

Sum Rate Maximization of MIMO Broadcast Channels with Coordination of Base Stations

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Abstract—We consider cooperative downlink transmission in multiuser, multi-cell and multiple-antenna cellular networks. Recently, it has been shown that multi-base coordinated transmission has significant spectral efficiency gains over that without coordination. The capacity limits can be achieved using a non-linear precoding technique known as dirty paper coding, which is still infeasible to implement in practice. This motivates investigation of a simpler linear precoding technique based on generalized zero-forcing known as block diagonalization (BD).

In this paper, an enhanced form of BD is proposed for multiple-input multiple-output (MIMO) multi-base coordinated network. It involves optimizing the precoding over the entire null space of other users' transmissions. The performance limits of the multiple-antenna downlink with multi-base coordination are studied using duality of MIMO broadcast channels (BC) and MIMO multiple-access channels (MAC) under per-antenna power constraint, which has been established recently.

I. INTRODUCTION

While the capacity gains in point-to-point [1], [2] and multiuser [3] multiple input multiple output (MIMO) wireless systems are significant, due to intra and inter-cell interference in cellular networks this increase is very limited. To mitigate this limitation on the cellular downlink and achieve MIMO capacity gains, there has been a growing interest in network coordination [4]–[7]. Network coordination is based on cooperative transmission by base stations in multiuser, multiple-cell MIMO systems.

The multi-base coordinated transmission is often analyzed using a large MIMO Gaussian broadcast channel (BC) model with one base station and more antennas [8]–[10]. However, in this channel the sum power constraint must be replaced with per-antenna (or per-base station) power constraints. Moreover, the per-antenna power constraint is more realistic in practice. MIMO BC capacity region with sum power constraint has been previously established in [3], [11]–[13] using uplink-downlink duality. Under per-antenna power constraint, uplink-downlink duality for the multi-antenna downlink channel has been presented in [14]–[16] using Lagrangian duality concepts in convex optimizations [17].

It has been recognized that the so-called dirty paper coding strategy [18] achieves the capacity region for a downlink channel under the sum power constraint [3], [11], [12], [19] and also with the per-antenna power constraints [14]–[16].

Dirty paper coding is a technique that can pre-subtract interference at the transmitter. This requires the transmitted signals to be a result of successive encoding of information intended for the different users. Given an ordering of the

users, π , at the time of encoding information for user $\pi(j)$, signals of users $\pi(i < j)$ are known and can be taken into account in the encoding process to generate the signal for user $\pi(j)$. This means that the transmitter requires full non-causal knowledge of interfering signals for each user. Thus, perfect dirty paper coding implementation is infeasible. Moreover, finding the optimal ordering of users for successive encoding is a non-convex optimization problem. Furthermore, successive encoding to completely suppress interference requires adequate codes. The existence of such codes was proved in [18] and was extended later [20]. However, these proofs use random codes that lack algebraic structure and detectors, which is also difficult to implement. Consequently, due to its simplicity, block diagonalization (BD) is a more realistic technique to be considered [21]–[24].

The key idea of BD is linear precoding of data in such a way that transmission for each user lies within the null space of other users' transmissions. Therefore, the interference to other users is eliminated. BD has been employed for multi-base coordinated transmission in [4]–[7] but precoder optimization is not done over the entire null space of other users' transmissions. Also, the objective is maximizing the minimum rate among users and optimal precoders are not given in closed-form and left as convex optimization problems.

In this work, we aim to maximize the throughput of multiple-antenna multi-base coordinated network. Enhanced form of BD is presented which gives the optimal transmit covariances over the entire null space of other users' transmissions. The Lagrangian duality of throughput maximization problem is utilized to obtain the optimal precoder design. Despite the previous results [4]–[7], [25]–[27], we provide the optimal precoders structure for BD in multi-base coordinated network precisely and not via the iterative algorithms. The performance limits of the multi-base coordinated network has so far been discussed for single antenna case [6]. The generalization to multiple-antenna systems can be found through uplink-downlink duality of MIMO BC under per antenna power constraint introduced in [14]–[16].

II. SYSTEM MODEL

We consider the downlink of a multiuser MIMO system with K users and M base stations. Each user is equipped with N_r receive antennas and each base station is equipped with N_t transmit antennas. The multiple-cell (i.e., $M > 1$) downlink environment with cooperation between base stations has been

previously described in [4]–[7]. In this scheme, the base stations are connected via high-speed links and are capable of cooperatively transmitting information to mobile users. Therefore, each user's receive antennas may receive signal from all $N_t M$ transmit antennas. If we define $\mathbf{H}_{i,j} \in \mathbb{C}^{N_r \times N_t}$ to be the downlink channel matrix of user i from base station j , then the composite downlink channel matrix of user i is $\mathbf{H}_i = [\mathbf{H}_{i,1} \mathbf{H}_{i,2} \cdots \mathbf{H}_{i,M}]$. The composite downlink channel matrix for all users is defined as $\mathbf{H} = [\mathbf{H}_1^T \cdots \mathbf{H}_K^T]^T$, where $(\cdot)^T$ denotes the matrix transpose. The downlink channel is also called MIMO BC. Assuming that the same channel is used on the uplink and downlink, the composite uplink channel matrix is \mathbf{H}^H , where $(\cdot)^H$ denotes the matrix transpose conjugate (Hermitian). The uplink MIMO channel is also called MIMO multiple-access channel (MAC). In the BC, let $\mathbf{x} \in \mathbb{C}^{N_t M \times 1}$ denote the transmitted vector signal (from $N_t M$ base stations' antennas) and let $\mathbf{y}_k \in \mathbb{C}^{N_r \times 1}$ be the received signal at the receiver of the mobile user k . The noise at receiver k is represented by $\mathbf{z}_k \in \mathbb{C}^{N_r \times 1}$ containing N_r circularly symmetric complex Gaussian components ($\mathbf{z}_k \sim \mathcal{CN}(0, \sigma^2 \mathbf{I})$). The received signal for user k can be expressed as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \mathbf{z}_k, \quad k = 1, \dots, K \quad (1)$$

Thus, the transmit covariance matrix can be defined as $\mathbf{S}_x \triangleq \mathbb{E}[\mathbf{x}\mathbf{x}^H]$. The base stations are subject to the per-antenna power constraints $P_1, \dots, P_{N_t M}$, which imply

$$[\mathbf{S}_x]_{i,i} \leq P_i, \quad i = 1, \dots, P_{N_t M} \quad (2)$$

where $[\cdot]_{i,i}$ is the i th diagonal element of a matrix.

III. SUM CAPACITY OF COORDINATED NETWORK

The sum capacity of a MIMO BC with sum power constraint has been previously discussed in [3], [11], [12]. The sum capacity of a Gaussian vector broadcast channel under per-antenna power constraint is the saddle-point of a minimax problem [12]

$$\begin{aligned} C = \max_{\mathbf{S}_x} \min_{\mathbf{S}_z} \quad & \log \frac{|\mathbf{H}\mathbf{S}_x\mathbf{H}^H + \mathbf{S}_z|}{|\mathbf{S}_z|} \\ \text{subject to} \quad & [\mathbf{S}_x]_{i,i} \leq P_i, \quad \text{for } i = 1, \dots, N_t M \\ & \mathbf{S}_z^{(i)} = \sigma^2 \mathbf{I}_{N_r} \end{aligned} \quad (3)$$

where \mathbf{S}_z is the noise covariance matrix of \mathbf{z} such that $\mathbf{z}^T = [\mathbf{z}_1^T \cdots \mathbf{z}_K^T]$, and $\mathbf{S}_z^{(i)}$ refers to the i th block-diagonal term of \mathbf{S}_z . The maximization is over all transmit covariance matrices \mathbf{S}_x and the minimization is over all off-block diagonal terms of the noise covariance matrix \mathbf{S}_z . This is due to the fact that the capacity of MIMO BC equals the Sato bound, which is the capacity of a cooperative system with the worst case noise \mathbf{S}_z [13]. The sum capacity of a MIMO BC with individual per-antenna transmit power constraints $P_1, \dots, P_{M N_t}$ is the same as the sum capacity of a dual MIMO MAC with a sum power constraint $\sum_{i=1}^{M N_t} P_i$ and with an uncertain noise $\hat{\mathbf{S}}_z$ [14]–[16]. The Lagrangian dual of the minimax problem (3)

can be stated as [15], [16]

$$\begin{aligned} \max_{\hat{\mathbf{S}}_x} \min_{\hat{\mathbf{S}}_z} \quad & \log \frac{|\mathbf{H}^H \hat{\mathbf{S}}_x \mathbf{H} + \hat{\mathbf{S}}_z|}{|\hat{\mathbf{S}}_z|} \\ \text{subject to} \quad & \text{tr}(\hat{\mathbf{S}}_x) \leq \text{tr}(\mathbf{P}) \\ & \text{tr}(\hat{\mathbf{S}}_z \mathbf{P}) \leq \text{tr}(\mathbf{P}) \\ & \hat{\mathbf{S}}_z \text{ is diagonal, } \hat{\mathbf{S}}_z \succeq 0, \hat{\mathbf{S}}_x \succeq 0 \end{aligned} \quad (4)$$

where $\mathbf{P} = \text{diag}(P_1, \dots, P_{N_t M})$ is a diagonal matrix of individual maximum transmit power, $\text{tr}(\cdot)$ denotes the trace of a matrix, and \succeq represents matrix inequality defined on the cone of non-negative definite matrices. Thus, the Lagrangian dual corresponds to a MAC with linearly constrained noise. This duality result has been generalized to the entire capacity region [16]. The dual minimax problem is convex-concave and thus the original downlink optimization problem can be much more efficiently solved in the dual domain. An efficient algorithm using Newton's method [17] is used in [14] and [16] to solve the dual minimax problem, which finds an efficient search direction for the maximization and the minimization simultaneously. This capacity result is used to characterize the sum capacity of the multi-base coordinated network and thus presents the performance limits of proposed transmission schemes.

IV. BLOCK DIAGONALIZATION OF COORDINATED NETWORK

The transmitted symbol of user k is an N_r -dimensional vector \mathbf{u}_k which is multiplied by a $N_t M \times N_r$ precoding matrix \mathbf{W}_k and sent to the base station's antenna array. Thus, since all base station antennas are coordinated, the complex antenna output vector \mathbf{x} is composed of signals for all K users. Therefore, \mathbf{x} can be written as follows

$$\mathbf{x} = \sum_{k=1}^K \mathbf{W}_k \mathbf{u}_k \quad (5)$$

where $\mathbb{E}[\mathbf{u}_k \mathbf{u}_k^\dagger] = \mathbf{I}_{N_r}$. The received signal \mathbf{y}_k for user k can be represented as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{W}_k \mathbf{u}_k + \sum_{j \neq k} \mathbf{H}_k \mathbf{W}_j \mathbf{u}_j + \mathbf{z}_k \quad (6)$$

where \mathbf{z}_k denoted the additive white Gaussian noise (AWGN) vector for user k with variance $\mathbb{E}[\mathbf{z}_k \mathbf{z}_k^H] = \sigma^2 \mathbf{I}_{N_r}$. Entries of $\mathbf{H}_{i,j}$ are zero mean i.i.d. complex Gaussian random variables with variance $\sigma_{ij}^2 \propto d_{ij}^{-\beta}$ where d_{ij} is the distance between base station j and user i and β is the path loss exponent. Gaussian distributed channel gains ensure $\text{rank}(\mathbf{H}_{i,j}) = \min(N_r, N_t)$ for all i and j with probability one. Per-antenna power constraints (2) impose a power constraint

$$\begin{aligned} [\mathbf{S}_x]_{i,i} &= \mathbb{E}[\mathbf{x}\mathbf{x}^H]_{i,i} \\ &= \left[\sum_{k=1}^K \mathbf{W}_k \mathbf{W}_k^H \right]_{i,i} \leq P_i, \quad i = 1, \dots, N_t M \end{aligned} \quad (7)$$

on each transmit antenna.

The key idea of zero-forcing network coordination is BD [21]. Each user's data \mathbf{u}_k is precoded with the matrix \mathbf{W}_k , such that

$$\mathbf{H}_k \mathbf{W}_j = 0 \quad \text{for all } k \neq j \quad \text{and } 1 \leq k, j \leq K. \quad (8)$$

Hence the received signal for user k can be simplified to

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{W}_k \mathbf{u}_k + \mathbf{z}_k. \quad (9)$$

Let $\tilde{\mathbf{H}}_k = [\mathbf{H}_1^T \cdots \mathbf{H}_{k-1}^T \mathbf{H}_{k+1}^T \cdots \mathbf{H}_K^T]^T$. Zero-interference constraint in (8) forces \mathbf{W}_k to lie in the null space of $\tilde{\mathbf{H}}_k$ which requires a dimension condition $N_t M \geq N_r K$ be satisfied. For simplicity of our setup, we assume that $N_r = N_t$ and we focus on $K = M$ users which are assigned to one subband and the unserved users are referred to another subband (For setup details refer to Section V). To simplify further analysis, we normalize the vectors in (5) and divide each vector by the standard deviation of the additive noise component, σ . Then, the components of \mathbf{z}_k have unit variance. Assuming that $\tilde{\mathbf{H}}_k$ is a full rank matrix $\text{rank}(\tilde{\mathbf{H}}_k) = (K-1)N_r$, we perform singular value decomposition (SVD)

$$\tilde{\mathbf{H}}_k = \mathbf{U}_k \mathbf{\Lambda}_k [\mathbf{\Upsilon}_k \mathbf{V}_k]^T \quad (10)$$

where $\mathbf{\Upsilon}_k$ holds the first $(K-1)N_r$ right singular vectors corresponding to non-zero eigenvalues, and $\mathbf{V}_k \in \mathbb{C}^{M N_t \times N_r}$ contains the last N_r right singular vectors corresponding to zero eigenvalues of $\tilde{\mathbf{H}}_k$. It can be observed that $\mathbf{V}_k^H \mathbf{V}_k = \mathbf{I}_{N_r}$. The columns of \mathbf{V}_k form a basis set in the null space of $\tilde{\mathbf{H}}_k$, and hence \mathbf{W}_k can be any linear combination of \mathbf{V}_k , i.e.,

$$\mathbf{W}_k = \mathbf{V}_k \mathbf{\Psi}_k, \quad k = 1, \dots, K \quad (11)$$

where $\mathbf{\Psi}_k \in \mathbb{C}^{N_r \times N_r}$ can be any arbitrary matrix subject to the per-antenna power constraints. Despite the precoder design in [7] where $\mathbf{\Psi}_k$ is assumed to be diagonal, in our analysis $\mathbf{\Psi}_k$ is any arbitrary matrix which means that the entire null space of $\tilde{\mathbf{H}}_k$ is considered. Hence, the received signal for user k can be rewritten as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{V}_k \mathbf{\Psi}_k \mathbf{u}_k + \mathbf{z}_k. \quad (12)$$

Denote $\mathbf{\Phi}_k = \mathbf{\Psi}_k \mathbf{\Psi}_k^H \in \mathbb{C}^{N_r \times N_r}$, $k = 1, \dots, K$, which are positive definite matrices. The user k 's rate is given by

$$R_k = \log |\mathbf{I} + \mathbf{H}_k \mathbf{V}_k \mathbf{\Phi}_k \mathbf{V}_k^H \mathbf{H}_k^H|. \quad (13)$$

Therefore, the throughput maximization problem can be expressed as

$$\begin{aligned} & \text{maximize} \quad \sum_{k=1}^K \log |\mathbf{I} + \mathbf{H}_k \mathbf{V}_k \mathbf{\Phi}_k \mathbf{V}_k^H \mathbf{H}_k^H| \\ & \text{subject to} \quad \left[\sum_{k=1}^K \mathbf{V}_k \mathbf{\Phi}_k \mathbf{V}_k^H \right]_{i,i} \leq P_i, \quad i = 1, \dots, N_t M \\ & \quad \mathbf{\Phi}_k \succeq 0, \quad k = 1, \dots, K. \end{aligned} \quad (14)$$

where the maximization is over positive semidefinite matrices $\mathbf{\Phi}_1, \dots, \mathbf{\Phi}_K$. Thus, the transmit covariances can be defined as

$$\mathbf{S}_k = \mathbf{V}_k \mathbf{\Phi}_k \mathbf{V}_k^H, \quad k = 1, \dots, K. \quad (15)$$

The problem of maximizing throughput is a convex optimization of transmit covariance matrices

$$\begin{aligned} & \text{maximize} \quad \sum_{k=1}^K \log |\mathbf{I} + \mathbf{H}_k \mathbf{S}_k \mathbf{H}_k^H| \\ & \text{subject to} \quad \left[\sum_{k=1}^K \mathbf{S}_k \right]_{i,i} \leq P_i, \quad i = 1, \dots, N_t M \\ & \quad \mathbf{S}_k \succeq 0, \quad k = 1, \dots, K. \end{aligned} \quad (16)$$

where the optimization is over the set of positive semidefinite matrices $\mathbf{S}_1, \dots, \mathbf{S}_K$. Suppose $\mathbf{S}_1, \dots, \mathbf{S}_K$ to be optimal solution for problem (16), which are not full rank. The downlink channels \mathbf{H}_k , $k = 1, \dots, K$ are not necessarily square and invertible. Therefore, the first step is to factorize

$$\mathbf{S}_k = \mathbf{Q} \mathbf{S}_k \mathbf{Q}^H, \quad \mathbf{G}_k = \mathbf{H}_k \mathbf{Q}^H, \quad k = 1, \dots, K \quad (17)$$

where $\mathbf{S}_k \in \mathbb{C}^{N_r \times N_r}$, $k = 1, \dots, K$ are full rank matrices, $\mathbf{Q} \in \mathbb{C}^{N_r \times N_t M}$ is a matrix consisting of orthonormal rows ($\mathbf{Q} \mathbf{Q}^H = \mathbf{I}_{N_r}$). Therefore, \mathbf{G}_k is an equivalent channel for user k which is square and invertible. Thus, the optimization problem (16) over \mathbf{S}_k s can be rewritten as

$$\begin{aligned} & \text{maximize} \quad \sum_{k=1}^K \log |\mathbf{I} + \mathbf{G}_k \mathbf{S}_k \mathbf{G}_k^H| \\ & \text{subject to} \quad \left[\sum_{k=1}^K \mathbf{Q}^H \mathbf{S}_k \mathbf{Q} \right]_{i,i} \leq P_i, \quad i = 1, \dots, N_t M \\ & \quad \mathbf{S}_k \succeq 0, \quad k = 1, \dots, K. \end{aligned} \quad (18)$$

The Lagrangian function can be described as

$$\begin{aligned} L(\mathbf{\Sigma}_1, \dots, \mathbf{\Sigma}_K; \mathbf{\Omega}) &= \sum_{k=1}^K \log |\mathbf{I} + \mathbf{G}_k \mathbf{\Sigma}_k \mathbf{G}_k^H| \\ & \quad - \text{tr} \left[\mathbf{\Omega} \left(\sum_{k=1}^K \mathbf{Q}^H \mathbf{\Sigma}_k \mathbf{Q} - \mathbf{P} \right) \right] \end{aligned} \quad (19)$$

where $\mathbf{\Omega}$ is dual variable which is a diagonal with non-negative elements. The Karush-Kuhn-Tucker (KKT) conditions requires that at the optimal values of primal and dual variables [17]

$$\begin{aligned} \text{tr} \left[\mathbf{\Omega} \left(\sum_{k=1}^K \mathbf{Q}^H \mathbf{\Sigma}_k \mathbf{Q} - \mathbf{P} \right) \right] &= 0, \\ \nabla_{\mathbf{\Sigma}_k} L &= 0, \quad k = 1, \dots, K \\ \mathbf{\Omega}, \mathbf{\Sigma}_k &\succeq 0, \quad k = 1, \dots, K. \end{aligned} \quad (20)$$

Optimal values of $\mathbf{\Sigma}_k$ can be obtained from $\partial L / \partial \mathbf{\Sigma}_k = 0$, i.e.,

$$\mathbf{G}_k^H (\mathbf{G}_k \mathbf{\Sigma}_k \mathbf{G}_k^H + \mathbf{I})^{-1} \mathbf{G}_k = \mathbf{Q} \mathbf{\Omega} \mathbf{Q}^H, \quad k = 1, \dots, K. \quad (21)$$

Hence, the optimal values of $\mathbf{\Sigma}_k$ are given by

$$\mathbf{\Sigma}_k = (\mathbf{Q} \mathbf{\Omega} \mathbf{Q}^H)^{-1} - \mathbf{G}_k^{-1} \mathbf{G}_k^{-H}, \quad k = 1, \dots, K. \quad (22)$$

Since the constraint functions are affine, strong duality holds and thus dual objective reaches a minimum at the optimal value of the primal problem [17]. Therefore, by replacing the optimal values of $\mathbf{\Sigma}_k$ from (22) into (19)

$$\begin{aligned} L(\mathbf{\Omega}) &= - \sum_{k=1}^K \log |\mathbf{G}_k^{-H} (\mathbf{Q} \mathbf{\Omega} \mathbf{Q}^H) \mathbf{G}_k^{-1}| - K N_r \\ & \quad + \text{tr} \left[\mathbf{\Omega} \left(\sum_{k=1}^K \mathbf{Q}^H \mathbf{G}_k^{-1} \mathbf{G}_k^{-H} \mathbf{Q} + \mathbf{P} \right) \right]. \end{aligned} \quad (23)$$

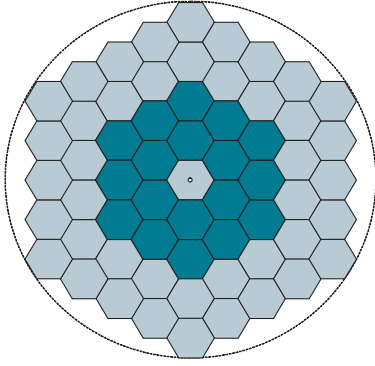


Fig. 1. 61-cell cellular layout with a base at the center of each hexagon. Each cell receives interference from two surrounding tiers of cells (highlighted).

The maximum value of the above dual problem arise when $\partial L/\partial \Omega = 0$ which gives

$$K \mathbf{Q} \mathbf{Q}^H (\mathbf{Q} \Omega \mathbf{Q}^T)^{-1} \mathbf{Q} = \sum_{k=1}^K \mathbf{Q}^H \mathbf{G}_k^{-1} \tilde{\mathbf{H}}_k^{-H} \mathbf{Q} + \mathbf{P}. \quad (24)$$

Hence, the optimal value of the dual variable Ω can be expressed as

$$\Omega = K \mathbf{Q} \mathbf{Q}^H \left(\sum_{i=1}^K \mathbf{G}_i^{-1} \mathbf{G}_i^{-H} + \mathbf{Q} \mathbf{P} \mathbf{Q}^H \right)^{-1} \mathbf{Q}. \quad (25)$$

Therefore, the optimal values of \mathbf{S}_k , $k = 1, \dots, K$ are

$$\mathbf{S}_k = \frac{1}{K} \mathbf{Q}^H \left(\sum_{i=1}^K \mathbf{G}_i^{-1} \mathbf{G}_i^{-H} \right) \mathbf{Q} + \frac{1}{K} \mathbf{P} - \mathbf{Q}^T \mathbf{G}_k^{-1} \mathbf{G}_k^{-H} \mathbf{Q}. \quad (26)$$

One can verify that the above transmit covariance matrices satisfy the constraints in the original primal problem. From (15) it can be observed that $\Phi_k = \mathbf{V}_k^H \mathbf{S}_k \mathbf{V}_k$, therefore,

$$\begin{aligned} \Phi_k &= \frac{1}{K} \mathbf{V}_k^H \mathbf{Q}^H \left(\sum_{i=1}^K \mathbf{G}_i^{-1} \mathbf{G}_i^{-H} \right) \mathbf{Q} \mathbf{V}_k + \frac{1}{K} \mathbf{V}_k^H \mathbf{P} \mathbf{V}_k \\ &\quad - \mathbf{V}_k^H \mathbf{Q}^T \mathbf{G}_k^{-1} \mathbf{G}_k^{-H} \mathbf{Q} \mathbf{V}_k, \quad k = 1, \dots, K \end{aligned} \quad (27)$$

which gives the precoders structures explicitly.

V. NUMERICAL RESULTS

Our cellular network setup consists of 4 tiers of hexagonal cells with a base station located at the center of each hexagon (Fig. 1). The propagation model of base stations to mobile users is characterized by three factors: a path loss component which is proportional to $d_{ij}^{-\beta}$ where d_{ij} denotes distance from base station j to mobile user i and β is the path loss component, and two other random components. Lognormal shadow fading and Rayleigh fading assumed to be the random components of the propagation model. Path loss characteristics follow the Hata model [28], [29] and are summarized in Table I (For details refer to [4], [7]).

The networks we study are with 100% loading which means each base stations is associated with one user on each subband.

Users are randomly, uniformly, and independently located on 61-cell network. Users are assigned to the base station with the strongest signal one by one. If the corresponding base station has already been loaded with a previous user, the unserved user will be referred to another subband other than the one we are focused on. At the end, in each subband, each base station has been associated with one user. For simulations of the proposed BD scheme, over 500 network instances are generated.

Fig. 2 shows the average sum rate per base station achievable with the optimal BD method for single-antenna system and multiple-antenna systems with 2 and 4 transmit/receive antennas at each base station and mobile user versus interference-free signal to noise ratios (SNR) at the reference distance (cell border). The BD network coordination methods are also compared to the sum capacity results using the infeasible-start Newton's method algorithm [17] for minimax sum capacity problem given in [16]. At higher SNRs, each mobile user receives signal from more base station antennas, therefore the sum rate difference between the BD and sum capacity increases. Achieving sum capacity requires dirty paper coding, which is infeasible to implement, while the BD method is implementable.

The MIMO capacity gains using proposed BD are shown in Fig. 3 for different SNRs at the cell border. Thus, using multi-base coordinated network enables capacity gains employing multiple antennas. In Fig. 4, we have compared the proposed BD technique with the zero-forcing coherently coordinated transmission (ZF-CCT) in [7] but for sum rate maximization. However, It is shown that our BD schemes outperforms the ZF-CCT due to optimality of precoders. The sum capacity results are given using the uplink-downlink duality established in [14]–[16].

VI. CONCLUSION

This paper illustrates sum rate maximization of multiple-antenna multi-base coordinated network. The multi-base coordinated network can be identified as a multiple-input multiple-output (MIMO) broadcast channel (BC) with per-antenna (or per-base) power constraint. It is well known that the so-called dirty paper coding strategy achieves the capacity region, however it is infeasible to implement in practice. Therefore, we have focused on more intuitive and simpler transmission techniques such as block diagonalization (BD).

TABLE I
SIMULATION PARAMETERS

| Parameter | Value |
|-----------------------------------|----------|
| Shadow fading standard deviation | 8 dB |
| Maximum transmit power, p_{max} | 10 W |
| Transmit antenna gain, G_t | 10.3 dBi |
| Path loss, β | 3.8 |
| Receiver noise figure | 5 dB |
| Receiver temperature | 300 K |
| Channel bandwidth | 5 MHz |
| Cell radius | 1.6 km |

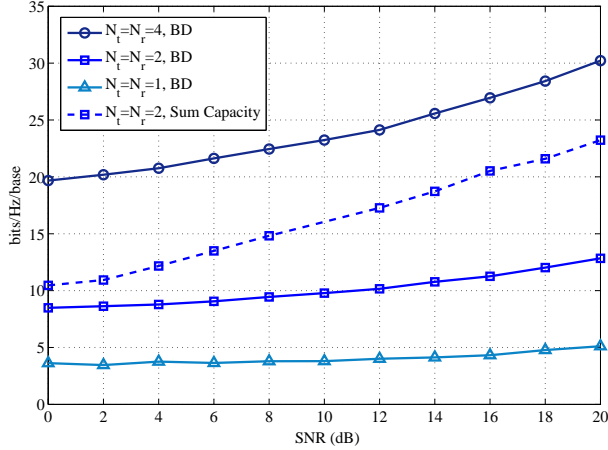


Fig. 2. Average sum rate per base with BD precoder (11) for (1,1), (2,2), and (4,4) systems. The sum capacity is given for (2,2) system.

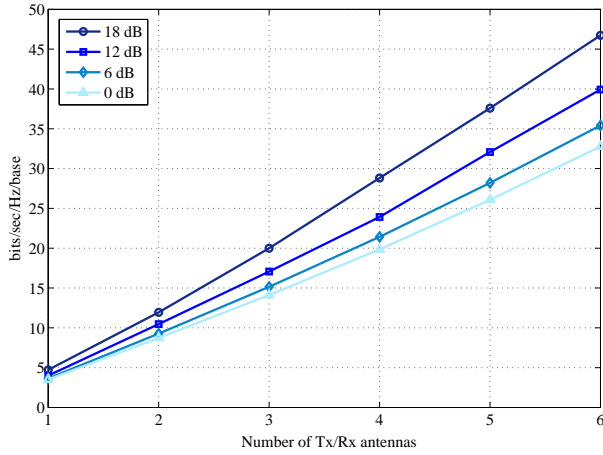


Fig. 3. MIMO capacity gains using the BD precoder (11) for different SNRs at the cell border.

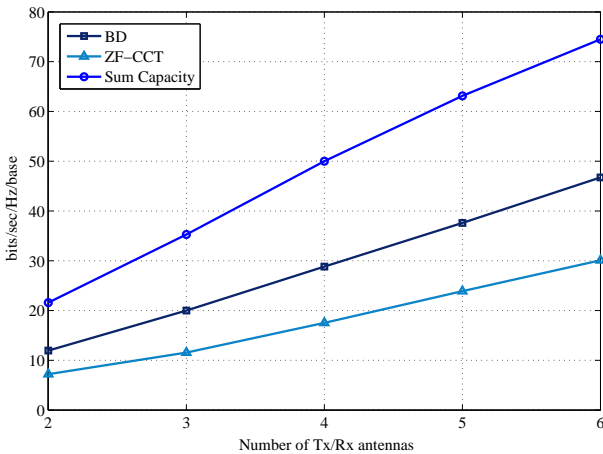


Fig. 4. Comparison of BD precoder (11), ZF scheme for sum rate maximization [7], and the sum capacity results [16]. The interference-free SNR at the cell border is 18 dB.

An enhanced form of BD has been derived under Lagrangian duality framework and by optimizing precoders over the entire null space of other users' transmissions. Optimal BD precoders are given. Moreover, it is shown that our precoders outperform previous BD results in multi-base coordinated networks. The sum capacity of the system can be determined using the uplink-downlink duality with the per-antenna power constraint.

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