BASE STATION CLUSTER PATTERNS FOR SEMI-STATIC MULTI-CELL COOPERATION IN IRREGULAR NETWORK TOPOLOGIES

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ABSTRACT

This paper proposes a clustering strategy for semi-static multicell cooperation. Semi-static multicell cooperation exploits multiple predefined base station (BS) cluster patterns for improving cell-edge user throughput. The proposed clustering guarantees that every user communicates with their two closest BSs, so that users are protected from the dominant interferer. The key idea of the proposed clustering is to use the 2nd-order Voronoi region to form BS clusters. Each of the formed BS clusters is mapped into a particular cluster pattern by exploiting the edge-coloring in graph theory. Through simulations, the performance is compared to that of other conventional strategies. Our major finding is that the proposed clustering provides performance gains for cell-edge users compared to that of the conventional strategies.

1. INTRODUCTION

One main benefit of cloud-based radio access networks (Cloud-RANs) [1], featured by distributed base stations (BSs) connected to centralized processing units, is that it inherently has an efficient structure for BS cooperation. BS cooperation is a strategy for mitigating inter-cell interference where the transmission strategy are cooperated, e.g., beamforming, scheduling, and power control. Since exchanging transmitted data or sharing estimated channel coefficients between cooperating BSs are often needed in BS cooperation strategy, in conventional cellular networks, an additional core processor is required to help the exchanging and sharing procedures [2]. In cloud-RANs, however, BS cooperation is rather a default option due to the centralized structure of processing units [3].

Considering BS cooperation in an entire network, a BS cluster, defined as a subset of BSs, is indispensable for practically implementing BS cooperation because cooperating all the BSs in the network is infeasible due to the unreasonable amount of overhead [4]. Therefore, it is natural to cooperate within a cluster. When cooperating with a limited number of BSs, however, the performance of a user is mainly limited by unmanageable out-of-cluster interference, especially when a user is in an edge-region [4, 5]. For this reason, the way of forming a BS cluster has a substantial influence to the performance of BS cooperation approaches.

Dynamic BS clustering [6, 7], where each BS cluster is formed by each user based on the users' conditions, e.g., a distance to each BS and channel quality, is an effective BS clustering strategy. There are limitations though with dynamic BS clustering: the overheads in dynamically forming the clusters and the high complexity of the user scheduling [8]. To overcome these shortcomings, in [9, 10], semi-static BS clustering was proposed. The main concept is to use multiple predefined cluster patterns so that edge-users can have a chance to be protected from dominant interference. Since the BS clusters are predefined, problems caused in dynamic clustering are relieved. The existing semi-static BS clustering approaches [9, 10], however, mainly focused on grid network topologies where the BSs' locations are regularly placed on a grid. This network model is far from a practical cellular environment, and also it is trivial to design BS cluster patterns in a regular network topology. In a more practical network model where BSs are irregularly placed, it is not clear how to form a BS cluster and how to construct the cluster patterns. This is mainly because when the network size is large, considering all the BS clusters jointly is infeasible, which requires a general rule for making BS clusters and their corresponding patterns.

In this paper, we propose a BS clustering strategy applied in irregular network topologies. The main benefit of the proposed clustering is to guarantee that every user in the network is able to communicate with their two closest BSs, so that users are protected from the dominant interference, i.e., the interference coming form the closest interfering BS. The key feature of the proposed clustering is to use the 2nd-order Voronoi region, defined as

$$\begin{aligned}&\mathcal{V}_2\left(\mathbf{d}_i, \mathbf{d}_j\right)\\ &=\left\{\mathbf{d}\in\mathbb{R}^2 \middle| \left\{\|\mathbf{d}-\mathbf{d}_i\| \leq \|\mathbf{d}-\mathbf{d}_k\|\right\} \cap \right.\\ &\quad\left. \left\{\|\mathbf{d}-\mathbf{d}_j\| \leq \|\mathbf{d}-\mathbf{d}_k\|\right\},\ \forall k \in \mathbb{Z}^+,\ k\neq i,j\right\}. \quad (1)\end{aligned}$$

The geometric meaning of the 2nd-order Voronoi region is a

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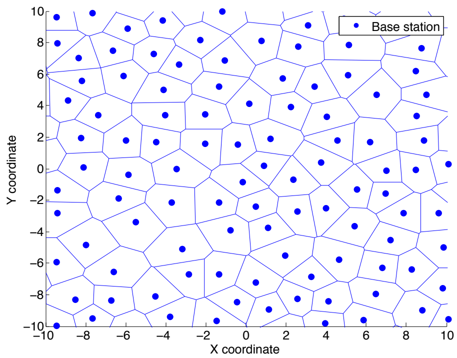

Fig. 1. An example of the network model. This example is generated by a repulsive point process where a distance between any two BSs is larger than 1.4km.

set of points that is closer to $\mathbf{d}_i$ and $\mathbf{d}_j$ than any other points. Due to this property, if the BSs located at $\mathbf{d}_i$ and $\mathbf{d}_j$ forms a BS cluster and serve a user in $\mathcal{V}_2(\mathbf{d}_i, \mathbf{d}_j)$, the served user is able to communicate with their two closest BSs. Applying this strategy in whole network, the network plane is tessellated into the 2nd-order Voronoi regions and users in each region are served by the corresponding BS pair, i.e., a user in $\mathcal{V}_2(\mathbf{d}_i, \mathbf{d}_j)$ are served by BS pair $\{\mathbf{d}_i, \mathbf{d}_j\}$. The formed BS clusters are mapped into multiple BS cluster patterns so that they can be used without conflict. To do this, edge-coloring in graph theory is exploited. For demonstration, the Signal-to-Interference ratio (SIR) coverage probability is compared to other conventional methods via Monte-Carlo simulations.

Our main novelty is to propose a clustering strategy that can be applied in any BS deployment scenario, and in the proposed clustering every user is ensured to communicate without the dominant interference, so that the performance improvement of cell-edge users is achieved.

2. SYSTEM MODEL

In this section, we first explain the network model and the cooperation model. Then we define the SIR metric.

2.1. Network Model

A fixed downlink cellular network where each BS has a single antenna is considered. The location of BS i is denoted as $\mathbf{d}_i$ for $i \in \mathbb{Z}^+$ and $\mathbf{d}_i \in \mathbb{R}^2$, and a set of BSs' location is denoted as $\mathcal{N} = \left\{\mathbf{d}_i \in \mathbb{R}^2 \middle| i \in \mathbb{Z}^+\right\}$. As in the conventional cellular system, each network plane is tessellated into $|\mathcal{N}|$ numbers of the 1st-order Voronoi regions $\mathcal{V}_1(\mathbf{d}_i)$ for $\mathbf{d}_i \in \mathcal{N}$. An example of the considered network is illustrated in Fig. 1.

2.2. Cooperation Model

It is assumed that a BS pair located at $\{\mathbf{d}_i, \mathbf{d}_j\}$ for $\mathbf{d}_i, \mathbf{d}_j \in \mathcal{N}$ can cooperate. The reason behind that only pair-wise BS cooperation is assumed is not only its simplicity, but also that the pair-wise BS cooperation is considered as the optimal cooperation size in particular setups. In [11], it was shown that forming a BS cluster including more than two BSs actually degrades the spectral efficiency performance when considering the signaling overheads for estimating channel coefficients within the cluster. Obviously, this is only true in a frequency division duplexing (FDD) system, while the most of current cellular systems are operated based on the FDD system. When the BS i and BS j form a BS cluster, they exchange the data and transmit it to one user, i.e., one user is served per one BS cluster.

2.3. Signal-to-Interference Ratio

We focus on a user located at $\mathbf{u}$, denoted as the tagged user. By shifting BS i's location to $\mathbf{d}'_i = \mathbf{d}_i - \mathbf{u}$ for $i \in \mathbb{Z}^+$, we are able to assume that the tagged user is located on the origin without loss of generality. For simplicity, we write $\mathbf{d}'_i$ as $\mathbf{d}_i$ and $\mathbf{u} = \mathbf{0}$. It is assumed that a BS pair located at $\{\mathbf{d}_0, \mathbf{d}_\mathrm{c}\}$ jointly serves the tagged user by transmitting the same data through the designed precoder. Denoting that h_i is the channel fading coefficient from BS i to the tagged user, the precoder of the BS i is designed as $v_i = h_i^* / |h_i|$ if $i \in \{0, \mathrm{c}\}$. If $i \in \mathbb{Z}^+ \backslash \{0, \mathrm{c}\}$, v_i is independent to the interfering channel h_i. The perfect channel state information at the transmitter (CSIT) is assumed in this paper. Then, as in [3], the SIR is given by

$$\mathrm{SIR} = \frac{\|\mathbf{d}_0\|^{-\beta} H_0 + \|\mathbf{d}_\mathrm{c}\|^{-\beta} H_\mathrm{c}}{\sum_{\mathbf{d}_i \in \mathcal{N}\backslash\{0,\mathrm{c}\}} \|\mathbf{d}_i\|^{-\beta} H_i}, \tag{2}$$

where $H_i = |h_i v_i|^2$. The SIR coverage probability is defined as

$$\mathbb{P}[\mathrm{SIR} > \theta] = \mathbb{P}\left[\frac{\|\mathbf{d}_0\|^{-\beta} H_0 + \|\mathbf{d}_\mathrm{c}\|^{-\beta} H_\mathrm{c}}{\sum_{\mathbf{d}_i \in \mathcal{N}\backslash\{0,\mathrm{c}\}} \|\mathbf{d}_i\|^{-\beta} H_i} > \theta\right], \tag{3}$$

where θ is a SIR target.

3. MAIN RESULTS

In this section, we first explain the concept of forming an efficient BS cluster, which guarantees that a user is served by the two nearest BSs. Next, we propose how the proposed BS cluster is implemented with the multiple cluster patterns in a network. A toy example is exploited for an intuitive explanation, which is subsequently extended to a general network.

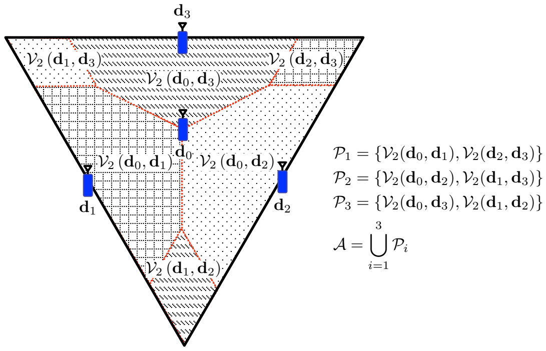

Fig. 2. The considered toy example where the network plane is a finite triangular plane $\mathcal{A}$, and each BS is located at $\mathbf{d}_i$ for $i \in \{0, 1, 2, 3\}$. By using the edge-coloring for the constructed graph as in Fig. 3, each 2nd-order Voronoi region is mapped into particular cluster pattern, resulting in that the 2nd-order Voronoi region whose the shade pattern is same is included in the same cluster pattern.

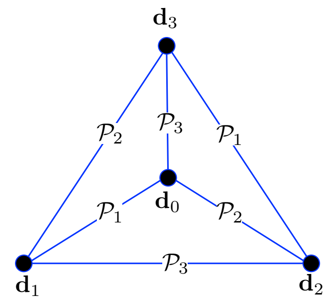

Fig. 3. The graph where vertices in the example Fig. 2 and edges are made by the Delaunay triangulation corresponding to the toy example. By the edge-coloring, each edge is assigned by the cluster patterns $\mathcal{P}_i$ for $i = \{1, 2, 3\}$.

3.1. Toy Example

In a toy example, it is assumed that there are four BSs, denoted as BS i for $i \in \{0, ..., 3\}$. BS i is located at $\mathbf{d}_i$ as illustrated in Fig. 2, thereby $\mathcal{N} = \{\mathbf{d}_i \in \mathcal{A} | \, i \in \{0, 1, 2, 3\}\}$. In this network, we tessellate the network plane into the 2nd-order Voronoi regions defined in (1). The tessellated network plane is also described in Fig. 2. Then, from the geometric meaning of the 2nd-order Voronoi region, a user in $\mathcal{V}_2(\mathbf{d}_i, \mathbf{d}_j)$ has the two nearest BSs pair $\{\text{BS } i, \text{BS } j\}$. When BS i and BS j form a BS cluster, therefore, a user in $\mathcal{V}_2(\mathbf{d}_i, \mathbf{d}_j)$ is served from the two nearest BSs, which guarantees that the served user is protected from the dominant interference. When applying this clustering strategy in the whole network, however, it is possible that a BS conflict occurs [12], i.e., the situation where more than two users want to be served from one BS simultaneously. For instance, assume that there are two users, where user 1 is in $\mathcal{V}_2(\mathbf{d}_0, \mathbf{d}_1)$ and user 2 is in $\mathcal{V}_2(\mathbf{d}_0, \mathbf{d}_2)$. Since BS 0 cannot transmit two data symbols simultaneously, user 1 or user 2 cannot be served from the two nearest BSs. To avoid this, each of the 2nd-order Voronoi regions needs be covered by a different time-frequency resource. When the 2nd-order Voronoi regions covered by the same time-frequency resource are mapped into the same cluster pattern, it is guaranteed that every user in the network communicates with their two nearest BSs without the dominant interference by using the multiple cluster patterns.

Now we propose how to map each of the 2nd-order Voronoi region into a particular cluster pattern. The key idea is to use the edge-coloring in graph theory. Assuming an arbitrary graph, edge-coloring assigns a color to each edge in the graph so that any edge sharing the same vertex does not have the same color with the minimum number of colors. To this end, we construct the graph $G(\mathcal{N})$ corresponding to the considered network. In $G(\mathcal{N})$, each vertex is the location of each BS, and each edge is the Delaunay triangulation defined in $\mathcal{N}$. The Delaunay triangulation in $\mathcal{N}$ is defined by the three following conditions: 1) It is a triangulation of a plane, 2) Each vertex in $\mathcal{N}$ is a vertex of a triangle, and 3) The circumcircle of each triangle should not include any vertex in $\mathcal{N}$. The following Lemma 1 provides the core feature of the graph $G(\mathcal{N})$ related to the 2nd-order Voronoi region.

Lemma 1. *The 2nd-order Voronoi region $\mathcal{V}_2(\mathbf{d}_i, \mathbf{d}_j)$ for $i, j \in \mathbb{Z}^+$ and $i \neq j$ is not empty if and only if $\mathbf{d}_i$ and $\mathbf{d}_j$ is connected by the Delaunay triangulation.*

Proof. See [13] and the references therein. □

By the Lemma 1, when considering cluster patterns as "colors," edge-coloring is equivalent to map each non-empty 2nd-order Voronoi region into the cluster patterns. Since there is no vertex (BS) sharing the edges assigned by the same color (the same cluster pattern), a BS conflict is avoided. Fig. 3 describes the example of edge-coloring of the graph corresponding to the toy example. It is observed that no vertex has the same colored edges, i.e., the edges mapped into the same cluster pattern. Exploiting this edge-coloring, the cluster patterns are constructed as $\mathcal{P}_1 = \{\mathcal{V}_2(\mathbf{d}_0, \mathbf{d}_1), \mathcal{V}_2(\mathbf{d}_2, \mathbf{d}_3)\}$, $\mathcal{P}_2 = \{\mathcal{V}_2(\mathbf{d}_0, \mathbf{d}_2), \mathcal{V}_2(\mathbf{d}_1, \mathbf{d}_3)\}$, and $\mathcal{P}_3 = \{\mathcal{V}_2(\mathbf{d}_0, \mathbf{d}_3), \mathcal{V}_2(\mathbf{d}_1, \mathbf{d}_2)\}$. By allocating different time-frequency resources to each cluster pattern, no BS conflict occurs and therefore every user in $\mathcal{A}$ is guaranteed to be protected from the dominant interference.

The required number of colors for edge-coloring is equivalent to the required number of time-frequency resources to avoid a BS conflict. In this example, since three colors (cluster patterns) are used for edge-coloring, three time-frequency resources are needed to avoid a BS conflict.

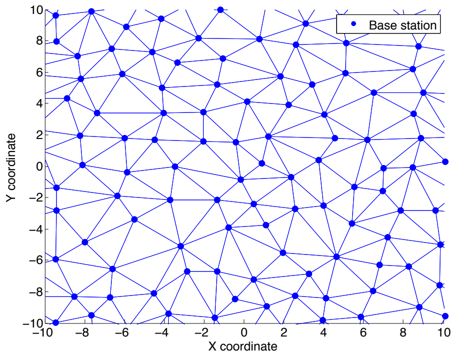

Fig. 4. The graph corresponding to $\mathcal{N}$ in Fig. 1. Each vertex of $G(\mathcal{N})$ is $\mathbf{d}_i \in \mathcal{N}$, and each edge is the Delaunay triangulation.

3.2. General Network

Now we extend the toy example to a general network. The procedure is equivalent to the toy example case. We first tessellate the network plane $\mathbb{R}^2$ into multiple 2nd-order Voronoi regions $\mathcal{V}_2(\mathbf{d}_i, \mathbf{d}_j)$ for $\mathbf{d}_i, \mathbf{d}_j \in \mathcal{N}$ and $i \neq j$, and a BS pair located at $\{\mathbf{d}_i, \mathbf{d}_j\}$ serves a user in $\mathcal{V}_2(\mathbf{d}_i, \mathbf{d}_j)$ by transmitting the same data symbol for the user. To design cluster patterns, we draw the graph $G(\mathcal{N})$ according to the Delaunay triangulation of $\mathcal{N}$. When $\mathcal{N}$ is corresponding to the example illustrated in Fig. 1, the graph $G(\mathcal{N})$ is drawn as in Fig. 4. Once $G(\mathcal{N})$ is made, by using the edge-coloring for $G(\mathcal{N})$, each edge in $G(\mathcal{N})$ is assigned by particular color (cluster pattern). Since edge-coloring is not restricted to a specific topology of vertices, the edge-coloring used in a general network is similar to that applied in the toy example, as illustrated in Fig. 3. Due to the page limitation, we provide more rigorous explanations in our extended work [14]. Exploiting the result of the edge-coloring, different time-frequency resources are allocated to each cluster pattern, and thanks to this a BS conflict is prevented. With the proposed clustering strategy, every user in the network is guaranteed to receive the desired data symbol from two closest BSs without the dominant interference.

Denoting the constructed cluster patterns as $\mathcal{P}_i$ for $i \in \{1, ..., L\}$ and $\cup_{i\in\{1,...,L\}}\mathcal{P}_i = \mathbb{R}^2$, L time-frequency resources are required to cover the whole network without a BS conflict. In contrast to the toy example, however, it is not trivial to find L in a general case. It turns out that the value of L is closely related to the chromatic index of the graph $G(\mathcal{N})$, which is determined by the maximum degree, i.e., the maximum number of edges connected to a certain vertex in $G(\mathcal{N})$. We explore this point further in our other work [14].

One point worth noticing is that although drawing $G(\mathcal{N})$ and solving the general edge-coloring for $G(\mathcal{N})$ might cause high computational complexity, the complexity is not an important issue in the proposed clustering strategy. This is mainly because the proposed clustering is a semi-static BS cooperation, where the exploited BS cluster and the cluster patterns are predefined. Since the proposed clustering only depends on the BS geometry, unless the BSs' locations are changed, the designed BS cluster and cluster patterns are preserved irrespective of the instantaneous channel condition. Conventionally, the BS geometry would not be changed on the order of months or years.

4. SIMULATION RESULTS

For the simulation, we use the same network model with the example described in Fig. 1. To generate this network model, we first drop each BS by a homogeneous Poisson point process with density $\lambda = 3 \times 10^{-7}$ per m^2, and perform dependent thinning for each point if a distance between two points is less than 1.4km. This mimics the actual BS deployment scenario where each BS is implemented with a guard distance to prevent that BSs are located very close together. Although the particular network model is considered for the simulation, one should note that the proposed strategy is not limited by specific network topologies. The proposed clustering can be applied in any network topology regardless of the distribution of BSs. We assume that the tagged user is uniformly dropped in the network and we shift $\mathbf{d}_i - \mathbf{u}$ for $\mathbf{d}_i \in \mathcal{N}$, where $\mathbf{u}$ is a location where the user is initially dropped. By this construction, the tagged user is located on the origin. The pathloss exponent β is set to be 4, which is a typical value for a terrestrial wireless environment [11]. The channel coefficients are assumed to follow Rayleigh fading, so that H_i follows the exponential distribution with unit mean. For performance comparison, two baseline methods are considered, i.e., single cell operation and fractional frequency reuse. In single cell operation, each BS serves its own user without interference management technique. In fractional frequency reuse, one of two orthogonal sub-bands is randomly allocated to each cell [15], so that approximately half of the total interference affects to the performance of the tagged user. Monte-Carlo simulations are performed by 10×10^3 times.

The simulation result for the SIR coverage probability of each case is illustrated in Fig. 5. As observed in Fig. 5, the proposed clustering provides better SIR coverage probability in the low SIR regime. Specifically, at $\theta = 0\text{dB}$, the proposed clustering has the performance gain of 12.5% compared to fractional frequency reuse, and 23% compared to single cell operation. The performance gain comes from the fact that with the proposed clustering, the tagged user is ensured to be protected from the dominant interference, while in fractional frequency reuse, there is a non-zero possibility that the tagged user is exposed to the dominant interference. Combined with this fact, in the low SIR regime, one dominant interference has significant effect to the SIR performance. From these two reasons, although the number of the total interfering sources is clearly smaller in fractional frequency reuse, the proposed clustering is able to provide the better SIR coverage in the

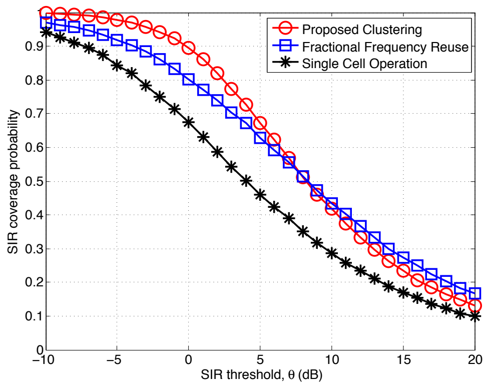

Fig. 5. The SIR coverage probability depending on the SIR threshold θ when $\beta = 4$ and each channel coefficient follows Rayleigh fading.

low SIR regime. This can be concluded into the following statement: By using the proposed clustering, cell-edge users whose the SIR threshold is conventionally low, have benefit of the SIR coverage performance.

5. CONCLUSIONS

In this paper, we propose a semi-static clustering strategy to guarantee every user to communicate their two nearest BSs without the dominant interference. The key idea is to use the 2nd-order Voronoi region for forming an efficient BS cluster, and to exploit the edge-coloring for mapping each BS cluster into cluster patterns for implementing the BS clusters while avoiding BS conflicts. Through the simulation, we demonstrate that the proposed clustering provides the SIR coverage gain compared to other methods for cell-edge users.

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REFERENCES

[1] China Mobile Research Institute, "C-RAN: The road toward Green RAN," *White Paper*, Oct. 2011.

[2] B. Clerckx, H. Lee, Y.-J. Hong, and G. Kim, "A practical cooperative multicell mimo-ofdma network based on rank coordination," *IEEE Trans. Wireless Comm.*, vol. 12, no. 4, pp. 1481–1491, Apr. 2013.

[3] N. Lee, R. Heath, D. Morales-Jimenez, and A. Lozano, "Base station cooperation with dynamic clustering in super-dense cloud-ran," in *Proc. IEEE Glob. Comm. Conf.*, Dec. 2013, pp. 784–788.

[4] A. Lozano, R. W. Heath, and J. G. Andrews, "Fundamental limits of cooperation," *IEEE Trans. Info. Th.*, vol. 59, no. 9, pp. 5213–5226, Sep. 2013.

[5] K. Huang and J. Andrews, "An analytical framework for multicell cooperation via stochastic geometry and large deviations," *IEEE Trans. Info. Th.*, vol. 59, no. 4, pp. 2501–2516, Apr. 2013.

[6] A. Papadogiannis, D. Gesbert, and E. Hardouin, "A dynamic clustering approach in wireless networks with multi-cell cooperative processing," in *Proc. IEEE Int. Conf. on Comm.*, May 2008, pp. 4033–4037.

[7] A. Papadogiannis and G. Alexandropoulos, "The value of dynamic clustering of base stations for future wireless networks," in *Proc. IEEE Int. Conf. on Fuzzy Sys.*, Jul. 2010, pp. 1–6.

[8] S. Ramprashad and G. Caire, "Cellular vs. Network MIMO: A comparison including the channel state information overhead," in *Proc. IEEE Int. Symp. on Pers., Indoor and Mobile Radio Comm.*, Sep. 2009, pp. 878–884.

[9] J.-Y. Hwang, J. Kim, T. Kim, and Y. Han, "A periodic frequency band rotation scheme for multi-cell coordination clustering," *IEEE Comm. Lett.*, vol. 15, no. 9, pp. 956–958, Sep. 2011.

[10] H. Purmehdi, R. Elliott, W. Krzymien, and J. Melzer, "Rotating clustering with simulated annealing user scheduling for coordinated heterogeneous mimo cellular networks," in *Proc. IEEE Int. Conf. on Comm.*, Jun. 2014, pp. 5293–5298.

[11] N. Lee, D. Morales-Jimenez, A. Lozano, and R. Heath, "Spectral efficiency of dynamic coordinated beamforming: A stochastic geometry approach," *IEEE Trans. Wireless Comm.*, vol. 14, no. 1, pp. 230–241, Jan. 2015.

[12] X. Hou, E. Bjrnson, C. Yang, and M. Bengtsson, "Cell-grouping based distributed beamforming and scheduling for multi-cell cooperative transmission," in *Proc. IEEE Int. Symp. on Pers., Indoor and Mobile Radio Comm.*, 2011, pp. 1929–1933.

[13] I. Fischer and C. Gotsman, "Fast approximation of high-order Voronoi diagrams and distance transforms on the GPU," *J. Graphics Tools*, vol. 11, no. 4, pp. 39–60, 2006.

[14] J. Park, N. Lee, and R. Heath, "Cooperative base station coloring for pair-wise multi-cell coordination," *Submitted to IEEE Trans. Comm.*, 2015. [Online]. Available: http://arxiv.org/abs/1503.01102

[15] J. Andrews, F. Baccelli, and R. Ganti, "A tractable approach to coverage and rate in cellular networks," *IEEE Trans. Comm.*, vol. 59, no. 11, pp. 3122–3134, Nov. 2011.