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Distributed Robust Sum Rate Maximization in Cooperative Cellular Networks

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***Abstract*—Linear precoding for cooperative multi-cell transmission can provide substantial gains in user throughput, while channel state information (CSI) need to be available at the transmitter. Performance degradation due to imperfect CSI can be partially compensated by robust precoding techniques. For distributed precoding the pre-processing of the user data is performed locally at each base station (BS), while CSI of all participating users is needed. Hence, CSI need to be exchanged between BSs. However, in practice CSI sharing is affected by backhaul latency or limited backhaul capacity resulting in different CSI versions available at the BSs. In this paper, we present a novel robust sum rate maximizing precoding solution, which accounts for imperfect CSI sharing between BSs. Applying the proposed scheme, each BS optimizes its precoding matrix based on local knowledge and by assuming a certain precoding matrix is applied at the other BSs. The assumed precoding matrix results from degrading local knowledge to common but less accurate knowledge. We show that our solution can significantly boost the rate performance compared to existing precoding solutions.**

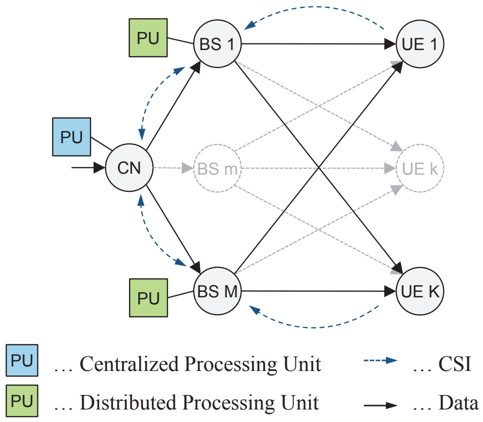

Fig. 1. Topologie of a toy scenario with 2 BSs and 2 UEs, employing centralized and distributed processing.

I. Introduction

Cooperative multi-cell transmission has the potential to significantly boost the user performance compared to non-cooperative transmission, especially for users located at cell edge areas [1]. A system where multiple collaborating base stations (BSs) jointly serving multiple user equipments (UEs) is referred to as network multiple-input–multiple-output (MIMO) system [2]. In the downlink, interference between UEs is already handled at the transmitter side by means of precoding, where the user data is pre-equalized according to the current channel situation requiring channel state information (CSI). While capacity can be achieved with non-linear dirty paper coding [3], linear precoding is attractive for practical implementation due to complexity advantages [4]–[7].

The processing of the precoding can basically be performed either at a central node (CN) or in a distributed fashion at each BS individually [8]–[10], referring to *centralized* and *distributed precoding*, respectively. In both cases, CSI of the complete channel matrix, i.e., the channel from all BSs to all UEs, need to be available at the processing units (PUs). We assume a frequency division duplex system, where each UE feeds CSI only back to its local BS, as illustrated in Fig. 1. For centralized precoding, CSI of all UEs is forwarded to the CN via the backhaul. After processing, the precoded data is fed back to the respective BSs, which transmit it to the UEs. In contrast, for distributed precoding each BS forwards the CSI of its local UEs directly to the other BSs using the CN as routing node.

The precoding schemes referenced above, assume that CSI is perfectly available at the PUs. However, in practice CSI is typically impaired by channel estimation errors, lossy compression for feedback transmission and feedback delays [10], [11], which causes substantial performance degradation [12]. Additionally, in cooperative systems latency and rate restrictions of backhaul connections are of major interest. In general, imperfect CSI can be addressed by employing robust precoding techniques [13], [14], exploiting statistical knowledge of the imperfection. Distributed precoding with imperfect backhaul connections causes the additional issue, that BSs do not share the same CSI version. Each BS sees the channel of its local UEs with higher accuracy then the channel of all other cell UEs, which are additionally affected by the backhaul [10]. Considering different CSI versions at the BSs, the achievable rate region for distributed linear precoding with single antenna UEs was presented in [15], while a degrees of freedom analysis was shown in [16].

In this paper, we present a novel distributed robust precoding solution, targeting sum rate maximization and taking into account that different CSI versions are available the BSs.

The remainder of this paper is structured as follows. The system model is introduced in Section II before we present out novel precoding solution in Section III. Section IV shows simulation results followed by conclusions in Section V.

Notation: Conjugate, transposition and conjugate transposition is denoted by $(\cdot)^*$, $(\cdot)^T$ and $(\cdot)^H$, respectively. The trace of a matrix is $\mathrm{tr}(\cdot)$, $\det(\cdot)$ denotes determinant while $||\cdot||$

is used for Frobenius norm. $\mathrm{dg}(\cdot)$ replaces each off diagonal matrix element with zero, $\mathrm{vec}(\cdot)$ stacks all matrix columns into a vector and $\odot$ refers to element wise multiplication. Expectation is $\mathbb{E}\{\cdot\}$, $\mathbb{C}$ denotes the set of complex numbers and $\mathcal{N}_{\mathbb{C}}(\mathbf{m}, \mathbf{\Phi})$ refers to a multi-variate complex normal distribution with mean vector $\mathbf{m}$ and covariance matrix $\mathbf{\Phi}$.

II. System Model

We consider a network MIMO system with M BSs jointly transmitting data to K UEs using the same radio resource. The set of BSs and UEs is denoted by $\mathcal{M} = \{1, \ldots, M\}$ and $\mathcal{K} = \{1, \ldots, K\}$, respectively. Each UE k is assigned to a single BS which we call *local* BS. $\mathcal{A}_m$ denotes the set of UEs which are assigned to BS m, where $\cap_{m=1}^{M} \mathcal{A}_m = \emptyset$ and $\cup_{m=1}^{M} \mathcal{A}_m = \mathcal{K}$ need to be satisfied. Each BS $l \neq m$ to which UE $k \notin \mathcal{A}_l$ is not assigned, is called *remote* BS. Note, that the UE assignment is only relevant for uplink CSI feedback, where only local BSs decode CSI of its UEs, while in the downlink all K UEs are jointly served by all M BSs.

Furthermore, each BS m is equipped with B_m transmit antennas while each UE k employs U_k receive antennas. The overall number of antennas at the BS and UE side is B and U, respectively. The data vector $\mathbf{d} = [\mathbf{d}_1^T, \ldots, \mathbf{d}_K^T]^T \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \mathbf{I})$ is jointly precoded at all M BSs using the precoding matrix $\mathbf{B} = [\mathbf{B}_1^T, \ldots, \mathbf{B}_M^T]^T = [\bar{\mathbf{B}}_1, \ldots, \bar{\mathbf{B}}_K]$. $\mathbf{B}_m \in \mathbb{C}^{[B_m \times U]}$ is the part of $\mathbf{B}$ which is applied at BS m while $\bar{\mathbf{B}}_k \in \mathbb{C}^{[B \times U_k]}$ is used at all BSs in order to precode the data of UE k. Each BS m needs to restrict its transmit power to $\mathrm{tr}\{\mathbf{B}_m \mathbf{B}_m^H\} \leq \rho_m$. The precoded symbol vector $\mathbf{x} = \mathbf{B}\mathbf{d}$ is transmitted over a frequency flat complex Gaussian distributed channel denoted by $\mathbf{H} = [\mathbf{H}_1^T, \ldots, \mathbf{H}_K^T]^T$. Matrix $\mathbf{H}_k = [\mathbf{H}_{k,1}, \ldots, \mathbf{H}_{k,M}]$ is the channel to UE k and $\mathbf{H}_{k,m} \in \mathbb{C}^{[U_k \times B_m]}$ is the channel from BS m to UE k. It is assumed that the entries of $\mathbf{H}$ are uncorrelated and the elements of $\mathbf{H}_{k,m}$ are independent and identically distributed (i.i.d.) according to $\mathrm{vec}(\mathbf{H}_{k,m}) \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \lambda_{k,m}\mathbf{I})$, $\forall k, m$, where the mean channel gain of each link between BS m and UE k is

$$\lambda_{k,m} = \beta d_{k,m}^{-\alpha} \tag{1}$$

with path loss exponent α, distance $d_{k,m}$ between UE k and BS m and coefficient β to further adjust the model. The mean channel gains of all BS-UE links are collected in matrix $\mathbf{\Lambda} = [\lambda_{1,1}, ..., \lambda_{1,M}; ...; \lambda_{K,1}, ..., \lambda_{K,M}]$. It is assumed that the channel remains constant over the duration of a data block. The received signal vector at UE k is impaired by additive white Gaussian noise (AWGN) $\mathbf{n}_k \sim \mathcal{N}_{\mathbb{C}}\left(\mathbf{0}, \sigma_n^2 \mathbf{I}\right)$ before it is equalized using the linear receive filter $\mathbf{U}_k$. The transmission equation is obtained by stacking the equalized data symbols of all K UEs into a single vector

$$\hat{\mathbf{d}} = \mathbf{U}\left(\mathbf{H}\mathbf{B}\mathbf{d} + \mathbf{n}\right) = \mathbf{U}\mathbf{y}. \tag{2}$$

The receive filters of all UEs are collected in matrix $\mathbf{U} = \mathrm{blkdiag}\left(\mathbf{U}_1, \ldots, \mathbf{U}_K\right)$, where the operator $\mathrm{blkdiag}(\cdot)$ constructs a block diagonal matrix. Additionally, $\mathbf{n} = [\mathbf{n}_1^H, \ldots, \mathbf{n}_K^H]^H$ is the overall noise vector.

A. CSI Impairments

Due to channel estimation errors, feedback quantization and delays between channel observation and transmission, CSI is only imperfectly available for precoding. A detailed mathematical framework for modeling these impairments is stated in Sec. II B of [10]. In this work, we abstract from the details and express the CSI impairment of the link between BS m and UE k just by the error variance $\sigma_{k,m}^2$. The actual channel known at the PU can be interpreted as random variable

$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E} \tag{3}$$

where the CSI matrix $\hat{\mathbf{H}} = [\hat{\mathbf{H}}_1^T, \ldots, \hat{\mathbf{H}}_K^T]^T$ with $\hat{\mathbf{H}}_k = [\hat{\mathbf{H}}_{k,1}, \ldots, \hat{\mathbf{H}}_{k,M}]$ is uncorrelated with the Gaussian error matrix $\mathbf{E} = [\mathbf{E}_1^T, \ldots, \mathbf{E}_K^T]^T$ with $\mathbf{E}_k = [\mathbf{E}_{k,1}, \ldots, \mathbf{E}_{k,M}]$ and $\mathrm{vec}(\mathbf{E}_{k,m}) \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \sigma_{k,m}^2 \mathbf{I})$. Note, that the error variances $\sigma_{k,n}^2$ of each BS-UE link are potentially different due to independent mean channel gains $\lambda_{k,m}$ in combination with unequal feedback bit allocation and user specific velocities. The elements of $\mathbf{E}_{k,m}$ have equal variances due to the same mean channel gain of all sub-links of a certain BS-UE link. Equation (3) follows from the assumption, that the CSI is obtained by minimum mean square error (MMSE) estimation [17]. Additionally, the CSI for each BS-UE link can be stated as a downscaled and noisy version of the actual channel

$$\hat{\mathbf{H}}_{k,m} = v_{k,m}\mathbf{H}_{k,m} + \mathbf{W}_{k,m}, \tag{4}$$

where $v_{k,m} = 1 - \sigma_{k,m}^2 / \lambda_{k,m}$ is a real value and the noise matrix $\mathbf{W}_{k,m}$ with $\mathrm{vec}(\mathbf{W}_{k,m}) \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \sigma_{k,m}^2 v_{k,m}\mathbf{I})$ is uncorrelated with the actual channel $\mathbf{H}_{k,m}$ [10].

Following the topology of Fig. 1, each UE k observes the channels from M BSs with potentially different mean channel gains $\lambda_{k,m}$. As stated before, we only consider CSI feedback from a UE to its local BS. However, decoding CSI also at the remote BS directly from the uplink can be beneficial for UEs located at the cell edge [11].

For centralized precoding each BS forwards the CSI of its assigned UEs to the CN, where the precoding is performed. The precoded data is fed to the respective BSs from where it is transmitted to the UEs. For distributed precoding each BS also transmits its CSI to the CN. However, the CN does not perform any processing but forwards the CSI to all other BSs (see Fig. 1). Consequently, each BS obtains CSI of all K UEs, while backhaul impairments lead to inconsistent CSI versions available at the BSs. Regarding (3) and (4) for distributed precoding, the quantities $\sigma_{k,m}^2[l]$ and $v_{k,m}[l]$ depend on the BS l, where the CSI is available. We collect the channel uncertainties of all BS-UE links available at BS l in matrix

$$\mathbf{\Sigma}[l] = [\sigma_{1,1}^2[l], ..., \sigma_{1,M}^2[l]; ...; \sigma_{K,1}^2[l], ..., \sigma_{K,M}^2[l]]. \tag{5}$$

Also $\hat{\mathbf{H}}[l]$, $\mathbf{E}[l]$ and $\mathbf{W}[l]$ as well as all their sub-matrices are labeled with the additional index l. Note, that for each UE $k \in \mathcal{A}_l$, $\sigma_{k,m}^2[l] \leq \sigma_{k,m}^2[n]$, $\forall k, l, m, n \neq l$, i.e., the CSI accuracy at each remote BSs n cannot be higher then the accuracy at the local BS l. This assumption results from the practical property that backhaul transmission cannot improve CSI quality.

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We define the CSI of the BS-UE link k, m which is available at BS l as:

$$\hat{\mathbf{H}}_{k,m}[l] = \begin{cases} v_{k,m}[l]\mathbf{H}_{k,m} + \mathbf{W}_{k,m}[l] & \text{if } k \in \mathcal{A}_l \\ v_{k,m}[l]\mathbf{H}_{k,m} + \bar{\mathbf{W}}_{k,m}[l,n] & \text{if } k \in \mathcal{A}_n, \forall n \neq l. \end{cases} \quad (6)$$

The noise matrix $\bar{\mathbf{W}}_{k,m}[l,n] = \mathbf{W}_{k,m}[n] + \mathbf{W}_{k,m}[l,n]$ consists of the error matrix $\mathbf{W}_{k,m}[n]$ due to feedback transmission to BS n and the additional error matrix $\mathbf{W}_{k,m}[l,n]$ referring to the impairment resulting from backhaul forwarding from BS n to BS l, where $\text{vec}(\mathbf{W}_{k,m}[l,n]) \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \sigma^2_{k,m}[l]v_{k,m}[l] - \sigma^2_{k,n}[n]v_{k,m}[n]\mathbf{I})$. Note, that if UE $k \in \mathcal{A}_n$ is assigned to BS n, the variance of the error which results only from backhaul transmission from BS n to BS l is $\sigma^2_{k,m}[l] - \sigma^2_{k,n}[n]$. This is exactly the difference between the error variance $\sigma^2_{k,m}[l]$, which includes CSI feedback transmission to BS n plus additional backhaul forwarding to BS l and the variance $\sigma^2_{k,n}[n]$ which only reflects feedback transmission to the local BS n.

B. Objective

We are targeting the maximization of the sum rate under per BS power constraints and imperfect CSI conditions by properly choosing the precoding matrix $\mathbf{B}$. The problem for centralized precoding was already solved in [14] by means of a weighted sum MSE minimization problem. For distributed precoding the optimization is performed at different BSs, where the set of side information known at BS l is

$$\mathcal{S}_l = \left\{ \hat{\mathbf{H}}[l], \hat{\mathbf{H}}_k[m], \mathbf{\Lambda}, \mathbf{\Sigma}[m], \sigma^2_n \quad \middle| \quad \forall k \in \mathcal{A}_l, m \right\}. \quad (7)$$

Note, that BS l is also aware of its local UEs' CSI, which is available at the each BS m. This is due to the fact that BS l previously forwarded this information to BS m.

With weighs ν_k we can formulate the objective at BS l as

$$\begin{aligned} \mathbf{B}^\star_l = \quad & \underset{\mathbf{B}_l}{\text{argmax}} \quad \textstyle\sum_{k=1}^K \nu_k R_k(\mathbf{B}_l, \mathcal{S}_l) \\ & \text{s.t.} \quad \text{tr}(\mathbf{B}_l\mathbf{B}_l^H) \leq \rho_l \quad \forall l. \end{aligned} \quad (8)$$

where the rate of UE k calculated by BS l reads

$$R_k(\mathbf{B}_l, \mathcal{S}_l) = \mathbb{E}\left\{\log\det\left(\mathbf{I} + \mathbf{A}_{k,k}[l]\mathbf{C}_k^{-1}[l]\right)\right\}. \quad (9)$$

The signal portion aimed for UE j and received at UE k is

$$\mathbf{A}_{k,j}[l] = (\hat{\mathbf{H}}_k[l] + \mathbf{E}_k[l])\bar{\mathbf{B}}_j[l]\bar{\mathbf{B}}_j^H[l](\hat{\mathbf{H}}_k[l] + \mathbf{E}_k[l])^H \quad (10)$$

and the term according to noise plus interference results in

$$\mathbf{C}_k[l] = \sigma^2_n\mathbf{I} + \sum_{j=1, j\neq k}^{K} \mathbf{A}_{k,j}[l]. \quad (11)$$

Note, that $\bar{\mathbf{B}}_k[l] = [\mathbf{B}_{k,1}[l], \ldots, \mathbf{B}_{k,M}[l]]$ in (9) consists of parts of the optimization variable $\mathbf{B}_{k,l}[l]$ but also of parts $\mathbf{B}_{k,m}[l]$ which are applied at other BSs $m \neq l$ and which can only be statistically known at BS l. Hence, the expectation in (9) is not only w.r.t the error matrix $\mathbf{E}_k[l]$ but also w.r.t. the parts of the precoding matrix $\mathbf{B}_{k,m}[l]$ which are applied at each BS $m \neq l$.

III. Distributed Sum Rate Maximization

In this Section we present our solution for the distributed optimization problem (8), which is the main contribution of this paper. Therefore, we identify two major tasks:

A. Finding the distribution of $\mathbf{B}_{k,m}[l] \quad \forall k, m \neq l$

B. Solving the rate optimization problem (8) with a given distribution of $\mathbf{B}_{k,m}[l] \quad \forall m \neq l$

Preliminary Assumption: In order to simplify the following derivations, we assume that the backhaul links between each BS and the CN are equivalent in terms of causing CSI impairments, i.e., $\sigma^2_{k,l}[m] = \sigma^2_{k,l}[n]$, $\forall k \notin \mathcal{A}_m \cup \mathcal{A}_n, l, m, n$. Hence, the CSI of a UE is equivalently available at all remote BSs. Only the local BS owns a more accurate CSI version.

A. Precoding Matrix Distribution at the other BSs

BS l needs to reconstruct the precoding matrix which is applied at BS $m \neq l$. For that purpose, BS l uses the CSI it assumes to be available at BS m. From our preliminary assumption we identify 3 cases:

1) $k \notin \mathcal{A}_l \cup \mathcal{A}_m$: The CSI $\hat{\mathbf{H}}_k[l] = \hat{\mathbf{H}}_k[m]$ available at BS l and m is equivalent.

2) $k \in \mathcal{A}_m$: The best which BS l knows about the CSI available at BS m $\hat{\mathbf{H}}_k[m]$ is its own CSI of UE $\hat{\mathbf{H}}_k[l]$. However, BS l is aware of the higher accuracy BS m actually has and assesses this knowledge with a higher error variance. As resulting from (3), this is equivalent to the error variance $\sigma^2_{k,n}[l]$ BS l observes for its own CSI of UE k.

3) $k \in \mathcal{A}_l$: In this case the CSI $\hat{\mathbf{H}}_k[l]$ has higher accuracy then $\hat{\mathbf{H}}_k[m]$, $\forall m \neq l$. Since BS l previously forwarded the CSI of UE k to BS m, it already knows the CSI available at BS m $\hat{\mathbf{H}}_k[m] \in \mathcal{S}_l$.

Based on the considerations above, we define the CSI BS l assumes to be available at BS m as

$$\hat{\mathbf{H}}[m,l] = [\mathbf{G}_1^T, \ldots, \mathbf{G}_K^T]^T, \quad (12)$$

with

$$\mathbf{G}_k = \begin{cases} \hat{\mathbf{H}}_k[m] & \text{if } k \in \mathcal{A}_l, \forall m \neq l \\ \hat{\mathbf{H}}_k[l] & \text{if } k \notin \mathcal{A}_l. \end{cases} \quad (13)$$

Based on (12) all matrices $\hat{\mathbf{H}}_C = \hat{\mathbf{H}}[m,l]$ are equal with $\forall l, m \neq l$, i.e., $\hat{\mathbf{H}}_C$ is the most accurate channel knowledge which is *commonly* known at all BSs. Precoding based on common knowledge $\hat{\mathbf{H}}_C$ is equivalent with centralized precoding and can be solved by **Algorithms 1** (see [14]), which equivalently solves the weighted sum MSE minimization problem

$$\begin{aligned} \mathbf{B}^\star = \quad & \underset{\mathbf{B}}{\text{argmin}} \quad \textstyle\sum_{k=1}^K \text{tr}(\mathbf{V}_k\mathbf{M}_k) \\ & \text{s.t.} \quad \text{tr}(\mathbf{B}_l\mathbf{B}_l^H) \leq \rho_l \quad \forall l, \end{aligned} \quad (14)$$

with the fixed weighting matrix $\mathbf{V}_k = \nu_k\mathbf{M}_k^{-1}$, which is not affected by the optimization over $\mathbf{B}$. The MSE matrix

$$\mathbf{M}_k = (\mathbf{I} + \bar{\mathbf{B}}_k^H\hat{\mathbf{H}}_k^H\bar{\mathbf{C}}_k^{-1}\hat{\mathbf{H}}_k\bar{\mathbf{B}}_k)^{-1} \quad (15)$$

is affected by the optimization. The interference and noise

Algorithm 1: General approach for maximizing the WSR
set iteration index $i = 0$
initialize $\mathbf{B}^i = \mathbf{B}^{\text{init}}$
repeat
  update $i = i + 1$
  (a) update of the receive filter $\mathbf{U}_k^i|\mathbf{B}^{i-1}\ \forall k$
  (b) update of the weighting matrix $\mathbf{V}_k^i|\mathbf{B}^{i-1}\ \forall k$
  (c) update of the precoding matrix $\mathbf{B}^i|\mathbf{U}^i, \mathbf{V}^i$
until convergence

covariance matrix included in (15) reads

$$\bar{\mathbf{C}}_k = \sigma_n^2\mathbf{I} + \mathbf{\Phi}_k + \sum_{l=1, l\neq k}^{K} \hat{\mathbf{H}}_k\bar{\mathbf{B}}_l\bar{\mathbf{B}}_l^H\hat{\mathbf{H}}_k^H \tag{16}$$

with $\mathbf{\Phi}_k = \text{diag}(\mathbf{\Sigma}_k \text{diag}^{-1}(\mathbf{B}\mathbf{B}^H))$ and the reshaped error covariance matrix $\mathbf{\Sigma}_k = [\sigma_{k,1}^2 \mathbf{1}_{U_k\times B_1}, \ldots, \sigma_{k,M}^2\mathbf{1}_{U_k\times B_M}]$. The operator diag$(\cdot)$ creates a diagonal matrix out of a column vector, while diag$^{-1}(\cdot)$ stacks the diagonal elements of a matrix into a column vector. Equation (15) result from the assumption that MMSE receive filters

$$\mathbf{U}_k = \bar{\mathbf{B}}_k^H\hat{\mathbf{H}}_k^H(\hat{\mathbf{H}}_k\mathbf{B}\mathbf{B}^H\hat{\mathbf{H}}_k^H + \mathbf{\Phi}_k + \sigma_n^2\mathbf{I})^{-1} \tag{17}$$

are applied at the UEs. However, since optimizing $\mathbf{B}$ with variable MMSE receive filters is still hard to solve, the precoding matrix can be obtained with fixed receive filters, resulting in the alternating solution as stated in **Algorithm 1**. Details for obtaining the precoding matrix in step (c) with fixed weighting matrix $\mathbf{V} = \text{blkdiag}(\mathbf{V}_1, ..., \mathbf{V}_K)$ and fixed receive filter matrix $\mathbf{U}$ can be found in [14].

B. Rate Optimization

In this section we present the solution for problem (8) with fixed precoding matrices $\mathbf{B}_{k,m}[l]$, $\forall m \neq l$. According to the derivations in [14] a lower bound for the original problem can be found by solving the weighted MSE minimization problem

$$\begin{aligned} \mathbf{B}_l^\star = \quad & \underset{\mathbf{B}_l}{\text{argmin}} \quad \textstyle\sum_{k=1}^K \nu_k \text{tr}(\mathbf{V}_k\mathbf{M}_k) \\ & \text{s.t.} \quad \text{tr}(\mathbf{B}_l\mathbf{B}_l^H) \leq \rho_l \quad \forall l. \end{aligned} \tag{18}$$

To solve problem (18) we introduce the CSI matrix $\hat{\mathbf{H}}_{\bar{l}}$ which excludes the CSI of BS l by replacing the respective coefficients with zeros. Additionally, $\mathbf{B}_{\bar{l}}$ is the precoding matrix applied at all BSs except BS l, resulting from setting the respective elements equal to zero. Similar to **Algorithm 1** (18) can be solved alternately, where the last step results in

$$\mathbf{B}_l^\star = b\mathbf{P}_l^{-1}\hat{\mathbf{H}}_l^H\mathbf{U}^H\mathbf{V}\left(\mathbf{I} - \mathbf{U}\hat{\mathbf{H}}_{\bar{l}}\mathbf{B}_{\bar{l}}\right) \tag{19}$$

with fixed $\mathbf{V}$ and fixed $\mathbf{U}$. Matrix

$$\mathbf{P}_l = \left(\hat{\mathbf{H}}_l^H\mathbf{U}^H\mathbf{V}\mathbf{U}\hat{\mathbf{H}}_l + \mathbf{D}_l + \frac{\sigma_n^2}{\rho}\text{tr}(\mathbf{V}\mathbf{U}\mathbf{U}^H)\mathbf{I}\right) \tag{20}$$

is regularized by the filtered and reshaped error covariance matrix $\mathbf{D}_l = \text{dg}(\mathbf{\Gamma}_l\text{diag}^{-1}(\mathbf{U}^H\mathbf{U})\mathbf{1})$. The error covariance of the local BS reads $\mathbf{\Gamma}_l = [\sigma_{1,l}, ..., \sigma_{K,l}] \otimes \mathbf{1}_{B_l\times U}$. The overall resulting algorithm for our proposed distributed precoding scheme is stated in **Algorithm 2**.

Algorithm 2: Distributed optimization at BS l
obtain $\mathbf{B}_{\bar{l}}$ by solving **Algorithm 1** with $\hat{\mathbf{H}}_C$ and replacing the elements of BS l with zeros
set iteration index $i = 0$
initialize $\mathbf{B}_l^i = \mathbf{B}_l^{\text{init}}$
repeat
  update $i = i + 1$
  (a) construct $\mathbf{B}$ based on $\mathbf{B}_{\bar{l}}$ and $\mathbf{B}_l^i$
  (b) update of the receive filter $\mathbf{U}_k^i|\mathbf{B}^{i-1}\ \forall k$
  (c) update of the weighting matrix $\mathbf{V}_k^i|\mathbf{B}^{i-1}\ \forall k$
  (d) update of the precoding matrix $\mathbf{B}_l^i|\mathbf{U}^i, \mathbf{V}^i$
until convergence

IV. Simulation Setup

In this section our proposed distributed precoding scheme is investigated based on a toy scenario with $M = 2$ BSs and $K = 2$ UEs as illustrated in Fig. 2. Each UE is assigned to

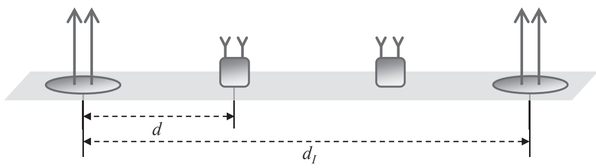

Fig. 2. Toy scenario for simulations including 2 BSs and 2 UEs placed symmetrically on a line between the BSs.

the nearest BS. The distance between the BSs is d_I and the relative user separation is $\delta = d/d_I$, where d is the distance between the BS and its assigned UE. Both UEs are placed symmetrically on a line between the two BSs. The maximum transmit power is ρ resulting in a signal-to-noise ratio (SNR) at the cell edge (CE) of

$$\text{SNR}_{\text{CE}} = \log_{10}\left(\rho\beta(d_I/2)^{-\alpha}/\sigma_n^2\right). \tag{21}$$

Further simulation parameters can be found in Table I. Fig. 3 shows the achievable rate over the cell edge SNR. As upper bound we use the multi-cell algorithm of [14] assuming perfect CSI, which is equivalent to the non-robust algorithm of [6]. The robust scheme of [14] is also plotted for the case of imperfect CSI, applying centralized precoding (CP) as well as distributed precoding (DP). Although DP would provide more accurate CSI of local UEs, the precoding scheme is sensitive

TABLE I
Simulation Parameters

Parameter	Value
Number of BS antennas	$B_m = 2\quad \forall m$
Number of UE antennas	$U_k = 2\quad \forall k$
Noise power	$\sigma_n^2 = 1$
Path loss exponent	$\alpha = 3.5$
Model coefficient	$\beta = 10^{-14.5}$
Feedback delay	$\Delta_F = 5$ ms
Backhaul delay	$\Delta_B = 10$ ms
User velocity	$v = 5$ km/h
Coherence time	$T_C = 20$ ms
Inter side distance	$d_I = 500$ m
User weights	$\nu_k = 1\quad \forall k$
Max. number of iterations	$i_{max} = 30$

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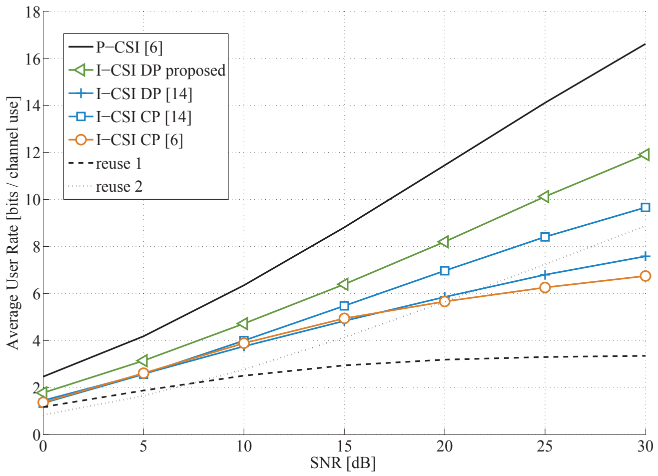

Fig. 3. Achievable rate over the cell edge SNR based on the setup described in Fig. 2 with $\delta = 0.5$.

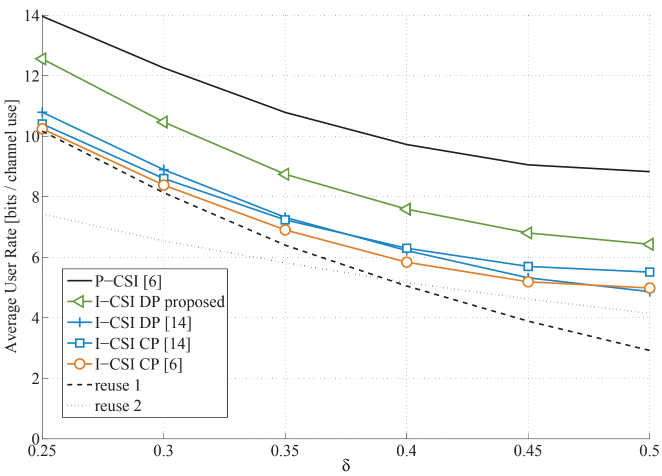

Fig. 4. Achievable rate over the relative user separation based on the setup described in Fig. 2 with $\text{SNR}_{\text{CE}} = 15$ dB.

to inconsistencies caused by different CSI versions available at the cooperating BSs. In contrast, our proposed precoding scheme is more robust against inconsistencies and can achieve a significant performance gain compared to [14]. Note, that for perfect CSI our proposed scheme is equivalent with the upper bound. The non-robust solution of [6] performs worst. As lower bound we plotted the performance of non-cooperative reuse 1 and reuse 2 transmission, where no precoding is needed. Using a fixed cell edge SNR of 15 dB, the rate performance over the relative user separation δ is illustrated in Fig. 4. Our proposed solution clearly outperforms the other schemes within the complete area.

V. Conclusions

We proposed a novel robust solution for distributed precoding, where the cooperating BSs do not share the same CSI. Our solution consists of two steps: First, each BS calculates the precoding matrix it assumes to be available at the other BSs. Secondly, our novel precoding scheme is used, which considers the assumed precoding matrix of the other BSs for optimization. Simulation results showed the performance gain compared to robust state of the art solutions.

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