Networked MIMO with Clustered Linear Precoding

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Abstract

A clustered base transceiver station (BTS) coordination strategy is proposed for a large cellular MIMO network, which includes full intra-cluster coordination—to enhance the sum rate—and limited inter-cluster coordination—to reduce interference for the cluster edge users. Multi-cell block diagonalization is used to coordinate the transmissions across multiple BTSs in the same cluster. To satisfy per-BTS power constraints, three combined precoder and power allocation algorithms are proposed with different performance and complexity tradeoffs. For inter-cluster coordination, the coordination area is chosen to balance fairness for edge users and the achievable sum rate. It is shown that a small cluster size (about 7 cells) is sufficient to obtain most of the sum rate benefits from clustered coordination while greatly relieving channel feedback requirement. Simulations show that the proposed coordination strategy efficiently reduces interference and provides a considerable sum rate gain for cellular MIMO networks.

Index Terms

MIMO systems, cellular technology, resource allocation and interference management, base station coordination.

I. INTRODUCTION

Multi-antenna transmission and reception (known as MIMO) is a key technique for improving the throughput of future wireless broadband systems. For a point-to-point link with multiple
antennas at both the transmitter and receiver, it has been shown that the capacity grows linearly with the minimum number of transmit and receive antennas, i.e. the number of spatial degrees of freedom\[^{1}\] [2], [3]. Due to space constraints, however, mobile terminals can only have a small number of antennas, normally one or two, which bounds the capacity gain promised by MIMO. Multi-user MIMO (MU-MIMO), where a BTS communicates with multiple mobile users simultaneously, provides an opportunity to boost the sum capacity through joint precoding (downlink) or joint decoding (uplink) even when each user has only one antenna [4]. For MU-MIMO with a large number of mobile users, however, the sum capacity of both the uplink and downlink is restricted by the number of antennas at the BTS, as it determines the number of spatial degrees of freedom.

Although theoretically attractive, deploying MIMO in a commercial cellular system is fundamentally different as the transmission in each cell acts as interference to other cells, and the entire network is essentially interference-limited. While the problem of interference is inherent to cellular systems, its effect on MIMO is more significant because each neighboring BTS antenna element can act as a unique interfering source, thereby making it difficult for the mobile to estimate and suppress them. With \( N_r \) receive antennas, each mobile can only cancel/decode up to \( N_r \) different sources using linear techniques [5]. Furthermore, interference is more severe for the downlink because complicated interference suppression techniques are not practical for mobile terminals, which need to be power-efficient and compact. Coordination between users is usually not allowed. The capacity gains promised by MIMO techniques have been shown to degrade severely in the multi-cell environment [6]–[8]. Conventional approaches to mitigate multi-cell interference, such as static frequency reuse, sectoring, and spread spectrum, are not efficient for MIMO networks as each has important drawbacks [9]. The difficulty in combating interference for MIMO is essentially due to the limitation of spatial degrees of freedom, most of which are used to suppress the spatial interference introduced by spatial multiplexing at the cell site while few are left to suppress other-cell interference.

Thanks to the fast improvement of processing capability at BTSs and the increase of the

\[^{1}\text{In this paper, the definition of the number of spatial degrees of freedom follows [1]. It represents the dimension of the transmitted signal as modified by the MIMO channel, and is equal to the rank of the channel matrix when it has full rank. Therefore, for a point-to-point link with } N_t \text{ transmit antennas and } N_r \text{ receive antennas, it is } \min (N_t, N_r); \text{ for multiuser MIMO channels with } K \text{ users, it is } \min (N_t, KN_r); \text{ for BTS coordination system with } B \text{ BTSs, it is } \min (BN_t, KN_r).} \]
backhaul capacity, coordinated multi-cell MIMO communications with cooperative processing among BTSs have drawn significant amount of interest in recent years. The conventional MIMO network with single-cell processing forms a MIMO interference channel, whose spatial degrees of freedom are determined by the number of transmit antennas at each BTS [10]. With full coordination across $B$ BTSs and a large number of mobile users, the coordination system forms a virtual MIMO broadcast channel, which increases the spatial degrees of freedom by $B$ times. Similar to the transition from single-user MIMO to MU-MIMO, such cooperation across multiple BTSs can provide great advantages over single-BTS processing [11]–[14]. This paper proposes a BTS coordination strategy with clustered linear precoding for the downlink of cellular MU-MIMO systems, which efficiently reduces interference provides a great sum rate gain by exploiting the expanded spatial degrees of freedom.

A. Related Work

**Intercell scheduling**, where neighboring BTSs cooperatively schedule their transmissions, is a practical strategy to reduce interference, as each time slot only one BTS in each cluster is transmitting and it only requires message change comparable to that for handoff. In [15], it was shown that one major advantage of intercell scheduling compared with conventional frequency reuse is the expanded multiuser diversity gain. The interference reduction is at the expense of a transmission duty cycle, however, and it does not make full use of the available spatial degrees of freedom.

Recently, **BTS coordination** has been proposed as an effective technique to mitigate interference in the downlink of multi-cell networks [11]. By sharing information across BTSs and designing downlink signals cooperatively, signals from other cells may be used to assist the transmission instead of acting as interference, and the available degrees of freedom are fully utilized. In [12], BTS coordination with DPC was first proposed with single-antenna transmitters and receivers in each cell. BTS coordination in a downlink multi-cell MIMO network was studied in [13], with a per-BTS power constraint and various joint transmission schemes. The maximum achievable common rate in a coordinated network, with zero-forcing (ZF) and DPC, was studied in [14], [16], which demonstrated a significant gain over the conventional single BTS transmission. With simplified network models, analytical results were derived for multi-cell ZF beamforming in [17] and for various coordination strategies with grouped cell interior and edge users in [18]. Studies
considering practical issues such as limited-capacity backhaul and asynchronous interference can be found in [19]–[22].

With BTSs coordinating for transmission, it forms an effective MU-MIMO broadcast channel, for which DPC has been shown to be an optimal precoding technique [23]–[27]. DPC, while theoretically optimal, is an information theoretic concept that is difficult to implement in practice. A more practical precoding technique for broadcast MIMO channels is block diagonalization (BD) [28]–[32], which provides each user an interference-free channel with properly designed linear precoding matrices. In addition, it was shown in [33] that BD can achieve a significant part of the ergodic sum capacity of DPC. Therefore, we will apply BD in the multi-cell scenario as the precoding technique for the proposed BTS coordination.

Most previous studies on BTS coordination assume a global coordination which eliminates inter-cell interference completely. However, in realistic cellular systems, issues such as the complexity of joint processing across all the BTSs, the difficulty in acquiring full CSI from all the mobiles at each BTS, and time and phase synchronization requirements will make full coordination extremely difficult, especially for a large network. Therefore, it is of great interest to develop coordination schemes at a local scale, to lower the system complexity and maintain the benefits of BTS coordination. For the uplink, an overlapping coordination cluster structure was proposed in [34], where each BTS is at the center of a unique cluster and coordinated combining is performed to suppress interference for the central BTS of each cluster. With such an overlapping cluster structure, each user is in the interior of a cluster and enjoys interference reduction, but the cluster number is as large as the number of BTSs and it cannot be easily extended to the downlink. In [35], the downlink coordination over a 3-cell cluster was investigated with both ZF and DPC, but no inter-cluster coordination was considered.

B. Contributions

In this paper, we propose a clustered BTS coordination strategy for the downlink of a large cellular MIMO network. With full coordination within the same cluster, the available spatial degrees of freedom are greatly increased, which are then used to reduce inter-cluster interference and exploit the sum rate gain. This strategy consists of a full intra-cluster coordination and a limited inter-cluster coordination. The intra-cluster coordination results in precoding across BTSs within the same cluster for MU-MIMO, while the inter-cluster coordination is used to pre-cancel...
interference for the users at the edge of neighboring clusters. In this way, interferences for both cluster interior and cluster edge users are efficiently mitigated. Meanwhile, the system complexity and CSI requirements at the BTSs, which are on a cluster scale, are greatly reduced compared to global coordination. As the main complexity is at the BTSs, mobile users can enjoy a simple conventional receiver. In addition, the universal frequency reuse is applied, and there is no need for cell planning.

We apply multi-cell BD as the precoding technique for such coordination. The precoder matrix design is modified from conventional single-cell BD, for which we consider other-cluster interference suppression. In contrast to the classical MIMO broadcast channel, the BTS coordination system has a per-BTS power constraint. As there is no closed-form solution for the power allocation problem with such a power constraint, three different power allocation algorithms are proposed. For inter-cluster coordination, we show that there is a tradeoff between fairness and sum rate while choosing the inter-cluster coordination area. It is shown that a small cluster size (about 7 cells) can achieve a significant part of the sum rate gain provided by the clustered coordination while greatly reducing channel information feedback compared to global coordination. Simulations show that the proposed coordination strategy improves the sum rate over conventional systems and reduces the impact of interference for cluster-edge users.

The BTS coordination considering two classes of users (edge and interior) was also investigated in [18], which derived information-theoretic results based on a simplified Wyner-type circular network model. In this paper, we consider a more practical setting—a large tesselated 2-D network. We propose clustered coordination based on low-complexity linear precoding, design parameters for such coordination and demonstrate the achievable performance with simulation. We have made some idealized assumptions in this paper, such as perfect information about channel state and interference. We demonstrate through simulation that the coordination system is sensitive to imperfect channel knowledge. The full investigation of these practical issues is, however, left to future work.

C. Organization

The rest of the paper is organized as follows: In Section II, we make necessary assumptions, and describe the proposed coordination strategy and the received signal model. Section III presents the precoding matrix design for multi-cell BD. The detail for inter-cluster coordination
II. System Model

A. Clustered MIMO Network Structure

Consider a cellular MIMO network, where both BTSs and mobile users have multiple antennas, $N_t$ and $N_r$, respectively. The system parameters used in this paper are summarized in Table I. We consider a large network, i.e. the number of cells in the network is very large, so it is impractical to do coordination across all the BTSs. We propose to divide the network into a number of disjoint clusters, where each cluster contains a group of adjacent cells, as in Fig. 1. With coordination among the BTSs within the same cluster, we effectively increase the number of spatial degrees of freedom, which will be used to suppress interference, including inter-user and inter-cluster interference, and provide sum rate gain.

We apply universal frequency reuse, so the users at the cluster edge may suffer a high degree of interference from neighboring clusters. To efficiently accommodate all the users, we group them into two classes: cluster interior users and cluster edge users. A discussion about user grouping will be given in Section IV. To do the proposed clustered coordination, we make several assumptions.

**Assumption 1:** The BTSs within a cluster have perfect CSI of all the users in this cluster, and perfect CSI of the edge users in the neighboring clusters.

For a time-division duplexing (TDD) system, the BTS can obtain the downlink CSI through direct uplink channel estimation due to channel reciprocity. For a frequency-division duplexing (FDD) system, the downlink CSI can be obtained by feedback from mobile users, and limited feedback for MU-MIMO is an ongoing topic [36]–[38], which we will not explore in this paper and perfect CSI is assumed. The assumption of the availability of CSI of the edge users is based on the fact that for handoff such users have CSI of multiple neighboring clusters and can feed back such information. The full CSI of the users in the same cluster is for MU-MIMO precoding to cancel the inter-user interference. The CSI of the edge users in the neighboring clusters is for pre-canceling the inter-cluster interference for these users.

**Assumption 2:** The BTSs within the same cluster can fully share CSI and user data. The BTSs in different clusters can exchange traffic information, such as the number of active users and
The capability of full coordination of the BTSs within the same cluster enables doing MU-MIMO precoding across all the BTS antennas in this cluster. The limited coordination between BTSs in different clusters can be used for scheduling, e.g. the cluster with a large number of active users may not do inter-cluster coordination for the neighboring clusters.

Assumption 3: BTSs within the same cluster are perfectly synchronized in time and phase, and different propagation delays from these BTSs to mobile users in this cluster are compensated.

This assumption is to ensure synchronous reception from the home BTSs at mobile users. It is difficult to realize perfect synchronization in practice, and the investigation of the impact of asynchronous reception is out of the scope of this paper. Recently, there has been some study on this subject [22].

From these assumptions, the system requirements for clustered coordination are based on a cluster scale, which is much lower than that for global coordination, especially in a large network.

B. Coordination Strategy

Based on the clustered structure and assumptions in the last section, we propose a clustered coordination strategy, including full intra-cluster coordination and limited inter-cluster coordination. The transmission strategies for different user groups are described as follows.

Cluster interior users: BTSs within the same cluster work together as a “super BTS” to serve the interior users in that cluster with MU-MIMO precoding. In this way, there will be no intra-cluster interference, i.e. inter-user interference, for these users. In addition, the interior users are protected to a large degree from inter-cluster interference by path loss.

Cluster edge users: Multiple neighboring clusters have channel information of edge users, and they coordinate for the data transmission: one of these clusters is selected to act as the home cluster to transmit data to such a user, and other neighboring clusters will take this user into consideration when designing precoding matrices. With pre-cancelation of intra-cluster interference provided by the home cluster and pre-cancelation of inter-cluster interference at other neighboring clusters, there will be no interference for this edge user from those clusters.

With such a coordination strategy, the interference for both cluster interior and cluster edge users are efficiently mitigated. Fractional frequency reuse (FFR) is another technique for interference management where BTSs cooperatively schedule users in different downlink bandwidths.
However, FFR is a frequency-domain interference management technique. The proposed coordi-
nation strategy is a spatial domain technology that can be implemented with a universal
frequency reuse. For a highly-loaded system, FFR alone cannot accommodate all the edge users.
Networked MIMO offers another opportunity to serve them.

C. Received Signal Model

Without loss of generality, we consider the cluster $c$. The $N_r \times 1$ received signal vector at the
$k$th user in the cluster $c$ is given as

$$y^{(c)}_k = \sum_{b=1}^{B} H^{(c,b)}_k T^{(c,b)}_k x^{(c)}_k + \sum_{b=1}^{B} H^{(c,b)}_k \sum_{i=1, i \neq k}^{K} T^{(c,b)}_i x^{(c)}_i + \sum_{\hat{c}=1, \hat{c} \neq c}^{C} \sum_{b=1}^{B} H^{(\hat{c},b)}_k \sum_{j=1}^{K} T^{(\hat{c},b)}_j x^{(\hat{c})}_j + n^{(c)}_k$$

where

- $x^{(c)}_k$ is the $l_k \times 1$ transmitted vector for user $k$ in cluster $c$. Denote $\tilde{x}^{(c)} = [x^{(c)*}_1 x^{(c)*}_2 \cdots x^{(c)*}_K]^*$, where $*$ denotes the conjugate transpose of a matrix. The covariance matrix for $\tilde{x}^{(c)}$ is denoted as $Q^{(c)} = \mathbb{E}[\tilde{x}^{(c)}\tilde{x}^{(c)*}]$.
- $H^{(c,b)}_k$ is the $N_r \times N_t$ channel matrix from BTS $b$ in cluster $c$ to user $k$.
- $T^{(c,b)}_k$ is the $N_t \times l_k$ precoding matrix for user $k$ at the $b$th BTS in cluster $c$.
- $n^{(c)}_k$ is the additive white Gaussian noise at user $k$ in cluster $c$, with zero mean and variance

$$\mathbb{E}(n^{(c)}_k n^{(c)*}_k) = \sigma^2 n I_{N_r}.$$

Because the $B$ BTSs within this cluster coordinate to work as a super BTS, the signal model can be written as

$$y^{(c)}_k = H^{(c)}_k \sum_{i=1}^{K} T^{(c)}_i x^{(c)}_i + n^{(c)}_k + \sum_{\hat{c}=1, \hat{c} \neq c}^{C} H^{(\hat{c})}_k \sum_{j=1}^{K} T^{(\hat{c})}_j x^{(\hat{c})}_j$$

where $H^{(c)}_k = [H^{(c,1)}_k, H^{(c,2)}_k, \cdots, H^{(c,B)}_k]$ is the $N_r \times N_t B$ aggregate channel transfer matrix from the super BTS to user $k$, and

$$T^{(c)}_k = [T^{(c,1)*}_k, T^{(c,2)*}_k, \cdots, T^{(c,B)*}_k]^*$$

is the aggregate transmit precoder for user $k$ over all $B$ BTSs. Unlike traditional downlink with co-located MIMO channels, the channel gains from any two antennas at different BTSs are guaranteed to be independent.
Denote $z_k^{(c)} = n_k^{(c)} + \sum_{\hat{c}=1,\hat{c}\neq c}^{C} H_k^{(\hat{c})} \sum_{j=1}^{K_k^{(\hat{c})}} T_j^{(\hat{c})} x_j^{(\hat{c})}$ as the sum of the noise and interference from other clusters, the covariance matrix of which is

$$R_k^{(c)} = \sigma_n^2 I_{N_r} + \sum_{\hat{c}=1,\hat{c}\neq c}^{C} \sum_{j=1}^{K_k^{(\hat{c})}} H_k^{(\hat{c})} T_j^{(\hat{c})} \mathbb{E}[x_j^{(\hat{c})} x_j^{(\hat{c})*}] T_j^{(\hat{c})*} H_k^{(\hat{c})*}$$

$$= \sigma_n^2 I_{N_r} + \sum_{\hat{c}=1,\hat{c}\neq c}^{C} \sum_{j=1}^{K_k^{(\hat{c})}} H_k^{(\hat{c})} T_j^{(\hat{c})} Q_j T_j^{(\hat{c})*} H_k^{(\hat{c})*}.$$  \hspace{1cm} (3)

**Assumption 4**: The interference plus noise covariance matrix is perfectly known at the mobile users and BTSs in the same cluster.

This covariance matrix can be estimated at mobile users by various methods, including the usage of silent period of the desired signal [39], the usage of pilot signal [40] and blind estimation [41] according to multiple access strategies. After such estimation, each user will feed back it to the BTS, which will be used to design precoding matrix.

### III. Clustered Multi-cell BD

In the proposed coordination strategy, both cluster interior and cluster edge users are served by multi-cell BD with pre-cancelation at the “super BTS”. BD is a linear precoding technique for downlink MU-MIMO systems, and single-cell BD has been well studied [28]–[32]. A major difference between multi-cell BD and single-cell BD is the power constraint. While single-cell BD has a total power constraint (TPC), each BTS in the cluster has its own power constraint, so multi-cell BD has a per-BTS power constraint (PBPC). In this section, we will design the clustered multi-cell BD, which can be separated into two parts: the precoding matrix design and the power allocation design. The design of the precoding matrix will consider other-cell interference (OCI) and follow the algorithm proposed in [32], which combines interference whitening at the receiver and a statistical OCI-aware precoder at the transmitter to reduce OCI and is shown to provide better sum rate performance than conventional BD. For the power allocation, three different algorithms will be proposed for PBPC.

#### A. Precoding Matrix Design

To suppress other-cell interference, we apply an $N_r \times N_r$ whitening filter $W_k^{(c)}$ at the receiver for each user, which is shown to be related with $R_k^{(c)}$ as [32]

$$[R_k^{(c)}]^{-1} = W_k^{(c)} W_k^{(c)*}.$$
With this whitening filter, the received signal for user $k$ after post-processing is
\[ r_k^{(c)} = W_k^{(c)} H_k^{(c)} \sum_{i=1}^{K} T_i^{(c)} x_i^{(c)} + W_k^{(c)} z_k^{(c)} = \hat{H}_k^{(c)} \sum_{i=1}^{K} T_i^{(c)} x_i^{(c)} + \hat{z}_k^{(c)} \] (4)
where $\hat{H}_k^{(c)} = W_k^{(c)} H_k^{(c)}$ and $\hat{z}_k^{(c)} = W_k^{(c)} z_k^{(c)}$ are equivalent channel matrix and noise vector.

Based on the equivalent signal model in (4), we can get the precoder for multi-cell BD. First, construct the aggregate interference matrix for user $k$ in cluster $c$ as
\[ \tilde{H}_k^{(c)} = [\tilde{H}_1^{(c)*} \cdots \tilde{H}_{k-1}^{(c)*} \tilde{H}_{k+1}^{(c)*} \cdots \tilde{H}_K^{(c)*}]^* . \] (5)
The principle idea of BD is to find the precoding matrix $T_k^{(c)}$ such that $\tilde{H}_k^{(c)} T_k^{(c)} = 0$, which means there is no inter-user interference. Thus $T_k^{(c)}$ lies in the null space of $\tilde{H}_k^{(c)}$. A sufficient condition for the existence of a nonzero effective channel matrix for user $k$, $\tilde{H}_k^{(c)} T_k^{(c)}$, is that at least one row of $\tilde{H}_k^{(c)}$ is linearly independent of the rows of $\tilde{H}_k^{(c)}$ [42]. This introduces the constraint that the number of total transmit antennas ($BN_t$) is no smaller than the number of total receive antennas ($KN_r$). Therefore, there is a constraint on the total number of users that can be served simultaneously in each cluster [29], [30], specified as follows:

**Lemma 1 (User constraint for multi-cell BD):** For a clustered MIMO network with $B$ BTSs per cluster, the maximum number of users that can be supported simultaneously in each cluster by multi-cell BD is bounded by
\[ K_{\text{max}} \leq \left\lfloor \frac{BN_t}{KN_r} \right\rfloor . \]
where $\lfloor x \rfloor$ is the maximum integer less than or equal to $x$.

Assuming $K \leq \left\lfloor \frac{BN_t}{KN_r} \right\rfloor$, we describe the precoding matrix design as follows. Let $\tilde{l}_k = \text{rank}(\tilde{H}_k^{(c)})$, and denote the singular value decomposition (SVD) of $\tilde{H}_k^{(c)}$ as
\[ \tilde{H}_k^{(c)} = \tilde{U}_k^{(c)} \tilde{\Lambda}_k^{(c)} \tilde{V}_k^{(c)*} \tilde{V}_k^{(c)*} \tilde{V}_k^{(c)*}, \]
where $\tilde{V}_{k,1}$ contains the first $\tilde{l}_k$ right singular vectors and $\tilde{V}_{k,0}$ contains the last $BN_t - \tilde{l}_k$ right singular vectors. Therefore, $\tilde{V}_{k,0}$ forms a null space basis of $\tilde{H}_k^{(c)}$, from which we can get $T_k^{(c)}$. In this paper, we assume the number of spatial streams for each user is $l_k = N_r$. If $l_k < N_r$ or there are extra transmit antennas, additional optimization can be done by picking the appropriate precoder subset [44] or doing coordinated beamforming [43].

2If antenna selection or a decoding matrix is applied at the mobile user, it is possible to support more users than this bound [30], [43], which we will not consider in this paper.
With the derived $T_k^{(c)}$, the received signal becomes

$$r_k^{(c)} = \hat{H}_k^{(c)} T_k^{(c)} x_k^{(c)} + z_k^{(c)}.$$  

Denote $T_b^{(c)} = [T_1^{(c,b)} \quad T_2^{(c,b)} \quad \cdots \quad T_K^{(c,b)}]$ as the submatrix associated with BTS $b$. Then the transmit power constraint for each BTS is

$$\text{Tr}(T_b^{(c)} Q^{(c)} T_b^{(c)*}) \leq P.$$  

The achievable sum rate per cell for the clustered multi-cell BD is then given by [32]

$$R_{CBD} = \max_{\text{Tr}(T_b^{(c)} Q^{(c)} T_b^{(c)*}) \leq P} \frac{1}{B} \sum_{k=1}^{K} \log_2 \left| I_{N_r} + \hat{H}_k^{(c)} T_k^{(c)} Q_k^{(c)} T_k^{(c)*} \hat{H}_k^{(c)*} \right|,$$  

where $Q_k^{(c)}$ is the covariance matrix for $x_k^{(c)}$, and $[Q_1^{(c)*}, Q_2^{(c)*}, \cdots ; Q_K^{(c)*}]^* = Q^{(c)}$.  

Denote the SVD of the effective channel $\hat{H}_k^{(c)} T_k^{(c)}$ as

$$\hat{H}_k^{(c)} T_k^{(c)} = U_k^{(c)} \begin{bmatrix} \Lambda_k^{(c)} & 0 \\ 0 & 0 \end{bmatrix} V_k^{(c)},$$  

where $\Lambda_k^{(c)} = \text{diag}(\lambda_{k,1}, \cdots, \lambda_{k,r_k})$, and $r_k = \text{rank}(\hat{H}_k^{(c)} T_k^{(c)})$. Let $\Lambda^{(c)} = \text{blockdiag}\{\Lambda_1^{(c)}, \cdots, \Lambda_K^{(c)}\}$. Then the sum rate can be written as

$$R_{CBD} = \max_{\text{Tr}(T_b^{(c)} Q^{(c)} T_b^{(c)*}) \leq P} \frac{1}{B} \log_2 \left| I + \Lambda^{(c)} \hat{Q}^{(c)} \Lambda^{(c)*} \right|,$$  

where $\hat{Q}^{(c)} = V^{(c)*} Q^{(c)} V^{(c)}$, and $V^{(c)} = \text{blockdiag}\{V_1^{(c)}, \cdots, V_K^{(c)}\}$.

### B. Power Allocation with PBPC

For the power allocation with PBPC, we propose one optimal and two sub-optimal schemes: user scaling and scaled water-filling. Both the optimal scheme and user scaling scheme are convex optimization problems, and the scaled water-filling scheme is modified from the conventional water-filling power allocation algorithm.

1) **Optimal Power Allocation:** The optimal power allocation matrix to maximize (7) is a diagonal matrix [2], denoted as $\hat{Q}_{OPT}^{(c)} = \text{diag}(\gamma_1, \cdots, \gamma_K)$, where $\gamma_1, \cdots, \gamma_K$ are the optimal coefficients. The corresponding achievable sum rate is given as

$$R_{CBD} = \max_{\text{Tr}(T_k^{(c)} Q^{(c)} T_b^{(c)*}) \leq P} \frac{1}{B} \sum_{k=1}^{K} \log_2 \left( 1 + \lambda_k^2 \gamma_k \right).$$
The power constraint can be rewritten as
\[
\sum_{k=1}^{K} \sum_{l=1}^{l_k} \|t_{k,l}^{(c,b)}\|^2 \gamma_{k,l} \leq P, b = 1, \ldots, B
\]
where \(t_{k,l}^{(c,b)}\) is the \(l\)th column of \(T_{k}^{(c,b)}\).

Thus, the optimal power allocation problem with PBPC can be formulated as
\[
R_{CBD} = \max_{\gamma_{i,j}} \frac{1}{B} \sum_{k=1}^{K} \sum_{l=1}^{l_k} \log \left(1 + \lambda_{k,l}^2 \gamma_{k,l}\right) \tag{8}
\]
subject to
\[
\begin{align*}
\sum_{k=1}^{K} \sum_{l=1}^{l_k} \|t_{k,l}^{(c,b)}\|^2 \gamma_{k,l} & \leq P, b = 1, \ldots, B \\
\gamma_{k,l} & \geq 0, l = 1, \ldots, l_k, k = 1, \ldots, K.
\end{align*}
\]
For this optimization problem, the power constraints for different users are coupled. Similar problems with per-antenna power constraints have been studied in [45], [46]. To the best of our knowledge, no efficient algorithm as water-filling for power allocation problems with per-antenna or per-BTS power constraints is available at this point. The objective function, however, is concave and the constraint functions are linear, so this is a convex optimization problem and can be solved numerically, e.g. with the interior-point method [47]. However, with a large number of users, and multiple transmit and receive antennas, it is quite complex to solve this optimization problem, and we propose two sub-optimal schemes in the following sections.

2) User Scaling (US): One sub-optimal power allocation scheme is user scaling, for which we weight the precoding matrix for each user, by choosing \(Q_{US}^{(c)} = \text{blockdiag}(\mu_1 I_{L_1}, \mu_2 I_{L_2}, \ldots, \mu_K I_{L_K})\), where \(\mu_k\) is to scale the precoding matrix of the \(k\)th user to meet the power constraint.

There are several reasons for doing this. First, with fewer weight terms it reduces the complexity for solving the optimization problem compared with the optimal scheme. Second, for each user an equal power allocation only results in a negligible capacity loss compared to the optimal water-filling, especially at high SINR, and with shadowing the power allocation across users plays a more important role than across streams of each user. Third, user scaling makes it easy to adjust transmit power between different users, for example, to meet a fixed rate constraint.

Denote \(\omega_k^{(c,b)} = \|T_k^{(c,b)}\|_F^2\). The optimization problem for the user scaling scheme is
\[
R_{US} = \max_{\gamma_{i,j}} \frac{1}{B} \sum_{k=1}^{K} \sum_{l=1}^{l_k} \log \left(1 + \lambda_{k,l}^2 \mu_k \right) \tag{9}
\]
subject to \[
\begin{align*}
\sum_{k=1}^{K} \omega_k^{(c,b)} \mu_k & \leq P, b = 1, \ldots, B \\
\mu_k & \geq 0, k = 1, \ldots, K.
\end{align*}
\]
Again, this is a convex optimization problem.

3) Scaled Water-Filling (SWF): As it is difficult to get an efficient algorithm to solve (8) and (9), we propose another sub-optimal scheme based on the water-filling algorithm.

First, consider a multi-cell BD system with TPC, whose sum rate is given by

\[
R_{TPC} = \max_{\text{Tr}(T^{(c)}(c)^*) \leq B P_{\text{max}}} \frac{1}{B} \log_2 | I + \Lambda^{(c)} \tilde{Q}_{TPC}^{(c)} \Lambda^{(c)*} |.
\]

The optimal power loading matrix \( \tilde{Q}_{TPC}^{(c)} = \Sigma^{(c)} \) is derived by water-filling [29]. To meet PBPC, we scale this matrix and choose \( \tilde{Q}_{SWF}^{(c)} = \mu \tilde{Q}_{TPC}^{(c)} \). The scaling factor \( \mu \in (0, 1) \) is given by

\[
\mu = \frac{P}{\max_{b=1,2,\ldots,B} \text{Tr}(T_b^{(c)} \tilde{Q}_{TPC}^{(c)} T_b^{(c)*})}
\]

Therefore, the sum rate per cell is given by

\[
R_{SWF} = \frac{1}{B} \log_2 | I + \mu \Lambda^{(c)} \Sigma^{(c)} \Lambda^{(c)*} |.
\]

C. Scheduling Schemes

From Lemma [7], there is a constraint on the maximum number of users a multi-cell BD system can support simultaneously. Therefore, with a large number of users in each cluster, it is necessary to schedule transmission for a subset of users, according to some performance criterion. The sum rate optimal scheduling algorithm is to exhaustively search over all the possible user combinations and pick the user set which maximizes the chosen performance metric, which is extremely complicated. We propose to use a sum rate based sub-optimal user selection algorithm inspired by [48], which has low complexity and approaches optimal performance.

Let \( U \) and \( S \) denote the sets of unselected and selected users respectively, and \( f_k \) denotes the performance metric for user \( k \). The proposed user selection algorithm is described in Table II. This is a greedy algorithm. In each step, one user is selected from the un-selected user set which adds the maximum performance gain, and the process stops when no more user can be added or the performance metric begins to decrease. We consider two different kinds of scheduling, maximum sum rate (MSR) and proportional fairness (PF), for different scenarios.
IV. INTER-CLUSTER COORDINATION

With the proposed coordination strategy, BTSs within a cluster serve their interior users with multi-cell BD, while the neighboring clusters coordinate with each other to serve edge users. It is possible for multiple BTSs to transmit data to an edge user, but for simplicity we consider that each user is served by one cluster. In this section, we will describe inter-cluster coordination in detail, and investigate two important system parameters: coordination distance and cluster size.

A. Inter-cluster Coordination with Multi-cell BD

The main idea of inter-cluster coordination is to do interference pre-cancelation at all the neighboring clusters for the active edge user, and select one cluster to transmit information data to this user. The precoding technique used in this paper for inter-cluster coordination is multi-cell BD, the same as for intra-cluster coordination. Each edge user selects a cluster based on the channel state, denoted as the home cluster, and feeds back this decision, while the other neighboring clusters act as helpers for the data transmission. The remaining clusters are interferer clusters. Different kinds of clusters and inter-cluster transmission are illustrated in Fig. 2.

For the following discussion and simulation, we focus on a home cluster and assume that when this cluster schedules an edge user, the neighboring clusters of this edge user will always help. This will happen if there are a small number of users in each cluster so that there are spare degrees of freedom at neighboring clusters. With a large number of users, joint scheduling across clusters is required. While we leave the full investigation of such a scheduling problem to future work, we propose a simple two-step approach: first, each cluster does scheduling within its own cluster, and the scheduled edge users inform the neighboring helper clusters; in the second step, each cluster deals with the requests from edge users in the neighboring clusters, and it selects to help some of these users while drops some scheduled users of its own. After this scheduling process, each cluster designs precoding matrices.

To the home cluster, there is no difference between the edge user and interior users, and the BD precoding matrix is designed as in Section III. For helper clusters, the precoding matrix design will be different. Without loss of generality, we consider the precoding matrix design at the helper cluster $c_1$ for the edge user $k_0$, which is served by its home cluster $c_0$. Denote

$$\mathbf{H}_{k_1}^{(c_1)} = [\mathbf{H}_{k_1}^{(c_1)*} \mathbf{H}_{k_0}^{(c_1)*}]_*, $$
where $H_{k_1}^{(c_1)}$ is the aggregate interference matrix of user $k_1$ to all the other active users in the cluster $c_1$ as in $(5)$, and $\hat{H}_{k_0}^{(c_1)} = W_{k_0}^{(c_0)} H_{k_0}^{(c_1)}$ is the effective channel after whitening filter from the cluster $c_1$ to the edge user $k_0$.

To pre-cancel the interference for both the edge user $k_0$ and other active users in the cluster $c_1$, the precoding matrix $T_{k_1}^{(c_1)}$ should satisfy the condition $\hat{H}_{k_1}^{(c_1)} T_{k_1}^{(c_1)} = 0$, i.e. it should lie in the null space of $\hat{H}_{k_1}^{(c_1)}$, which can be designed with SVD of $\hat{H}_{k_1}^{(c_1)}$ in the same way as in Section III. Similar to Lemma 1, there is a constraint on the number of users that can be supported simultaneously in the helper cluster, stated as follows:

**Lemma 2 (User constraint for the helper cluster):** For a helper cluster with $B$ BTSs and $k_e$ edge users to help, the maximum number of users that can be supported simultaneously by multi-cell BD in this cluster is bounded by

$$K_{\text{max}}^h \leq \left\lfloor \frac{B N_t}{N_r} \right\rfloor - k_e.$$ 

Therefore, to serve an edge user with inter-cluster coordination, the total number of users the network can support will be reduced, which induces a tradeoff between mitigating interference for edge users and maximizing the total throughput. This makes the choice of the inter-cluster coordination area important. Actually, the user constraints in Lemma 1 and Lemma 2 are due to the constraint on the total spatial degrees of freedom in each cluster, determined by the cluster size and the number of transmit antennas at each BTS. To serve an edge user all the neighboring clusters need to provide a certain number of degrees of freedom, which leaves fewer degrees of freedom to serve their own cluster interior users.

### B. Inter-cluster Coordination Distance

In this section, we present one method for grouping the users into cluster interior and cluster edge users, which will be employed in our simulations to illustrate our algorithms’ performance. Our proposed metric is based on the channel model in this paper, which includes Rayleigh fading, shadowing and path loss, and omnidirectional antennas. With this model, users near the cluster edge will have low signal power and high interference on average, and require inter-cluster coordination. Therefore, we do user grouping based on user locations, and determine an

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3The active users in a cluster are the users currently being served.
inter-cluster coordination area by the coordination distance, which is defined as follows and illustrated in Fig. 2.

**Definition 1:** Coordination distance, $D_c$, is the boundary between interior and edge users. If the distance of the user to the cluster edge is no larger than $D_c$, this user is classified as a cluster edge user; otherwise, it is a cluster interior user.

In a real implementation, this grouping could be performed based on average signal strength measurements (as employed in the handoff algorithm for example). We defer development of measurement based approaches, however, to future work.

Naturally there is a tradeoff when choosing $D_c$. If $D_c$ is large, more users will be treated as edge users and enjoy a substantial interference reduction, but the total throughout will be reduced as the total number of active users will be reduced. To balance fairness to edge users and the total sum rate, we will investigate the mean minimum rate and effective sum rate, as a function of $D_c$.

**Mean Minimum Rate:** Suppose that the mobile users are randomly distributed within each cluster. For a given $D_c$, for each realization of user locations, denote $R_{\text{min}}(D_c)$ as the minimum rate among all the users in the cluster. Mean minimum rate, $\bar{R}_{\text{min}}(D_c)$, is the mean value of $R_{\text{min}}(D_c)$, which is mainly determined by the edge users and will increase as $D_c$ increases.

**Effective sum rate:** As the edge user is served by multiple neighboring clusters, effectively its rate is shared by those clusters. If there are $N_{c,i}$ clusters serving user $i$, which is decided by its location and $D_c$, then the effective rate of this user for each coordinating cluster is $R_i/N_{c,i}$, where $R_i$ is given as follows according to (6)

$$R_i = \frac{1}{B} \log_2 \left| I_{N_r} + \hat{H}_i^{(c)} \mathbf{T}_i^{(c)} \mathbf{Q}_i^{(c)} \mathbf{T}_i^{(c)*} \hat{H}_i^{(c)*} \right|. \quad (12)$$

The effective sum rate for each cluster is defined as

$$R_{\text{sum}}(D_c) = \sum_{k=1}^{K} \frac{R_k}{N_{c,k}(D_c)}, \quad (13)$$

which will decrease with the increase of $D_c$ as more users become edge users.

For a home cluster, if all the users are interior users, then the effective sum rate is the conventional sum rate for this home cluster; if there is an edge user in this home cluster served

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4 Other similar performance metrics regarding the fairness to the edge users can also be applied, e.g., the achievable rate at a certain outage probability. The results, however, will not change.
by $N_c$ clusters, only $1/N_c$ of this user’s rate is counted into the effective sum rate of each serving cluster, including the home cluster. Therefore, the effective sum rate is the same for each cluster in a homogeneous network.

According to these definitions, $\bar{R}_{\min}(D_c)$ and $R_{\text{sum}}(D_c)$ characterize the opposing objectives of fairness to edge users and total sum throughput. We propose to use a utility function, $U(D_c)$, to evaluate the effect of $D_c$ on both $\bar{R}_{\min}$ and $R_{\text{sum}}$.

**Definition 2 (Utility Function $U(D_c)$):** The utility function $U(D_c)$ is defined by

$$U(D_c) = \alpha \frac{\bar{R}_{\min}(D_c)}{\max_{D_c} \bar{R}_{\min}(D_c)} + (1 - \alpha) \frac{R_{\text{sum}}(D_c)}{\max_{D_c} R_{\text{sum}}(D_c)}, 0 \leq \alpha \leq 1.$$  

(14)

where $\alpha$ is a variable reflecting the design objective. If it is more valuable to care about edge users, we can pick $\alpha \to 1$; if sum rate is more important, we can pick $\alpha \to 0$. As an example, we pick $\alpha = 1/2$, which means we treat relative changes of $\bar{R}_{\min}$ and $R_{\text{sum}}$ as of equal value to the system.

Simulation results of $U(D_c)$ for $D_c \in [0, R)$ are shown in Fig. with $B = 3$, $R = 1$ km and $K = 30$, and interference-free SNR at the cell edge is 18 dB. Totally 1000 realizations of user locations are run, and for each realization 1000 iterations are simulated with independent channel state. PF scheduling is used to provide fairness, and the scaled water-filling power allocation is used for computational efficiency. From the results we can see that the maximum value is achieved around $D_c = 0.35R$, which will be a proper choice.

Inter-cluster coordination may be designed for criterions other than $\bar{R}_{\min}$ and $R_{\text{sum}}$, but the idea of making a good tradeoff between the fairness for the edge users and the sum rate persists.

**C. Cluster Size**

With a fixed $D_c$, if the cluster size is small, the relative coordination area is large and there will be too many cluster edge users which will consume lots of the degrees of freedom and lower the effective sum rate. Alternatively, a large cluster size will have a relatively small coordination area, which has small sum rate loss. However, the requirement of full CSI and synchronization will prohibit a very large cluster size, and due to path loss the users benefit little from those

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5 When $D_c = R$, the area around the BTSs is classified as inter-cluster coordination area, which is not going to be the case as the nearby BTS can provide a high SINR for the users in this area. Therefore, we only consider $D_c \in [0, R)$ in this simulation.
BTSs far away. Therefore, to select a suitable cluster size is important for practical systems, which is also the motivation to propose the clustered coordination.

1) Sum Rates for Different Cluster Sizes: Fig. 4 shows the effective sum rates per cell for different cluster sizes, $B = 1, 3, 7, 19$, $D_c = 0.35R$, $R = 1$ km, and interference-free SNR at the cell edge is 18 dB. We can see that there is a diminishing gain with the increase of the cluster size: the 3-cell cluster has a much higher sum rate than the 1-cell cluster, and a 7-cell cluster has a rate gain about 2.5 bps/Hz over a 3-cell cluster, while from $B = 7$ to $B = 19$ the sum rate increases about 1 bps/Hz. The lower sum rate for $B = 1$ is due to its relative large edge area. Therefore, a 7-cell cluster can already achieve a significant part of the performance gain of the clustered coordination.

2) CSI Feedback Reduction: The CSI requirement for clustered coordination is on a cluster scale, which is greatly reduced compared to global coordination. With $C$ clusters and $B$ cells each cluster, totally there are $BC$ BTSs in the network. For global coordination, the effective channel matrix for each user is $N_r \times BCN_t$, while for clustered coordination it is $N_r \times BN_t$. Therefore, we get the following lemma:

Lemma 3 (CSI Reduction): For a cellular network with $N_{cell}$ cells, the amount of CSI feedback for clustered coordination with cluster size $B$ is $\frac{B}{N_{cell}}$ of that for global coordination.

The amount of CSI feedback for a 7-cell cluster system is only $\frac{7}{19}$ of that for a 19-cell cluster, while the performance of the 7-cell cluster system does not degrade much as shown in Fig. 4, so a cluster size of 7 is a reasonable choice for clustered coordination with the given transmit power.

V. Numerical Results

In this section, the performance of the proposed coordination strategy is shown via monte carlo simulation. We choose the number of antennas to be $N_t = 4$ and $N_r = 2$. The standard deviation of shadowing is 8dB, the path loss exponent is 3.7, and the cell radius is 1 km. Other than stated, the interference-free SNR at the cell edge is 18 dB, accounting for path loss and ignoring shadowing and Raleigh fading. We assume all the BTSs in other clusters transmit at full power. Mobile users are uniformly distributed within each cluster, and they are associated with clusters based on locations.
A. Sum Rates for Different Systems

First, we consider sum rates for different systems with maximum sum rate (MSR) scheduling. Besides the proposed multi-cell BD systems, we also compare with the following systems.

- **Multi-cell DPC with Total Power Constraint (TPC):** This is an upper bound for the downlink channel of multi-cell systems. We assume a total power constraint. DPC is applied across BTSs within the same cluster, and algorithm 2 in [49] is used for power allocation.

- **Multi-cell BD with TPC:** This is similar to the single-cell BD, and the water-filling algorithm can be applied to the aggregated channel for power allocation. This serves as an upper bound for multi-cell BD with PBPC, and can indicate the capacity loss due to the PBPC.

- **TDMA with Intercell Scheduling [15]:** Neighboring BTSs cooperatively schedule their transmission, and only one BTS is active to serve one user at each time slot.

- **Intercell Scheduling with BD:** Compared to TDMA with intercell scheduling only, this technique allows one BTS to serve multiple users at each time slot with BD.

Fig. 5 compares sum rates for different systems. There are several key observations.

1) The sum rates of multi-cell BD systems are much higher than that of the TDMA system with intercell scheduling, and are pretty close to that of DPC.

2) All multi-cell BD schemes have about the same performance.

3) There is only a marginal rate loss of PBPC to TPC.

B. Distribution of User Rates

Fig. 6 shows the cumulative distribution function (CDF) of mean rates for users. There are 30 users uniformly distributed in the cluster, $B = 3$ and $D_c = 0.35R$, and PF scheduling is applied. The simulation setting is similar as that for Fig. 3. We run 100 realizations for user locations, and for each realization 1000 iterations are simulated with independent channel state and the mean rates are stored. Totally, there are 3000 samples of user rates, with which we can plot the CDF. For example, the rate with 10% outage for intercell scheduling is 0.4 bps/Hz, for intercell scheduling with BD is 0.1 bps/Hz, and for clustered multi-cell BD with and without inter-cluster coordination are 0.6 and 0.8 bps/Hz, respectively. For multi-cell BD with inter-cluster coordination, nearly 60% users have mean rate larger than 1 bps/Hz and 10% users have mean rate larger than 2 bps/Hz, while for intercell scheduling only less than 5% of users can have mean rate larger than 1 bps/Hz.
C. Imperfect Channel Knowledge

Pilot symbols are required for channel estimation, and such training overhead becomes greater for a larger cluster size. However, there will be inevitable estimation errors, and the simulation results accounting for imperfect channel knowledge are shown in Fig. 7. The channel estimation model in [31] is used. At the BTSs, the available knowledge of the small-scale fading channel matrix of the $k$th user is given by $\tilde{H}_{k}^{(c,b)} = H_{k}^{(c,b)} + E_{k}^{(c,b)}$, where $H_{k}^{(c,b)}$ is the true channel matrix and $E_{k}^{(c,b)}$ is the channel error. Entries of $E_{k}^{(c,b)}$ follows i.i.d. complex Gaussian distribution with zero mean and covariance $\sigma_{MSE}^2 / 2$ per real dimension. The channel knowledge error is denoted as $\text{MSE} = 10 \log_{10} \sigma_{MSE}^2$ dB. To demonstrate the impact of imperfect CSI, we assume equal MSE for each user. The unequal MSE case is left to future work. We can see that the sum rates for BD systems decrease as MSE increases, while TDMA system with intercell scheduling is not sensitive to channel error, but the sum rates of multicell BD systems are always higher for the simulated range. This is due to the imperfect inter-user interference cancelation with channel error for MU-MIMO systems, and such interference is from the same propagation channel as the information signal, so it will greatly degrade the performance. Therefore, robust precoding schemes are required in practical systems.

VI. CONCLUSION

In this paper, a clustered BTS coordination strategy is proposed to increase the available spatial degrees of freedom for MIMO networks, and thus to reduce interference and increase the sum rate. A cluster structure is formed, and the users are grouped into cluster interior users and cluster edge users, served with different coordination strategies. Cluster interior users are served with intra-cluster coordination, i.e. multi-cell BD, while cluster edge users are served by multiple neighboring clusters to reduce inter-cluster interference. The precoder for multi-cell BD and system parameters for inter-cluster coordination are designed. It is shown that a small cluster size (such as 7) is enough to provide the benefits of the clustered coordination while greatly reducing the amount of channel feedback. Numerical results show that the proposed coordination strategy can provide robust sum rate and edge user rate gains.

There are many practical issues associated with clustered BTS coordination, requiring much future work. Compared with global coordination, the cluster structure reduces the amount of CSI required at the BTS, but with multiple antennas at both the BTS and mobiles, the amount
of CSI is still daunting. Current schemes are sensitive to synchronization and CSI error, which is expected to increase in a cluster system, so robust precoding schemes are needed. In this paper, we have assumed that all users have perfect knowledge about other-cluster interference. The investigation of the imperfect interference estimation is of practical importance and is a worthy topic of future work. Generally, the analysis of cellular MIMO networks is an open problem, given the randomness of user locations, path loss, and matrix channels with fading and shadowing.

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TABLE I

| Symbol | Description |
|--------|-------------|
| $P$    | the maximum transmit power at each BTS |
| $B$    | number of BTSs in each cluster |
| $C$    | number of clusters we consider |
| $K$    | number of users per cluster |
| $l_k$  | length of data symbol for user $k$ |
| $N_t$  | number of transmit antennas at each BTS |
| $N_r$  | number of receive antennas at each mobile |
| $R$    | radius of each cell |
| $D_c$  | coordination distance |
TABLE II
USER SELECTION ALGORITHM

1) Initially, set $S = \emptyset$ and $U = \{1, 2, \cdots, K\}$. Set $C_{old} = 0$.

2) While $|S| < K$ and $|S| < \frac{BN}{N_r}$
   a) for every $k \in U$
      i) $S = S + \{k\}$.
      ii) Calculate $C_{new} = \sum_{s \in S} f_s$.
      iii) if $C_{new} > C_{old}$, set $C_{old} = C_{new}$, and $k' = k$.
   b) Let $S = S + \{k'\}$, $U = U - \{k\}$.

Fig. 1. An example of the clustered network, with $B = 7$. Node “C” in each cluster is the virtual controller, which means full coordination within each cluster. The dashed line between controllers in neighboring clusters denotes the limited coordination between these clusters.
Fig. 2. An example of inter-cluster coordination, $B = 3$. $C_1$ is the home cluster, $C_2$ is the helper cluster, and $C_3$ is the interferer cluster. Solid lines denote transmissions of information signals and dotted lines are interference, and the cross on the dotted line means that the interference is pre-canceled.

Fig. 3. $U(D_c)$ for different $D_c$, $R = 1$ km.
Fig. 4. Effective sum rate per cell with different cluster size, $B = 1, 3, 7, 19$, $R = 1$ km, and $D_c = 0.35R$. The standard deviation of shadowing is $8$ dB, the path loss exponent is $3.7$.

Fig. 5. Sum rate per cell for different systems, with cluster size $B = 3$. “OPT” denotes the optimal power allocation scheme, “US” denotes the user scaling scheme, and “SWF” denotes the scaled water-filling scheme. “DPC TPC” is the multi-cell dirty paper coding with total power constraint, and “TDMA” is the opportunistic intercell scheduling.
Fig. 6. CDF of the rates for users in the cluster, $B = 3$, $D_c = 0.35R$.

Fig. 7. Sum rates for different systems with imperfect channel knowledge.