Decentralized Base Station Processing for Multiuser MIMO Downlink CoMP

Winston W. L. Ho, Tony Q. S. Quek, and Sumei Sun,
Institute for Infocomm Research, A*STAR, 1 Fusionopolis Way, #21-01 Connexis (South Tower), Singapore 138632
Emails: {wlho,qsquek,sunsm}@i2r.a-star.edu.sg

***Abstract*—Coordinated multi-point transmission/reception (CoMP), in which base stations (BSs) cooperate during the downlink, has been identified as a tool for improving user rates and mitigating interference. The cost for existing coordination schemes with joint processing is the heavy exchange of channel state information and signal information over backhaul links. In this paper, we propose a decentralized BS processing method for the downlink of CoMP systems. Its key feature is that each BS performs decentralized processing without requiring any explicit information exchange between BSs. Unlike existing work, each BS maximizes the rate for multiple intra-cell users and cancels inter-cell interference in a decentralized manner.**

I. Introduction

The 3GPP Long Term Evolution (LTE) Release 8 [1] promises a 300 Mbps peak data rate in the downlink. Release 10, also known as LTE-Advanced, is more ambitious, aiming beyond 1 Gbps peak data rate for the downlink. Presently, the LTE-Advanced is undergoing standardization, with coordinated multi-point transmission/reception (CoMP) identified as a tool to improve coverage at high data rates, cell-edge throughput, and system throughput [2]. For downlink CoMP, base stations perform coordinated scheduling or beamforming to enable inter-cell interference coordination. Joint processing and transmission is also considered. In theory, a system-wide joint dirty paper coding (DPC), where all BSs perform transmit processing as though their antennas are co-located, achieves the capacity for downlink CoMP [3]. In this scenario, channel state information (CSI) and signal information (SI) need to be shared among all the cooperating BSs. Due to the latency of information exchange between BSs, this strategy can only serve as an ideal upper bound on practical achievable rates that CoMP communications can offer.

Accordingly, there is an increasing interest to investigate other CoMP designs, particularly for downlink channels [4]–[7]. 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 [5]. Zero-forcing beamforming [6] and game theory optimization for intelligent scheduling across frequency and time [7] have also been proposed. Current schemes rely on the backhaul for information exchange, which dilutes the gain from CoMP. Also, transmit processing over several BSs may not be practical due to the latency incurred by the exchange of CSI and SI between BSs [3].

In this work, we propose a decentralized precoder design for the downlink CoMP, where BSs and users are equipped with multiple antennas. Each BS designs its own precoder without requiring SI from other BSs. Furthermore, each BS only requires the CSI of the channels from itself towards its intra-cell (IC) users and out-of-cell (OC) users. The IC users are those inside the cell and served by the BS, while the OC users are those outside the cell and receiving undesirable interference from this BS. The OC users are identified if the BS is able to “hear” them during the uplink, when the users transmit their reference signals. If time division duplex (TDD) is used, the CSI of the channels from the BS to the IC and OC users can be obtained implicitly during the uplink phase, without the need for explicit feedback. The key feature of our proposed precoder is that BS cooperation is achieved implicitly, where a BS whose transmission can potentially be “heard” by the cell-edge users of neighbouring BSs will modify its transmission so as to mitigate interference to such users. The benefit of this technique is that it eliminates the need for explicit CSI and SI exchange between BSs.

Our precoder mitigates the interference caused to the OC users and supports multiple IC users via a nonlinear block diagonal processing. Unlike the projected channel SVD method of [8], our method handles multiple IC and OC users. Numerical results show that our proposed method outperforms the cases of no cooperation and orthogonal transmission at high SNR, when there are sufficient transmit antennas at each BS. This paper is organized as follows. In Section II, the downlink CoMP system model is described. In Section III, the proposed decentralized precoder design is introduced, and its rate is analyzed. Simulation results are shown in Section IV. Finally, the conclusion is given in the last section. The following notation is used. Bold lowercase letters, e.g. $\mathbf{a}$, are used to denote column vectors, bold uppercase letters, e.g. $\mathbf{A}$, are used to denote matrices, and non-bold letters in italics, e.g. a or A, are used to 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 $\mathbf{A}_k, k = 1, ..., K$.

II. System Model

We consider the downlink of a MIMO cellular network with M cells of N_T transmit antennas each, serving K users with N_R receive antennas each. Assuming a synchronous downlink CoMP, the received signal vector of the system can be written as

$$\mathbf{y}_\mathrm{sys} = \mathbf{H}_\mathrm{sys}\mathbf{x}_\mathrm{sys} + \mathbf{z}_\mathrm{sys}, \tag{1}$$

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

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

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

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

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

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 $\bar{\mathbf{H}}_m \in \mathbb{C}^{\bar{K}N_\mathrm{R}\times N_\mathrm{T}}$ represent the channel towards these OC users. Also, define $\bar{\mathbf{H}}_{m,k} = [\mathbf{H}_{m,1}^T, \ldots, \mathbf{H}_{m,k-1}^T, \mathbf{H}_{m,k+1}^T, \ldots, \mathbf{H}_{m,K}^T, \bar{\mathbf{H}}_m^T]^T \in \mathbb{C}^{(K-1+\bar{K})N_\mathrm{R}\times N_\mathrm{T}}$ as the channel from this BS to its served users other than the k-th user, as well as those OC users. In the following sections, we design precoding matrices for each BS by taking into account both IC and OC interference.

III. Projected Channel DPC

In this section, the projected channel DPC method for the downlink CoMP is introduced. 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 decentralized. As in Section II, $\bar{\mathbf{H}} \in \mathbb{C}^{\bar{K}N_\mathrm{R}\times N_\mathrm{T}}$ denotes the channel from the BS to the OC users. Firstly, evaluate the singular value decomposition (SVD) of $\bar{\mathbf{H}}$ as $\bar{\mathbf{U}}\bar{\mathbf{\Sigma}}\bar{\mathbf{V}}^H$. Let $\phi_\mathrm{a} = N_\mathrm{T} - Kd$. ϕ_a can be interpreted as the degrees of freedom (DoF) available for nulling the interference to the OC users. Denote ϕ_r as the rank of $\bar{\mathbf{H}}$. ϕ_r represents the DoF required to null the interference to the OC users completely. Let

$$\phi = \min(\phi_\mathrm{a}, \phi_\mathrm{r}). \tag{4}$$

Form the matrix $\bar{\mathbf{V}}_1$ that is composed of the columns of $\bar{\mathbf{V}}$ corresponding to the first ϕ largest singular values of $\bar{\mathbf{H}}$. Denote $\bar{\mathbf{V}}_2$ as the orthogonal complement of $\bar{\mathbf{V}}_1$. Next, project $\mathbf{H}$ using $\bar{\mathbf{V}}_1^H$ to get $\mathbf{H}_\perp$.

$$\mathbf{H}_\perp = \mathbf{H}\left(\mathbf{I} - \bar{\mathbf{V}}_1\bar{\mathbf{V}}_1^H\right) = \mathbf{H}\bar{\mathbf{V}}_2\bar{\mathbf{V}}_2^H. \tag{5}$$

Following that, the block diagonal DPC processing described in Section III-A can be applied to $\mathbf{H}_\perp$ for transmission to the IC users. The projected channel DPC works best when $\phi_\mathrm{a} \geq \phi_\mathrm{r}$, because the BS has sufficient DoF to eliminate interference to the OC users. In contrast, if $\phi_\mathrm{a} < \phi_\mathrm{r}$, some interference is caused to the OC users, resulting in reduced rates for those users. When $\bar{\mathbf{H}}$ is weak relative to $\mathbf{H}$, a smaller value of ϕ than (4) can be used to afford more DoF to the IC users, because interference to the OC users is negligible. For simplicity, (4) is used in this paper. The user rates are analyzed in Section III-B. Algorithm 1 summarizes the projected channel DPC method.

A. DPC for Multiuser Downlink Without BS Cooperation

Without BS cooperation, the BS in the m-th cell only considers its own IC users. To perform the DPC, a lower triangular equivalent channel is created via

$$\mathbf{P}^H\mathbf{H}_\perp\mathbf{Q} = \mathbf{L}, \tag{6}$$

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. If there is only a single user in the m-th cell, the SVD or geometric mean decomposition (GMD) [9] can be used to derive the matrices in (6). GMD creates subchannels of identical channel gains, for which equal power loading can be applied. If there are multiple users in the cell, block diagonal (BD) processing can be used to derive the matrices. To perform the BD processing, express the matrices in (6) as follows:

$$\mathbf{P}=\begin{bmatrix}\mathbf{P}_1 & \mathbf{0}\\ \mathbf{0} & \check{\mathbf{P}}_2\end{bmatrix}, \qquad \mathbf{H}_\perp=\begin{bmatrix}\mathbf{H}_{\perp,1}\\ \check{\mathbf{H}}_{\perp,2}\end{bmatrix},$$
$$\mathbf{Q}=\begin{bmatrix}\mathbf{Q}_1 & \check{\mathbf{Q}}_2\end{bmatrix}, \text{ and } \qquad \mathbf{L}=\begin{bmatrix}\mathbf{L}_1 & \mathbf{0}\\ \mathbf{\Xi}_1 & \check{\mathbf{L}}_2\end{bmatrix}. \tag{7}$$

$\check{\mathbf{P}}_k$, $\check{\mathbf{H}}_{\perp,k}$, $\check{\mathbf{Q}}_k$, and $\check{\mathbf{L}}_k$ refer to the receive beamforming, channel, transmit beamforming, and equivalent channel matrices of users k to K combined. For the first user, $\mathbf{P}_1^H\mathbf{H}_{\perp,1}\mathbf{Q}_1=\mathbf{L}_1$. SVD or GMD can be applied to the matrix $\mathbf{H}_{\perp,1}$. If subchannel selection is employed, the matrices $\mathbf{P}_1$ and $\mathbf{Q}_1$ would not be square. However, they always have orthonormal columns.

Next, to make sure that $\mathbf{P}_1^H\mathbf{H}_{\perp,1}\check{\mathbf{Q}}_2=\mathbf{0}$, the projection matrix $\mathbf{I}-\mathbf{Q}_1\mathbf{Q}_1^H$ is used on $\check{\mathbf{H}}_{\perp,2}$. The equivalent channel is, therefore, $\check{\mathbf{P}}_2^H\check{\mathbf{H}}_{\perp,2}(\mathbf{I}-\mathbf{Q}_1\mathbf{Q}_1^H)\check{\mathbf{Q}}_2=\check{\mathbf{L}}_2$. Notice that this equation has the same form as (6). Therefore, the algorithm to calculate the matrices can proceed recursively. This method is referred to as BD processing. If GMD is used for each user, the resultant transceiver design is known as BD-GMD [10]. $\mathbf{\Xi}_1$ is given by $\mathbf{\Xi}_1=\check{\mathbf{P}}_2^H\check{\mathbf{H}}_{\perp,2}\mathbf{Q}_1$. As an example, if there are 3 IC users, the equivalent channel, $\mathbf{L}$, is given by

$$\mathbf{L}=\left[\begin{array}{c|cc}\mathbf{L}_1 & \multicolumn{2}{c}{\mathbf{0}}\\ \hline \multirow{2}{*}{$\mathbf{\Xi}_1$} & \mathbf{L}_2 & \mathbf{0}\\ \cline{2-3} & \mathbf{\Xi}_2 & \mathbf{L}_3\end{array}\right], \tag{8}$$

where $\mathbf{\Xi}_2=\mathbf{P}_3^H\mathbf{H}_{\perp,3}\mathbf{Q}_2$. 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 $\mathbf{F}=\mathbf{Q}\mathbf{\Omega}$, where $\mathbf{\Omega}=\operatorname{blkdiag}(\mathbf{\Omega}_1,\ldots,\mathbf{\Omega}_K)$ is the diagonal power allocation matrix for the IC users. The receive beamforming matrix is $\mathbf{W}^H=\mathbf{P}^H$. Let $\mathbf{\Lambda}=\operatorname{diag}(\mathbf{L})$. $\mathbf{\Lambda}$ represents the subchannel gains of the data streams. The SNR matrix is, therefore, $\mathbf{\Gamma}=\mathbf{\Lambda}^2\mathbf{\Omega}^2/N_0$. The SNR for each data stream is given by the elements in the diagonal matrix $\mathbf{\Gamma}$. The monic lower triangular interference matrix is $\mathbf{B}=\mathbf{\Omega}^{-1}\mathbf{\Lambda}^{-1}\mathbf{L}\mathbf{\Omega}$.

Tomlinson-Harashima precoding (THP) is a simple suboptimal implementation of DPC. The block diagram of the THP transceiver design is shown in Fig. 1. Supposing $\mathbf{z}=\mathbf{0}$, we have

$$\tilde{\mathbf{y}}=\mathbf{W}^H\mathbf{H}\mathbf{F}\tilde{\mathbf{x}}=\mathbf{W}^H\mathbf{H}_\perp\mathbf{F}\tilde{\mathbf{x}}=\mathbf{\Lambda}\mathbf{\Omega}\mathbf{B}\tilde{\mathbf{x}}, \tag{9}$$
$$\hat{\mathbf{y}}=\mathbf{\Omega}^{-1}\mathbf{\Lambda}^{-1}\tilde{\mathbf{y}}=\mathbf{B}\tilde{\mathbf{x}}. \tag{10}$$

The second equality in (9) is due to

Lemma 1: $\mathbf{H}_\perp\mathbf{Q}=\mathbf{H}\mathbf{Q}$.

Proof: See Appendix A. □

The signal just before the modulo operation at the receiver is $\hat{\mathbf{y}}=\mathbf{s}+\boldsymbol{\delta}\in\mathbb{C}^{Kd\times1}$, where $\mathbf{s}$ is the vector of data symbols destined for the IC users. $\boldsymbol{\delta}$ is the THP offset vector which is removed by the receiver modulo. The data symbols are normalized such that $\mathcal{E}[\mathbf{s}\mathbf{s}^H]=\mathbf{I}_{Kd}$. Details of the THP processing can be found in [10]. The sum power of the signals intended for the IC users is given by

$$P=\mathcal{E}\left[(\mathbf{F}\tilde{\mathbf{x}})^H(\mathbf{F}\tilde{\mathbf{x}})\right]=\operatorname{Tr}\left(\mathbf{\Omega}^2\mathbf{R}_{\tilde{\mathbf{x}}}\right), \tag{11}$$

where $\mathbf{R}_{\tilde{\mathbf{x}}}=\mathcal{E}[\tilde{\mathbf{x}}\tilde{\mathbf{x}}^H]$.

B. User Rates for Projected Channel DPC Method

As long as $N_\mathrm{T}\geq K$, there can be data transmission towards the IC users. We wish to examine the user rates for the projected channel DPC method. Denote $\tilde{\mathbf{y}}_m=\mathbf{W}_m^H\mathbf{y}_m$ as the signal received by the users inside the m-th cell after equalization. Express $\tilde{\mathbf{y}}_m$ as a sum of the signal, interference, and noise terms.

$$\tilde{\mathbf{y}}_m=\tilde{\mathbf{y}}_m^{\mathrm{sig}}+\tilde{\mathbf{y}}_m^{\mathrm{int}}+\tilde{\mathbf{z}}_m, \text{ in which} \tag{12}$$
$$\tilde{\mathbf{y}}_m^{\mathrm{sig}}=\mathbf{W}_m^H\mathbf{H}_m\mathbf{F}_m\tilde{\mathbf{x}}_m, \tag{13}$$
$$\tilde{\mathbf{y}}_m^{\mathrm{int}}=\sum_{n\neq m}^{M}\tilde{\mathbf{y}}_{n\to m}, \text{ where } \tilde{\mathbf{y}}_{n\to m}=\mathbf{W}_m^H\mathbf{H}_{n\to m}\mathbf{F}_n\tilde{\mathbf{x}}_n, \text{ and} \tag{14}$$
$$\tilde{\mathbf{z}}_m=\mathbf{W}_m^H\mathbf{z}_m. \tag{15}$$

Due to independence of transmit signals from different BSs, the covariance matrix of the interference after equalization is

$$\mathbf{R}_{\tilde{\mathbf{y}}_m^{\mathrm{int}}}=\sum_{n\neq m}^{M}\mathbf{R}_{\tilde{\mathbf{y}}_{n\to m}}. \tag{16}$$

Once the projected channel DPC is in place, the rate for each data stream, using the Gaussian assumption on the transmitted signals and noise, is given by

$$\begin{aligned} r_i&=\log_2\left(1+\frac{\left[\mathbf{R}_{\tilde{\mathbf{y}}_m^{\mathrm{sig}}}\right]_{i,i}}{\left[\mathbf{R}_{\tilde{\mathbf{y}}_m^{\mathrm{int}}}\right]_{i,i}+\left[\mathbf{R}_{\tilde{\mathbf{z}}_m}\right]_{i,i}}\right)\\ &=\log_2\left(1+\frac{N_0\left[\mathbf{\Gamma}_m\right]_{i,i}}{\left[\mathbf{R}_{\tilde{\mathbf{y}}_m^{\mathrm{int}}}\right]_{i,i}+N_0}\right). \end{aligned} \tag{17}$$

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

Algorithm 1 Projected Channel DPC

1. Evaluate SVD of $\bar{\mathbf{H}}=\bar{\mathbf{U}}\bar{\mathbf{\Sigma}}\bar{\mathbf{V}}^H$.
2. Obtain $\phi_\mathrm{a}=N_\mathrm{T}-Kd$.
3. Get ϕ_r, the rank of $\bar{\mathbf{H}}$.
4. Calculate $\phi=\min(\phi_\mathrm{a},\phi_\mathrm{r})$.
5. Form the matrix $\bar{\mathbf{V}}_1$ that is composed of the columns of $\bar{\mathbf{V}}$ corresponding to the first ϕ largest singular values of $\bar{\mathbf{H}}$.
6. Derive the projected channel $\mathbf{H}_\perp=\mathbf{H}\left(\mathbf{I}-\bar{\mathbf{V}}_1\bar{\mathbf{V}}_1^H\right)$.
7. Apply the BD processing on $\mathbf{H}_\perp$: $\mathbf{P}^H\mathbf{H}_\perp\mathbf{Q}=\mathbf{L}$.
8. Perform DPC on the equivalent channel $\mathbf{L}$, with pre-equalization matrix $\mathbf{F}$ and receive beamforming matrices $\mathbf{W}_k^H$ given by Section III-A.

IV. Simulations

Consider a cellular system comprising of $M=4$ cells in a circular Wyner model [11], as in Fig. 2. Each BS has N_T transmit antennas and each cell has $K=4$ users. All

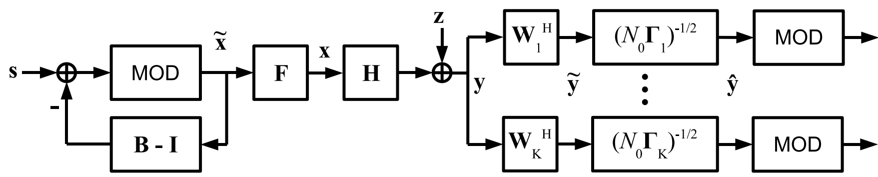

Fig. 1. Block diagram of projected channel DPC for MIMO downlink transmission that implements THP.

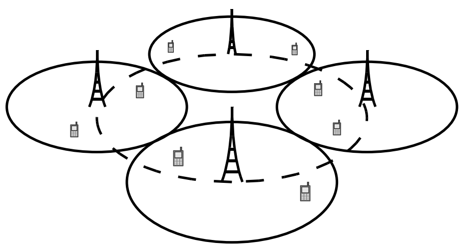

Fig. 2. Circular Wyner Model with $M = 4$ cells and $K = 2$ users per cell.

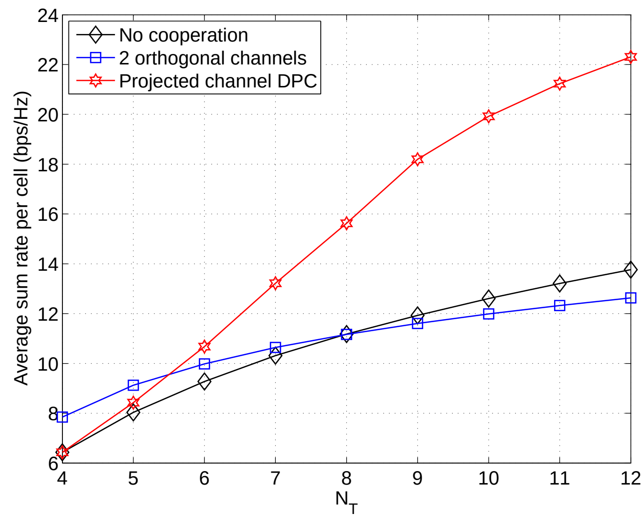

Fig. 3. Sum rate per cell vs number of BS transmit antennas N_{T} for $K = 4$.

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 [4], [12] 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 $K = 2$,

$$\mathbf{C}_{\mathrm{M}} = \begin{bmatrix} 1 & 0 & 0 & \alpha^2 \\ 1 & \alpha^2 & 0 & 0 \\ \alpha^2 & 1 & 0 & 0 \\ 0 & 1 & \alpha^2 & 0 \\ 0 & \alpha^2 & 1 & 0 \\ 0 & 0 & 1 & \alpha^2 \\ 0 & 0 & \alpha^2 & 1 \\ \alpha^2 & 0 & 0 & 1 \end{bmatrix}. \tag{18}$$

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.

Channel inversion power control enforces user fairness, but may not be desirable from the service provider's point of view, as it reduces the system sum rate. On the other hand, maximizing the sum rate via water-filling, by loading even higher powers for the users with good channels, may adversely affect the data rates for users with poor channel conditions. Therefore, in the simulations, equal power loading is utilized for all the downlink methods. For the purpose of comparison, ignore the THP precoding loss $\bar{M}/(\bar{M}-1)$ for $\bar{M}$-QAM constellations. This will result in $\mathbf{R}_{\tilde{\mathbf{x}}} = \mathbf{I}_{Kd}$. In practice, $\mathbf{R}_{\tilde{\mathbf{x}}} \approx \mathbf{I}_{Kd}$ for large $\bar{M}$.

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.

In Fig. 3, the sum rate per cell is plotted against the number of BS antennas N_{T}. When $N_{\mathrm{T}} = 4$, the projected channel DPC coincides with the case of no cooperation. This is because there are insufficient DoF to do any projection of the channel. As N_{T} increases, the proposed method, as well as the no cooperation case, improve. Its rate improvement over the no cooperation case also increases with N_{T}, due to the increase in the DoF. Although orthogonal transmission has the highest sum rate for $N_{\mathrm{T}} = 4$, the proposed method obtains significantly higher rates as N_{T} increases, for $N_{\mathrm{T}} \geq 6$.

The effect of SNR on the sum rate is shown in Fig. 4. 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 projected channel DPC is shown to increase linearly with SNR, for high SNR. Otherwise, the sum rate will level off due to insufficient DoF. The rate with no cooperation levels off at about 12 bps/Hz. At low SNR, the proposed method and the orthogonal transmission scheme have lower sum rates than the case of no cooperation, as the system is noise-limited. At high SNR, the system is interference-limited, so the projected channel DPC performs better than all

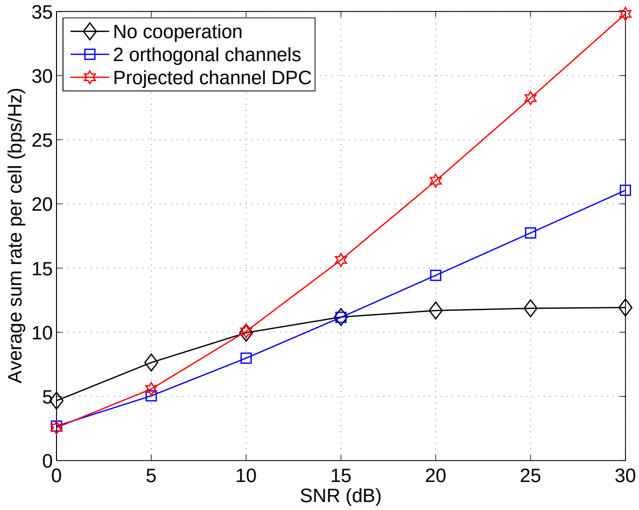

Fig. 4. Sum rate as a function of SNR P/N_0 for $N_\mathrm{T}=8$ and $K=4$.

other methods as it eliminates all the interference and supports the IC users with high rates via DPC. The projected channel DPC enjoys a higher sum rate than orthogonal transmission for SNR$>$ 2dB due to its efficient use of the frequency spectrum and its ability to tackle IC and OC interference.

V. Conclusion

CoMP is an appealing tool considered in the 3GPP LTE-Advanced for mitigating interference and boosting spectral efficiency. The cost of existing coordination schemes with joint processing is the extensive exchange of CSI or SI over back-haul links, which dilutes the gain from CoMP. In this work, we have proposed the projected channel DPC for decentralized base station processing for downlink CoMP. The key feature is that BS cooperation is achieved implicitly, without the need for explicit CSI or SI exchange among BSs. The proposed method cancels the OC interference via a channel projection and supports multiple IC users by a nonlinear block diagonal transmission. It experiences a linear increase in rate as SNR increases, as long as there are sufficient DoF at each BS, in the high SNR regime, while for the case without base station cooperation, the sum rate levels off at high SNR. Additionally, the proposed method outperforms the case of orthogonal transmission for moderate to high SNR, provided there are sufficient DoF at the BSs.

Appendix A
Proof of Lemma 1

Proof:

First consider $K=1$. Let the SVD of $\mathbf{H}$ be $\mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$. We have

$$\mathbf{H}_\perp = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H\bar{\mathbf{V}}_2\bar{\mathbf{V}}_2^H = \mathbf{U}\tilde{\mathbf{U}}\tilde{\mathbf{\Sigma}}\tilde{\mathbf{V}}^H\bar{\mathbf{V}}_2^H, \tag{19}$$

where the SVD of $\mathbf{\Sigma}\mathbf{V}^H\bar{\mathbf{V}}_2$ is $\tilde{\mathbf{U}}\tilde{\mathbf{\Sigma}}\tilde{\mathbf{V}}^H$. Rewriting the five matrices in the last expression of (19),

$$\begin{aligned}\mathbf{H}_\perp =& \mathbf{U}\left[\begin{array}{c|c}\tilde{\mathbf{U}}_d & \tilde{\mathbf{U}}_{\bar{d}}\end{array}\right]\times\\ & \left[\begin{array}{c|c|c}\tilde{\mathbf{P}}\mathbf{L}\tilde{\mathbf{Q}}^H & \mathbf{0} & \\ \mathbf{0} & \tilde{\mathbf{\Sigma}}_{\bar{d}} & \mathbf{0}\end{array}\right]\left[\begin{array}{c}\tilde{\mathbf{V}}_d^H\\ \tilde{\mathbf{V}}_{\bar{d}}^H\end{array}\right]\bar{\mathbf{V}}_2^H \qquad (20)\\ =& \left[\begin{array}{c|c}\mathbf{P} & \mathbf{U}\tilde{\mathbf{U}}_{\bar{d}}\end{array}\right]\left[\begin{array}{c|c|c}\mathbf{L} & \mathbf{0} & \\ \mathbf{0} & \tilde{\mathbf{\Sigma}}_{\bar{d}} & \mathbf{0}\end{array}\right]\left[\begin{array}{c}\mathbf{Q}\\ \tilde{\mathbf{V}}_{\bar{d}}^H\bar{\mathbf{V}}_2^H\end{array}\right]. \qquad (21)\end{aligned}$$

In (20), $\tilde{\mathbf{P}}\mathbf{L}\tilde{\mathbf{Q}}^H = \tilde{\mathbf{\Sigma}}_d$, which is a $d\times d$ real diagonal matrix corresponding to the data streams. $\tilde{\mathbf{U}}_d$ and $\tilde{\mathbf{V}}_d$ represent the d columns of $\tilde{\mathbf{U}}$ and $\tilde{\mathbf{V}}$, respectively, that correspond to the data streams. $\tilde{\mathbf{U}}_{\bar{d}}$ and $\tilde{\mathbf{V}}_{\bar{d}}$ represent the orthogonal complements of $\tilde{\mathbf{U}}_d$ and $\tilde{\mathbf{V}}_d$ respectively. From (21),

$$\mathbf{P} = \mathbf{U}\tilde{\mathbf{U}}_d\tilde{\mathbf{P}}, \text{ and } \mathbf{Q} = \bar{\mathbf{V}}_2\tilde{\mathbf{V}}_d\tilde{\mathbf{Q}}. \tag{22}$$

Note that the first and last matrices of the last line of (21) are unitary. From (22), $\bar{\mathbf{V}}_1^H\mathbf{Q} = \mathbf{0}$. The BD-GMD with $K>1$ involves successive user channel projections. For the k-th user, $\mathbf{Q}_k$ is orthogonal to $\bar{\mathbf{V}}_1$ and $\mathbf{Q}_l, 1\le l\le k-1$. Therefore,

$$\bar{\mathbf{V}}_1^H\mathbf{Q} = \mathbf{0}, \text{ and} \tag{23}$$

$$\mathbf{H}_\perp\mathbf{Q} = \mathbf{H}\left(\mathbf{I}-\bar{\mathbf{V}}_1\bar{\mathbf{V}}_1^H\right)\mathbf{Q} = \mathbf{H}\mathbf{Q}. \tag{24}$$

□

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