Distributed Precoding for Network MIMO

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***Abstract*—Network MIMO, in which base stations cooperate and coordinate through a centralized design, is an attractive technology that promises higher spectral efficiency and lower inter-cell interference. However, such performance gain comes at the cost of extensive exchange of signal information (SI), channel state information (CSI), and coordinated precoding information over backhaul links. In this paper, we propose a distributed precoding strategy for network MIMO which does not require explicit exchange of SI and CSI among the cooperating base stations. Instead, each base station derives its own precoder to simultaneously minimize the out-of-cell interference as well as maximize the intra-cell sum rate. A robust design is also proposed, to address CSI imperfectness, and which recovers some of the rate reduction due to the CSI uncertainty.**

I. Introduction

Demand for broadband wireless services is growing at an accelerated pace. Due to limited frequency spectrum resource, we inevitably need to increase base station (BS) density, or even deploy single frequency networks. Such aggressive reuse of frequencies leads to the undesirable situation of increased interference between BSs. Ironically, this results in lower data rates since interference becomes the critical limiting factor. Network MIMO promises to offer significant gains in spectral efficiency for such interference-limited systems [1]. The optimum capacity-achieving strategy requires a system-wide joint dirty paper coding (DPC) by treating all BSs' antennas collectively as though they are co-located [2]. Thus, channel state information (CSI) and signal information (SI) need to be shared among all the different BSs. Due to the latency of exchange of information among BSs, this strategy can only serve as an ideal upper bound on practical achievable rates that network MIMO can offer.

As a result, there is an increasing interest to investigate other network MIMO designs, particularly for broadcast channels [3]–[6]. Linear block diagonalization (LBD) methods null out inter-cell interference using linear zero-forcing (ZF) techniques to create a block diagonal effective channel from the BSs to the users, such that each user receives its desired signal with minimal interference [4]. Zero-forcing beamforming [5] and game theory optimization for intelligent scheduling across frequency and time [6] have also been proposed. In most cases, joint transmission is performed by multiple cooperating base stations. However, such transmit processing over several BSs may not be practical due to cost of backhaul capacities and the latency incurred by the exchange of CSI and SI between BSs [2].

In this work, we propose a distributed precoder design, called leakage projected DPC (LPD), for network MIMO broadcast channels. We consider a scenario where BSs are equipped with multiple antennas and each cell is occupied by multiple users equipped with multiple antennas. The main feature of our precoder design is that each BS designs its own precoder with no requirement on SI from other BSs. Each BS only requires the CSI associated with the random channels from itself towards its served users within its cell and the interfered users in other cells. If time division duplex (TDD) is used, this CSI can be obtained implicitly during the uplink phase, without the need for explicit feedback. Using the LPD, each base station simultaneously minimizes the interference caused to users outside the cell and maximizes the sum rate of the users inside the cell. Unlike prior works [7]–[9], our precoder is designed to tackle both intra-cell (IC) and out-of-cell (OC) interference in a distributed manner. Numerical results show that the LPD method outperforms the non-cooperating single-cell processing approach and orthogonal transmission in terms of sum rate. To enhance the robustness of the LPD method with respect to CSI uncertainty, we also propose a robust LPD strategy which provides rate improvement over the LPD method as the channel uncertainty increases.

The following notation is used. Bold lowercase letters denote column vectors, bold uppercase letters denote matrices, and non-bold letters in italics denote scalar values. $\min(a,b)$ is the minimum of two real numbers a and b. $(\cdot)^T$ and $(\cdot)^H$ denote the matrix transpose and conjugate transpose operations respectively. $\mathcal{E}[\cdot]$ stands for statistical expectation. $\mathbb{C}^{P\times Q}$ denotes the space of complex $P\times Q$ matrices. $\mathbf{1}_{P\times Q}$ is a $P\times Q$ matrix with all elements equal to 1. The distribution of a circularly symmetric complex Gaussian (CSCG) vector with mean vector $\mathbf{m}$ and covariance matrix $\mathbf{R}$ is denoted by $\mathcal{CN}(\mathbf{m},\mathbf{R})$, and $\sim$ means "distributed as". $\mathbf{R_x} = \mathcal{E}[\mathbf{x}\mathbf{x}^H]$ is the covariance matrix of a vector $\mathbf{x}$. $||\cdot||_2$ denotes the vector Euclidean norm, while $\mathbf{I}_N$ denotes the $N\times N$ identity matrix. $\mathrm{Tr}(\mathbf{A})$ stands for the trace of a matrix $\mathbf{A}$. $[\mathbf{A}]_{i,j}$ is the scalar entry of $\mathbf{A}$ in the i-th row and j-th column. $\mathrm{vec}(\mathbf{A})$ is a column vector composed of the entries of $\mathbf{A}$ taken column-wise. $\mathrm{diag}(\mathbf{A})$ represents the diagonal matrix with the same diagonal as the matrix $\mathbf{A}$. $\mathrm{blkdiag}(\mathbf{A}_1,\mathbf{A}_2,\ldots,\mathbf{A}_K)$ denotes a block diagonal matrix whose block diagonal elements are $\mathbf{A}_k, k=1,2,...,K$.

II. System Model

We consider a downlink cellular network with M cells of N_{T} base station antennas each, serving K users with N_{R} receive antennas each. Assuming a synchronous network MIMO system, the received signal vector of the system can be written as

$$\mathbf{y}_{\rm sys} = \mathbf{H}_{\rm sys}\mathbf{x}_{\rm sys} + \mathbf{z}_{\rm sys}, \quad (1)$$

where $\mathbf{y}_{\rm sys} = {\rm vec}([\mathbf{y}_1, \mathbf{y}_2, \ldots, \mathbf{y}_M]) \in \mathbb{C}^{MKN_{\rm R}\times 1}$ is the system receive signal vector, such that $\mathbf{y}_m \in \mathbb{C}^{KN_{\rm R}\times 1}$ is the received signal vector at the m-th cell, $\mathbf{x}_{\rm sys} = {\rm vec}([\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_M]) \in \mathbb{C}^{MN_{\rm T}\times 1}$ is the system transmit signal vector, such that $\mathbf{x}_m \in \mathbb{C}^{N_{\rm T}\times 1}$ is the transmit signal vector from the m-th BS with average power constraint P_m, and $\mathbf{z}_{\rm sys} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{MKN_{\rm R}})$ is the additive CSCG noise vector. The downlink random channel matrix $\mathbf{H}_{\rm sys} \in \mathbb{C}^{MKN_{\rm R}\times MN_{\rm T}}$ is given by

$$\mathbf{H}_{\rm sys} = \begin{bmatrix} \mathbf{H}_1 & \mathbf{H}_{2\to 1} & \cdots & \mathbf{H}_{M\to 1} \\ \mathbf{H}_{1\to 2} & \mathbf{H}_2 & \cdots & \mathbf{H}_{M\to 2} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H}_{1\to M} & \mathbf{H}_{2\to M} & \cdots & \mathbf{H}_M \end{bmatrix}, \quad (2)$$

where $\mathbf{H}_m \in \mathbb{C}^{KN_{\rm R}\times N_{\rm T}}$ denotes the random channel matrix from the m-th BS to all its served users and $\mathbf{H}_{n\to m}$ denotes the random channel matrix from the n-th BS to all the K users in the m-th cell.

By denoting $\mathbf{y}_m = {\rm vec}([\mathbf{y}_{m,1}, \mathbf{y}_{m,2}, \ldots, \mathbf{y}_{m,K}]) \in \mathbb{C}^{KN_{\rm R}\times 1}$, the received signal of the k-th user at the m-th cell is given by

$$\mathbf{y}_{m,k} = \mathbf{H}_{m,k}\mathbf{x}_m + \sum_{n\neq m}^{M} \mathbf{H}_{n\to m,k}\mathbf{x}_n + \mathbf{z}_{m,k}, \quad (3)$$

where $\mathbf{H}_{m,k} \in \mathbb{C}^{N_{\rm R}\times N_{\rm T}}$ is the random channel matrix from the m-th BS to the k-th user such that $\mathbf{H}_m = [\mathbf{H}_{m,1}^T, \mathbf{H}_{m,2}^T, \ldots, \mathbf{H}_{m,K}^T]^T \in \mathbb{C}^{KN_{\rm R}\times N_{\rm T}}$, $\mathbf{H}_{n\to m,k} \in \mathbb{C}^{N_{\rm R}\times N_{\rm T}}$ is the random channel matrix from the n-th BS to the k-th user in the m-th cell such that $\mathbf{H}_{n\to m} = [\mathbf{H}_{n\to m,1}^T, \mathbf{H}_{n\to m,2}^T, \ldots, \mathbf{H}_{n\to m,K}^T]^T$, and $\mathbf{z}_{m,k} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{N_{\rm R}})$. To accommodate for multiple data streams transmission, we allow each user to receive d data streams from its own serving BS, where $d \leq N_{\rm R}$.

Suppose there are $\bar{K}$ OC users close to the m-th BS, such that the transmission from this BS would potentially cause interference to these OC users. Let $\bar{\mathbf{H}}_m \in \mathbb{C}^{\bar{K}N_{\rm R}\times N_{\rm T}}$ represent the channel towards these OC users. In the following sections, we are interested to design the precoding matrix for each BS by taking into account both IC and OC interference.

III. Leakage Projected DPC Strategy

In this section, the leakage projected DPC is proposed as a distributed precoding strategy for the network MIMO broadcast channel. The key feature of this method is that each BS is able to perform transmit processing independently from other BSs, thereby circumventing the problems of limited backhaul capacities and latency of exchange of CSI or SI. The cell index subscript, m, is dropped for notational simplicity. However, the equations should still be clear as the BS processing is distributed.

The first step involves a channel projection based on maximizing the ratio of the desired signal strength within a cell, to the sum of OC leakage power and noise power. This ratio shall be referred to as cell signal-to-leakage-plus-noise-ratio (SLNR). The second step is the application of ZF DPC for transmission to the IC users. As a whole, the proposed LPD strategy also takes noise into account due to the first step of leakage-based projection. The first step will be presented in detail as follows.

Consider the hypothetical case in which the BS performs beamforming via the matrix $\mathbf{V} \in \mathbb{C}^{N_{\rm T}\times N_{\rm V}}$ where $\mathbf{V}^H\mathbf{V} = \mathbf{I}_{N_{\rm V}}$ and applies equal power loading of $P/N_{\rm V}$. $\mathbf{V}$ and $N_{\rm V}$ are to be determined. The desired signal vector received by the IC users is given by $\mathbf{y} \in \mathbb{C}^{KN_{\rm R}\times 1}$, where

$$\mathbf{y}^{\rm sig} = \mathbf{H}\mathbf{V}\sqrt{P/N_{\rm V}}\mathbf{s}. \quad (4)$$

As in Section II, $\mathbf{H} \in \mathbb{C}^{KN_{\rm R}\times N_{\rm T}}$. The noise vector received by the IC users is $\mathbf{z} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{KN_{\rm R}})$. The leakage to the OC users is given by $\mathbf{y}^{\rm leak} \in \mathbb{C}^{\bar{K}N_{\rm R}\times 1}$, where

$$\mathbf{y}^{\rm leak} = \bar{\mathbf{H}}\mathbf{V}\sqrt{P/N_{\rm V}}\mathbf{s}. \quad (5)$$

The covariance matrices of the desired signal, leakage, and noise are given, respectively, by

$$\begin{aligned} \mathbf{R}_{\mathbf{y}^{\rm sig}} &= \mathbf{H}\mathbf{V}\mathbf{V}^H\mathbf{H}^H P/N_{\rm V}, \\ \mathbf{R}_{\mathbf{y}^{\rm leak}} &= \bar{\mathbf{H}}\mathbf{V}\mathbf{V}^H\bar{\mathbf{H}}^H P/N_{\rm V}, \text{ and} \\ \mathbf{R}_{\mathbf{z}} &= N_0\mathbf{I}_{KN_{\rm R}}. \end{aligned} \quad (6)$$

The cell SLNR, $\zeta_{\rm C}$, is defined as

$$\begin{aligned} \zeta_{\rm C} &= \frac{{\rm Tr}\left(\mathbf{H}\mathbf{V}\mathbf{V}^H\mathbf{H}^H P/N_{\rm V}\right)}{{\rm Tr}\left(\bar{\mathbf{H}}\mathbf{V}\mathbf{V}^H\bar{\mathbf{H}}^H P/N_{\rm V}\right) + N_0KN_{\rm R}} \\ &= \frac{\sum_{k=1}^{N_{\rm V}} \mathbf{v}_k^H\left(\mathbf{H}^H\mathbf{H}P\right)\mathbf{v}_k}{\sum_{k=1}^{N_{\rm V}} \mathbf{v}_k^H\left(\bar{\mathbf{H}}^H\bar{\mathbf{H}}P + N_0KN_{\rm R}\mathbf{I}_{N_{\rm T}}\right)\mathbf{v}_k} \\ &= \frac{\sum_{k=1}^{N_{\rm V}} \mathbf{v}_k^H\mathbf{G}_{\rm A}\mathbf{v}_k}{\sum_{k=1}^{N_{\rm V}} \mathbf{v}_k^H\mathbf{G}_{\rm B}\mathbf{v}_k}, \text{ where} \end{aligned} \quad (7)$$

$$\begin{aligned} \mathbf{G}_{\rm A} &= \rho\mathbf{H}^H\mathbf{H}, \\ \mathbf{G}_{\rm B} &= \rho\bar{\mathbf{H}}^H\bar{\mathbf{H}} + KN_{\rm R}\mathbf{I}_{N_{\rm T}}, \text{ and} \\ \rho &= P/N_0. \end{aligned} \quad (8)$$

For a given $N_{\rm V}$, it is difficult to find $\mathbf{V}$ to maximize $\zeta_{\rm C}$. Therefore, we maximize a lower bound, $\zeta_{\rm L}$, of the cell SLNR, given by

$$\zeta_{\rm L} = \min_{k=1,\ldots,N_{\rm V}} \frac{\mathbf{v}_k^H\mathbf{G}_{\rm A}\mathbf{v}_k}{\mathbf{v}_k^H\mathbf{G}_{\rm B}\mathbf{v}_k}. \text{ Consequently,} \quad (9)$$

$$\begin{aligned} \zeta_{\rm L,max} &= \max_{\mathbf{V}^H\mathbf{V}=\mathbf{I}_{N_{\rm V}}} \min_{k=1,\ldots,N_{\rm V}} \frac{\mathbf{v}_k^H\mathbf{G}_{\rm A}\mathbf{v}_k}{\mathbf{v}_k^H\mathbf{G}_{\rm B}\mathbf{v}_k} \\ &= \max_{\mathcal{V}:\dim(\mathcal{V})=N_{\rm V}} \min_{\mathbf{v}\in\mathcal{V}} \frac{\mathbf{v}^H\mathbf{G}_{\rm A}\mathbf{v}}{\mathbf{v}^H\mathbf{G}_{\rm B}\mathbf{v}}. \end{aligned} \quad (10)$$

According to the generalized Courant-Fischer Max-Min Theorem [8], [10], $\zeta_{\rm L,max}$ is equal to the $N_{\rm V}$-th largest eigenvalue of $\mathbf{G}_{\rm S}$, where $\mathbf{G}_{\rm S} = \mathbf{G}_{\rm B}^{-1}\mathbf{G}_{\rm A}$. $\mathbf{V}$ is then given by the $N_{\rm V}$ orthonormal basis vectors of the space spanned by the $N_{\rm V}$ dominant eigenvectors of $\mathbf{G}_{\rm S}$. Denote $\mathbf{Q}_{\rm G} = \mathbf{V}$. After

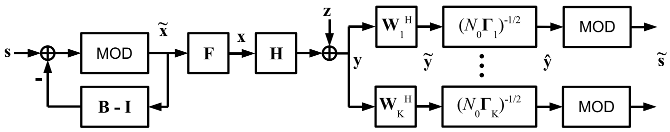

Fig. 1. MIMO downlink transmission that implements THP.

obtaining $\mathbf{Q}_{\mathrm{G}}$, we project the IC channel using $\mathbf{Q}_{\mathrm{G}}\mathbf{Q}_{\mathrm{G}}^{H}$ to get $\mathbf{H}_{\perp} = \mathbf{H}\mathbf{Q}_{\mathrm{G}}\mathbf{Q}_{\mathrm{G}}^{H}$.

The second step of the LPD method involves a block diagonal DPC processing on $\mathbf{H}_{\perp}$ to transmit to the IC users [11]: $\mathbf{P}^{H}\mathbf{H}_{\perp}\mathbf{Q} = \mathbf{L}$, where $\mathbf{P}$ and $\mathbf{Q}$ have orthonormal columns. $\mathbf{P}$ and $\mathbf{Q}$ are the receive and transmit beamforming matrices respectively. $\mathbf{L}$ is the lower triangular equivalent channel matrix. The off-diagonal elements in $\mathbf{L}$ represent the interference between the data streams, which are to be pre-cancelled via DPC. The transmit pre-equalization matrix is $\mathbf{F} = \mathbf{Q}\boldsymbol{\Omega}$, where $\boldsymbol{\Omega} = \mathrm{blkdiag}(\boldsymbol{\Omega}_1, \ldots, \boldsymbol{\Omega}_K)$ is the diagonal power allocation matrix for the IC users. The receive beamforming matrix is $\mathbf{W}^{H} = \mathbf{P}^{H}$. Let $\boldsymbol{\Lambda} = \mathrm{diag}(\mathbf{L})$. The SNR matrix is, therefore, $\boldsymbol{\Gamma} = \boldsymbol{\Lambda}^2\boldsymbol{\Omega}^2/N_0$. The monic lower triangular interference matrix is $\mathbf{B} = \boldsymbol{\Omega}^{-1}\boldsymbol{\Lambda}^{-1}\mathbf{L}\boldsymbol{\Omega}$. Tomlinson-Harashima precoding (THP) is a simple suboptimal implementation of DPC. Its transceiver design is shown in Fig. 1.

We shall now discuss the selection of the N_{V} value. It is clear that $N_{\mathrm{V}} \geq K$ in order to support the K users. Also, $N_{\mathrm{V}} \leq \min(N_{\mathrm{T}}, KN_{\mathrm{R}})$ due to the dimensions of the system. As N_{T} increases, it is better to use a larger value of N_{V}. For example, N_{V} may be chosen to be $N_{\mathrm{T}} - \bar{K}N_{\mathrm{R}}$, in order to have sufficient degrees of freedom (DoF) for suppressing the interference to the $\bar{K}N_{\mathrm{R}}$ antennas of the OC users. A heuristic value of N_{V} is thus given by

$$N_{\mathrm{V}} = N_{\mathrm{Q}} = \min\left(\max\left(K, N_{\mathrm{T}} - \bar{K}N_{\mathrm{R}}\right), KN_{\mathrm{R}}, N_{\mathrm{T}}\right). \tag{11}$$

The LPD method works best when the BS has sufficient DoF to mitigate the OC interference, i.e. $N_{\mathrm{T}} - Kd \geq \phi_{\mathrm{r}}$, where ϕ_{r} is the rank of $\bar{\mathbf{H}}$.

IV. Robust Precoding

In this section, we wish to analyze the effect of CSI uncertainty or error on the sum rate for the LPD method introduced earlier, and to propose a robust precoder. The following channel model shall be used [12].

$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E}, \tag{12}$$

where $\mathbf{H}$ is the actual channel, $\hat{\mathbf{H}}$ is the estimate of the channel available at the transmitter, and $\mathbf{E}$ is the probabilistic additive error component with independent and identically distributed (i.i.d.) elements $[\mathbf{E}]_{i,j} \sim \mathcal{CN}(0, \sigma_{\mathrm{e}}^2)$. The precoding and equalization matrices are determined by $\hat{\mathbf{H}}$.

A. Signal Model for THP Method With Channel Uncertainty and Without OC Interference

First, consider a single cell and assume there is no interference ingress from neighbouring cells. The received signal vector of the users within this cell can be expressed as

$$\begin{aligned}\tilde{\mathbf{y}} &= \mathbf{P}^{H}\mathbf{H}\mathbf{Q}\boldsymbol{\Omega}\tilde{\mathbf{x}} + \mathbf{P}^{H}\mathbf{z}\\ &= \mathbf{P}^{H}\hat{\mathbf{H}}\mathbf{Q}\boldsymbol{\Omega}\tilde{\mathbf{x}} + \mathbf{P}^{H}\mathbf{E}\mathbf{Q}\boldsymbol{\Omega}\tilde{\mathbf{x}} + \mathbf{P}^{H}\mathbf{z}\\ &= \boldsymbol{\Lambda}\boldsymbol{\Omega}\mathbf{B}\tilde{\mathbf{x}} + \mathbf{P}^{H}\mathbf{E}\mathbf{Q}\boldsymbol{\Omega}\tilde{\mathbf{x}} + \mathbf{P}^{H}\mathbf{z}\\ &= \boldsymbol{\Lambda}\boldsymbol{\Omega}\left(\mathbf{s} + \boldsymbol{\delta}\right) + \mathbf{P}^{H}\mathbf{E}\mathbf{Q}\boldsymbol{\Omega}\tilde{\mathbf{x}} + \mathbf{P}^{H}\mathbf{z}.\end{aligned} \tag{13}$$

After equalization with $\boldsymbol{\Omega}^{-1}\boldsymbol{\Lambda}^{-1}$ and modulo, the THP constellation offset $\boldsymbol{\delta}$ is removed, leaving the desired signal component $\mathbf{s}$ [13].

B. User Rates for LPD Strategy With Channel Uncertainty and With OC Interference

Now consider the case where there is OC interference, as in a cellular system. This subsection analyzes the user rates of the LPD method, in the presence of CSI errors.

$$\tilde{\mathbf{y}} = \tilde{\mathbf{y}}_{\mathrm{sig}} + \tilde{\mathbf{y}}_{\mathrm{err}} + \tilde{\mathbf{y}}_{\mathrm{int}} + \tilde{\mathbf{z}}, \text{ in which} \tag{14}$$

$$\tilde{\mathbf{y}}_{\mathrm{sig}} = \mathbf{W}^{H}\hat{\mathbf{H}}\mathbf{F}\tilde{\mathbf{x}}, \tag{15}$$

$$\tilde{\mathbf{y}}_{\mathrm{err}} = \mathbf{W}^{H}\mathbf{E}\mathbf{F}\tilde{\mathbf{x}}, \tag{16}$$

$$\tilde{\mathbf{y}}_{\mathrm{int}} = \sum_{n\neq m}^{M} \tilde{\mathbf{y}}_{n\to m}, \text{ where } \tilde{\mathbf{y}}_{n\to m} = \mathbf{W}_m^{H}\mathbf{H}_{n\to m}\mathbf{F}_n\tilde{\mathbf{x}}_n, \text{ and} \tag{17}$$

$$\tilde{\mathbf{z}} = \mathbf{W}^{H}\mathbf{z}. \tag{18}$$

$\mathbf{H}_{n\to m} \in \mathbb{C}^{KN_{\mathrm{R}}\times N_{\mathrm{T}}}$ is the actual channel matrix from the n-th BS to the users in the m-th cell. Due to the independence and zero mean of transmit signals from different BSs, $\mathbf{E}$, and $\tilde{\mathbf{z}}$,

$$\mathbf{R}_{\tilde{\mathbf{y}}} = \mathbf{R}_{\tilde{\mathbf{y}}_{\mathrm{sig}}} + \mathbf{R}_{\tilde{\mathbf{y}}_{\mathrm{err}}} + \mathbf{R}_{\tilde{\mathbf{y}}_{\mathrm{int}}} + \mathbf{R}_{\tilde{\mathbf{z}}}. \tag{19}$$

The covariance matrix of the error component, $\tilde{\mathbf{y}}_{\mathrm{err}}$, is given by

$$\begin{aligned}\mathbf{R}_{\tilde{\mathbf{y}}_{\mathrm{err}}} &= \mathcal{E}_{\mathbf{E}}\mathcal{E}_{\tilde{\mathbf{x}}}\left[\mathbf{P}^{H}\mathbf{E}\mathbf{Q}\boldsymbol{\Omega}\tilde{\mathbf{x}}\tilde{\mathbf{x}}^{H}\boldsymbol{\Omega}\mathbf{Q}^{H}\mathbf{E}^{H}\mathbf{P}\right]\\ &= \mathbf{P}^{H}\sigma_{\mathrm{e}}^2\mathrm{Tr}\left(\mathbf{Q}\boldsymbol{\Omega}\mathbf{R}_{\tilde{\mathbf{x}}}\boldsymbol{\Omega}\mathbf{Q}^{H}\right)\mathbf{I}_{KN_{\mathrm{R}}}\mathbf{P}\\ &= \sigma_{\mathrm{e}}^2 P\mathbf{I}_{Kd}.\end{aligned} \tag{20}$$

The effective additive noise, $\tilde{\mathbf{y}}_{\mathrm{err}} + \tilde{\mathbf{y}}_{\mathrm{int}} + \tilde{\mathbf{z}}$, is not Gaussian. Therefore, a lower bound of the rate for each data stream, assuming the given probability distribution of $\mathbf{E}$, and assuming the transmitted signals and noise are Gaussian, is obtained as

$$r_{\mathrm{L},i} = \log_2\left(1 + \frac{\left[\mathbf{R}_{\tilde{\mathbf{y}}_{\mathrm{sig}}}\right]_{i,i}}{\left[\mathbf{R}_{\tilde{\mathbf{y}}_{\mathrm{err}}}\right]_{i,i} + \left[\mathbf{R}_{\tilde{\mathbf{y}}_{\mathrm{int}}}\right]_{i,i} + \left[\mathbf{R}_{\tilde{\mathbf{z}}}\right]_{i,i}}\right). \tag{21}$$

The lower bound rate for each user can be obtained by summing up over the data streams of the user.

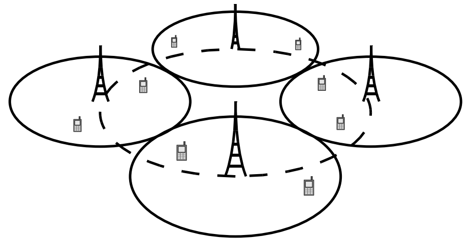

Fig. 2. Circular Wyner Model with $M = 4$ cells and $K = 2$ users per cell.

C. Robust LPD Method

In this section, we shall obtain a robust distributed precoder for the network MIMO downlink. This precoder, called the robust LPD, provides some robustness to uncertainty in the channel knowledge. First, assume σ_{e}^2 is known at the transmitter. Define the effective noise, due to the CSI error, at each receive antenna to be $N_{0,\mathrm{e}} = \sigma_{\mathrm{e}}^2 P$. The effective additive noise due to the receiver noise and the CSI error is therefore $\bar{N}_0 = N_0 + N_{0,\mathrm{e}}$. Next, calculate the projection matrix $\mathbf{Q}_{\mathrm{G}}$ by replacing N_0 by $\bar{N}_0$ in the cell SLNR expression in (7) and (8). Apply this robust projection to the downlink channel. The following steps are then identical to the LPD in Section III. The lower bound rate can then be calculated via the analysis in Section IV-B.

V. Simulations

Consider a cellular system comprising of $M = 4$ cells in a circular Wyner model [14], as in Fig. 2. Each BS has $N_{\mathrm{T}} = 8$ transmit antennas and each cell has $K = 4$ users. All users have $N_{\mathrm{R}} = 1$ receive antenna each. For the IC users, assume that each element of the channel matrix $\mathbf{H}_m$ is i.i.d. as $\mathcal{CN}(0, 1)$. $\bar{K} = K$ OC users are affected by the transmission from each BS. Let the interference factor [3], [15] be denoted by α. Each element of the channel matrix $\bar{\mathbf{H}}_m$ to these OC users is i.i.d. $\mathcal{CN}(0, \alpha^2)$. The input-output relationship for the system is given in (1). Let $\mathbf{C}_{\mathrm{M}}$ and $\mathbf{C}_{\mathrm{V}}$ represent the variances of the channel matrix elements. If $K = 2$,

$$\mathbf{C}_{\mathrm{M}} = \begin{bmatrix} 1 & 0 & 0 & \alpha^2 \\ 1 & \alpha^2 & 0 & 0 \\ \alpha^2 & 1 & 0 & 0 \\ 0 & 1 & \alpha^2 & 0 \\ 0 & \alpha^2 & 1 & 0 \\ 0 & 0 & 1 & \alpha^2 \\ 0 & 0 & \alpha^2 & 1 \\ \alpha^2 & 0 & 0 & 1 \end{bmatrix}. \tag{22}$$

Each row is for one user, while each column is for one BS. $\mathbf{C}_{\mathrm{V}} = \mathbf{C}_{\mathrm{M}} \otimes \mathbf{1}_{N_{\mathrm{R}}, N_{\mathrm{T}}}$, where $\otimes$ represents the Kronecker product of two matrices. Therefore, each element in $\mathbf{C}_{\mathrm{V}}$ is the variance of the corresponding element in $\mathbf{H}_{\mathrm{sys}}$. In other words, $[\mathbf{H}_{\mathrm{sys}}]_{i,j} \sim \mathcal{CN}(0, [\mathbf{C}_{\mathrm{V}}]_{i,j})$. For general K, the even numbered rows of $\mathbf{C}_{\mathrm{M}}$ given above are repeated $K - 1$ times.

Equal power loading is utilized for the downlink methods. For the purpose of comparison, ignore the THP precoding loss $\bar{M}/(\bar{M} - 1)$ for $\bar{M}$-QAM constellations. The simulation graphs include the curves for '2 orthogonal channels'. This represents the method of orthogonal transmission in which the frequency reuse factor $f_{\mathrm{reuse}} = 1/2$. For our 4-cell topology, 2 orthogonal channels are sufficient to create the idealized scenario of zero inter-cell interference. In frequency reuse, the rate becomes scaled by f_{reuse}. Unless otherwise indicated, the default system settings for the simulations are as follows. $N_{\mathrm{T}} = 8$, SNR $P/N_0 = 15$dB, $\alpha = 0.5$, and $K = 4$. 1000 Monte Carlo runs are used.

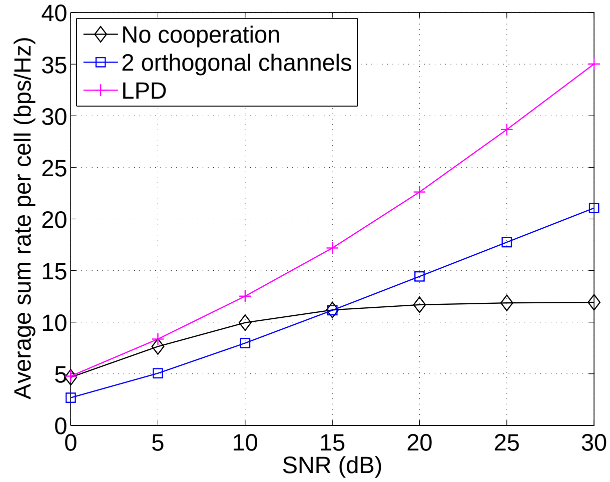

Fig. 3. Sum rate as a function of SNR P/N_0 for $N_{\mathrm{T}} = 8$ and $K = 4$.

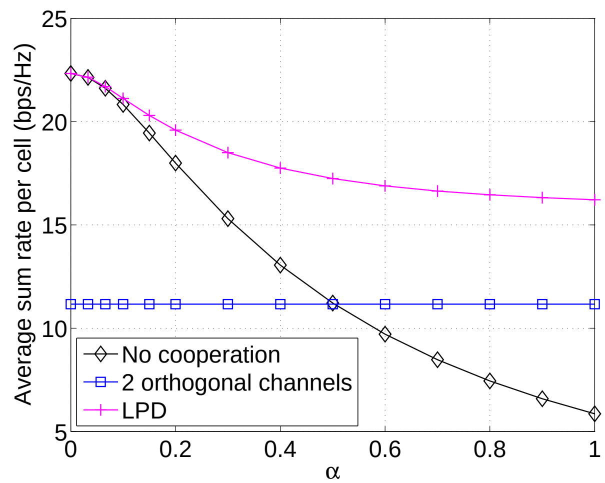

Fig. 4. Effect of the interference factor α on the sum rate for $N_{\mathrm{T}} = 8$ and $K = 4$.

The effect of SNR on the sum rate is shown in Fig. 3. As long as there are sufficient DoF, i.e. $N_{\mathrm{T}} \geq Kd + \bar{K}N_{\mathrm{R}}$, the sum rate per cell for the LPD is shown to increase linearly with SNR, for high SNR. Otherwise, the sum rates will level off due to insufficient DoF. The rate with no cooperation levels off at about 12 bps/Hz.

Next, in Fig. 4, the performance of the LPD technique is examined when the interference factor α is varied. As expected, the increasing α does not degrade the performance

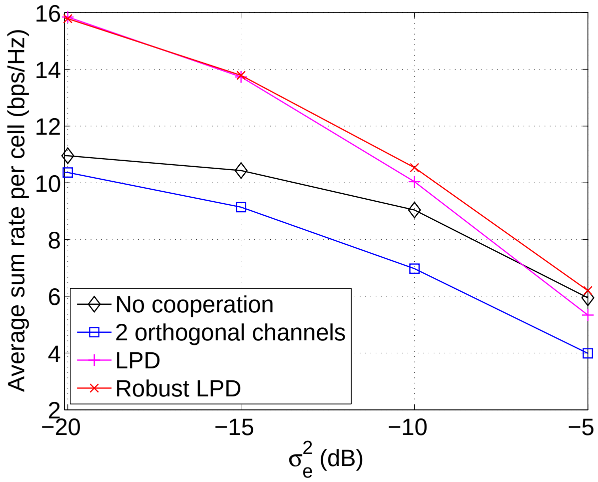

Fig. 5. Effect of channel uncertainty on the sum rates of various methods, including the robust LPD, for $N_{\mathrm{T}} = 8$ and $K = 4$.

of orthogonal transmission. The LPD method and the no cooperation case suffer rate loss as α increases. The LPD strategy consistently performs better than all the other methods. When $\alpha = 0$, the LPD method is as good as the case with no cooperation. The reason is that the leakage term in the cell SLNR expression (7) is zero. Consequently, the channel after projection, $\mathbf{H}_{\perp} = \mathbf{H}\mathbf{Q}_{\mathrm{G}}\mathbf{Q}_{\mathrm{G}}^{H}$, is identical to $\mathbf{H}$.

The effect of channel uncertainty on the sum rates of the different methods are compared in Fig. 5. To model the CSI uncertainty [12], the following is used to generate the channels.

$$
\begin{aligned}
[\hat{\mathbf{H}}]_{i,j} &= \sqrt{[\mathbf{C}_{\mathrm{V}}]_{i,j}(1-\sigma_{\mathrm{e}}^2)}[\mathbf{H}_{\mathrm{w}}]_{i,j} \\
[\mathbf{E}]_{i,j} &= \sqrt{[\mathbf{C}_{\mathrm{V}}]_{i,j}\sigma_{\mathrm{e}}^2}[\mathbf{E}_{\mathrm{w}}]_{i,j} \\
\mathbf{H} &= \hat{\mathbf{H}} + \mathbf{E},
\end{aligned} \tag{23}
$$

where $[\mathbf{H}_{\mathrm{w}}]_{i,j} \sim \mathcal{CN}(0,1)$ and $[\mathbf{E}_{\mathrm{w}}]_{i,j} \sim \mathcal{CN}(0,1)$. For the curve of the robust LPD, the CSI error variance σ_{e}^2 is assumed to be available at the transmitter. The robust LPD is observed to recover some of the rate loss of the LPD method as σ_{e}^2 increases.

VI. Conclusion

A distributed leakage projected DPC (LPD) precoding method has been proposed for network MIMO broadcast channel. Unlike prior works, our precoder tackles both intra-cell and out-of-cell interference in a distributed manner, hence eliminating the need for SI, CSI, and precoder information exchange among the cooperating base stations. It is shown that in the high SNR regime, with a sufficient number of transmit antennas, the proposed precoder enjoys a linear rate increase with SNR. This is in contrast to the case without base station cooperation, for which the sum rate levels off at high SNR. The proposed LPD method also outperforms the orthogonal transmission scheme significantly. To address the CSI uncertainty caused by channel estimation, we further proposed a robust LPD method which is able to recover some of the rate reduction due to the imperfectness of CSI.

References

[1] G. J. Foschini, K. Karakayali, and R. A. Valenzuela, "Coordinating multiple antenna cellular networks to achieve enormous spectral efficiency," *IEE Proc. Commun.*, vol. 153, no. 4, pp. 548–555, Aug. 2006.

[2] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, "Interference coordination and cancellation for 4G networks," *IEEE Commun. Mag.*, vol. 47, no. 4, pp. 74–81, Apr. 2009.

[3] S. Jing, D. N. C. Tse, J. B. Soriaga, J. Hou, J. E. Smee, and R. Padovani, "Multicell downlink capacity with coordinated processing," *EURASIP J. Wirel. Commun. Netw.*, vol. 2008, pp. 1–19, 2008.

[4] S. Shim, J. S. Kwak, R. W. Heath Jr., and J. G. Andrews, "Block diagonalization for multi-user MIMO with other-cell interference," *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2671–2681, Jul. 2008.

[5] O. Somekh, O. Simeone, Y. Bar-Ness, A. M. Haimovich, and S. Shamai (Shitz), "Cooperative multicell zero-forcing beamforming in cellular downlink channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 7, pp. 3206–3219, Jul. 2009.

[6] D. Gesbert, S. G. Kiani, A. Gjendemsjø, and G. E. Øien, "Adaptation, coordination, and distributed resource allocation in interference-limited wireless networks," *Proc. IEEE*, vol. 95, no. 12, pp. 2393–2409, Dec. 2007.

[7] M. Sadek, A. Tarighat, and A. H. Sayed, "A leakage-based precoding scheme for downlink multi-user MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 6, no. 5, pp. 1711–1721, May 2007.

[8] H. Zhang, N. B. Mehta, A. F. Molisch, J. Zhang, and H. Dai, "Asynchronous interference mitigation in cooperative base station systems," *IEEE Trans. Wireless Commun.*, vol. 7, no. 1, pp. 155–165, Jan. 2008.

[9] B. O. Lee, H. W. Je, I. Sohn, O.-S. Shin, and K. B. Lee, "Interference-aware decentralized precoding for multicell MIMO TDD systems," in *Proc. Global Commun. Conf.*, Nov. 2008, pp. 1–5.

[10] R. A. Horn and C. R. Johnson, *Matrix Analysis*. Cambridge University Press, 1990.

[11] S. Lin, W. W. L. Ho, and Y.-C. Liang, "Block diagonal geometric mean decomposition (BD-GMD) for MIMO broadcast channels," *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2778–2789, Jul. 2008.

[12] T. Yoo and A. Goldsmith, "Capacity and power allocation for fading MIMO channels with channel estimation error," *IEEE Trans. Inf. Theory*, vol. 52, no. 5, pp. 2203–2214, May 2006.

[13] M. Huang, S. Zhou, and J. Wang, "Analysis of Tomlinson-Harashima precoding in multiuser MIMO systems with imperfect channel state information," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2856–2867, Sep. 2008.

[14] A. D. Wyner, "Shannon-theoretic approach to a Gaussian cellular multiple-access channel," *IEEE Trans. Inf. Theory*, vol. 40, no. 6, pp. 1713–1727, Nov. 1994.

[15] S. Shamai (Shitz) and B. M. Zaidel, "Enhancing the cellular downlink capacity via co-processing at the transmitting end," in *Proc. IEEE Veh. Technol. Conf.*, vol. 3, May 2001, pp. 1745–1749.