station (BS), and show that it can dramatically expands the network capacity. However, since each small BS designs its precoding weight so as to align all inter-small-cell interferences, as the number of small-cells increases, it requires enormous numbers of spatial degrees of freedoms (DoFs), i.e., transmit antennas, which results in more costly small BSs.

In this letter, we perform clustering small-cells, and align the inter-small-cell interference only within each cluster, which reduces the number of required spatial DoF at small BSs, resulting in their reduced manufacturing cost. Although, in general, “clustering” is utilized for reducing the computational complexity, it has the significance in the context of IA, i.e., it can reduce the required DoF (time-slots, bandwidth, antennas, etc.) to perform IA based on the feasibility condition [5], which is exploited in our scheme. Through simulation we evaluate the effect of clustering small-cells in HetNet with IA. We find that although the achievable rate per small-cell decreases as the cluster size (the number of small-cells in a cluster) decreases, the rate per spatial DoF at each small BS, i.e., the achievable rate normalized by the number of antennas at each small BS, in turn, increases as the cluster size decreases.

2 System model

We consider a downlink heterogeneous network where $K_S$ small-cells coexist in the macro-cell area. $K_M$ macro-cell user equipments (UEs) are associated to the macro BS, and single small-cell UE is associated to each small BS. Macro BS and small BS respectively equip with $N_M$ and $N_S$ antennas, and each UE equips with $N_R$ antennas. Each BS transmits $d$ data streams to the corresponding UE(s). The system model is depicted in Fig. 1.
For the simplicity of the description, each small-cell UE (and corresponding small-cell, small BS) is indexed from 1 to $K_S$ and each macro-cell UE is indexed from $K_S + 1$ to $K_S + K_M$. The receive signal of small-cell UE $i$, $i \in \{1, 2, \ldots, K_S\}$ is given by eq. (1), where $\rho_{ij}$, $\rho_{j,m}$ are the path loss coefficients between small BS $j$ and small-cell UE $i$, macro BS and small-cell UE $j$, respectively. $H_{ij}$, $H_{j,m}$ are the channel matrices between small BS $j$ and small-cell UE $i$, macro BS and small-cell UE $j$, respectively. $V_j$ represents the precoding weight for the transmitted signal toward UE $j$, that is represented as $x_j$ whose transmit power is normalized to 1.

Small-cell UE $j$ estimates its desired signal $\hat{y}_j$ through the application of the postcoding weight $U_j$ to the received signal $y_j$, i.e., $\hat{y}_j = U_j^H y_j$. 

$$y_i = \sqrt{\rho_{ii}} H_{ii} V_i x_i + \sum_{j=1, j \neq i}^{K_S} \sqrt{\rho_{ij}} H_{ij} V_j x_j + \sum_{j=K_S+1}^{K_S+K_M} \sqrt{\rho_{j,m}} H_{j,m} V_j x_j.$$

Small cells (and corresponding BSs and UEs) are grouped into some clusters. A clustering formation $C$ is given as $C = \{C_1, C_2, \ldots, C_N\} \in \mathbb{C}$, where $C_n$ is the $n$th cluster and $\mathbb{C}$ is the set of all possible clustering formations, respectively. Each cluster satisfies $C_n \subset \{1, 2, \ldots, K_S\}$, $\forall n$, and $C_i \cap C_j = \emptyset$, $\forall i, j, i \neq j$, where $N$ is the number of clusters in the considered system, and satisfies $K_S = NL$. Note that $L$ is the cluster size (the number of small-cells in a cluster), and $L$ is set to the same value for all clusters, i.e., all clusters consist of the same number of small-cells. The clustering formation is determined so as to minimize the rate loss caused by inter-cluster interference through the exhaustive search of all possible clustering formations as [6]. Note that minimizing the rate loss caused by inter-cluster interference is equivalent to maximizing the rate loss caused by intra-cluster interference. Therefore, the clustering problem is formalized as follows.
\[
\max_{\mathcal{C}\in\mathcal{C}} \sum_{n=1}^{N} \sum_{i,j \in \mathcal{C}_n} \Delta_{i,j}
\]

(2)

where \(\Delta_{i,j} = \log_2(1 + p_{ii}) - \log_2\left(1 + \frac{p_{ii}}{1 + p_{ij}}\right)\),

where \(\Delta_{i,j}\) represents the rate loss of small-cell UE \(i\) incurred by the interference from small BS \(i\). Note that the first term in \(\Delta_{i,j}\) represents the pseudo-rate without interference from small BS \(j\), and the second term represents that with interference from small BS \(j\).

### 3 Beam and filter design

The design of the transmit beam (of small BS) and the receive filter (of small-cell UE) are described in the following. For the simplicity, we focus on the small BS and the small-cell UE in small cell \(i\), and assume \(i \in \mathcal{C}_n\) and \(\mathcal{C}_n = \{1, 2, \ldots, i, \ldots, L\}\), while the following descriptions are easily generalized. Note that in the macro-cell, multi-user multiple-input multiple-output (MU-MIMO) is applied. Thus, we omit the detail about the beam design of macro BS and the filter design of macro-cell UE.

#### Beam design

Small BS \(i\) designs its transmit beam so as to satisfy the following relationship for small-cell UEs in the belonging cluster.

\[
\text{span}(H_{ji}V_i) = \text{span}(H_{j,m}V_{j_{\text{max}}}), \quad \forall j \in \mathcal{C}_n \setminus \{i\},
\]

(3)

where \(j_{\text{max}}\) is the index of the macro-cell UE toward whose signal from macro BS becomes the maximum interference at small-cell UE \(j\), and given as follows.

\[
j_{\text{max}} = \arg\max_{k \in \{\mathcal{K}_s+1, \ldots, \mathcal{K}_s+\mathcal{K}_m\}} \|H_{j,m}V_k\|.
\]

(4)

Note that eq. (3) indicates that small BS \(i\) aligns its transmit signal to the maximum interference from macro BS at each small-cell UE (except its corresponding UE) within its belonging cluster.

The preceding weight \(V_i\) satisfying eq. (3) is given as follows, where \(A^\dagger\) is pseudo inverse matrix of \(A\).

\[
V_i = \begin{bmatrix}
H_{1i} & \cdots & H_{1,m}V_{1_{\text{max}}}
\end{bmatrix}
\begin{bmatrix}
\vdots \\
H_{i-1,i} & \cdots & H_{i-1,m}V_{(i-1)_{\text{max}}}
\end{bmatrix}
\begin{bmatrix}
H_{i+1,i} & \cdots & H_{i+1,m}V_{(i+1)_{\text{max}}}
\end{bmatrix}
\begin{bmatrix}
\vdots \\
H_{L,i} & \cdots & H_{L,m}V_{L_{\text{max}}}
\end{bmatrix}
\]

(5)

Note that the number of transmit antennas at small BS \(N_S\) must suffice \(N_S \geq (L - 1)N_R\) to ensure the existence of the pseudo inverse matrix in eq. (5), which indicates that the number of required antennas is reduced as the cluster size decreases.

#### Filter design

Small-cell UE \(i\) designs its receive filter so as to eliminate the aligned signal following the criterion of zero forcing, i.e., \(U_i = \text{null}(H_{i,m}V_i)\). Therefore, the
receive filter $\mathbf{U}_i$ is given, through singular value decomposition (SVD) of $\mathbf{H}_{i,m} \mathbf{V}_i$, as follows.

$$
\mathbf{H}_{i,m} \mathbf{V}_{i,\text{max}} = [\tilde{\mathbf{U}}_i] [\mathbf{U}_i] =
\begin{bmatrix}
\sqrt{\lambda_1} & 0 & & \\
0 & \sqrt{\lambda_2} & \cdots & 0 \\
0 & \cdots & \ddots & 0 \\
\vdots & \ddots & \ddots & \ddots \\
0 & \cdots & 0 & \sqrt{\lambda_d}
\end{bmatrix}
\begin{bmatrix}
\tilde{\mathbf{V}}_i \\
\end{bmatrix},
(6)
$$

where $\tilde{\mathbf{V}}_i, \tilde{\mathbf{U}}_i$ are unitary matrices derived by SVD, and $\lambda_s, s \in \{1, \ldots, d\}$ is the singular value of $\mathbf{H}_{i,m} \mathbf{V}_i$. Note that it must satisfy $N_R \geq 2d$ to ensure the null space in eq. (6).

4 Performance evaluation

The performance of clustering small-cells are evaluated through the computer simulations. In the simulation, 12 small-cells exist in one macro-cell. The macro-cell and small-cell radii are respectively 500 m and 50 m. Small-cells are distributed uniformly within the macro cell area. Macro-cell UEs are distributed uniformly within the macro-cell area without overlapping any small-cells, and small-cell UEs are distributed uniformly within the area of the corresponding small-cell. Each BS is located at the center of each cell. The cluster size ($L$) is configured as 2, 4, 6, or 12. Note that for a cluster size of 12 is the same configuration as that in [4] where all small-cells are considered as a single cluster. We assume that each BS transmits two data streams to the corresponding UE, and that each BS and UE equip with the minimum number of antennas to align or eliminate the interference.

Fig. 2(a) shows the average achievable rate per small-cell, where the horizontal axis represents signal-to-noise-ratio (SNR), that is, the ratio of transmitting power at each BS to the noise power at each UE, and the vertical axis represents the average rate in bps/Hz. As shown in the figure, the rate decreases as the cluster size decreases. This is because as the cluster size decreases, the number of clusters

![Graph](image-url)
increases and the inter-cluster interference becomes severer. However, it should be noted that the required spatial DoF at each small BS also decreases with the cluster size, which should be taken into consideration for the evaluation. Fig. 2(b) shows the average rate per small-cell normalized by the number of antennas at each small BS. As shown in the figure, the rate per transmit antenna, in turn, increases as the cluster size decreases. This result indicates that each small BS can utilize its transmit antennas more efficiently in terms of the achievable rate by clustering small-cells.

5 Conclusion

In this letter, we considered the effect of clustering small-cells in a heterogeneous network (HetNet) with interference alignment (IA). Although “clustering” has, in general, the significance on the computational complexity reduction, in the context of IA, it can reduce the required degrees of freedom (DoF) to achieve IA. We exploited this feature, i.e., conducted clustering small-cells and aligning inter-small-cell interference only within each cluster, which reduces the required spatial DoF at each small BS, resulting in the less costly configurations of the BSs. Simulation results showed that the achievable rate per small-cell normalized by the number of antennas at each small BS increases as the cluster size (the number of small-cells in a cluster) decreases, which indicates that each small BS can utilize its transmit antennas more efficiently.