Performance Benchmark for Network MIMO Systems: A Unified Approach for MMSE Transceiver Design and Performance Analysis

Jialing Li, Enoch Lu, and I-Tai Lu
Department of Electrical and Computer Engineering, Polytechnic Institute of New York University
5 Metrotech Center, Brooklyn, NY 11201, USA
jialing.li.phd2@gmail.com, enoch.school@gmail.com, and itailu@rama.poly.edu

Abstract—Network MIMO (multiple-input multiple output), also known as Coordinated Multipoint (CoMP), is a key enabling technology of future cellular systems. A unified framework and a novel generalized iterative approach (GIA) is proposed for the minimum mean square error (MMSE) transceiver design of general MTMR (multiple-transmitter multiple-receiver) MIMO systems with different CoMP configurations (including Non-Coordinated Multipoint, Coordinated Beamforming, Joint Processing Downlink, Joint Processing Uplink and Joint Processing Single User) subject to general linear power constraints. Performance analysis of the different CoMP configurations is provided for the per-antenna and total power constraints at each base station or user equipment. The result provides a benchmark for joint transceiver designs based on other criteria.

I. INTRODUCTION

To meet the demand for better cellular performance, Network MIMO (multiple-input multiple-output), also known as Coordinated Multipoint (CoMP), has been brought up as a key enabling technology of future cellular systems. It aims at lowering the inter-cell interference (ICI) at cell edges by having potential interfering cells cooperate. And its lowering of the interference allows for better use of the scarce spectrum.

A CoMP system is a multiple-transmitter multiple-receiver (MTMR) system where each transmitter or receiver may have multiple antennas. Five main CoMP configurations are considered in this paper. The first one is Non-CoMP (Non-Coordinated Multipoint) which does not take the advantage of Network MIMO at all. In it, each base station (BS) only has the channel state information (CSI) of its own desired channels and communicates with its own user-equipments (UE’s). Since there is no cooperation between BS’s of different cells, the ICI is the main contributing factor to the poor performance of the cell edge UE’s. The second one is Coordinated Beamforming (CBF). Here, each BS again only communicates with its own UE’s. But, the cells do share the CSI and cooperate in jointly designing precoders and decoders to minimize the ICI they cause to each other by jointly designing their precoders and decoders. (Note that data are not shared among cells in CBF.) The third one is Joint Processing Downlink (JP-DL). Like CBF, the CSI is shared among cells and all precoders and decoders are jointly designed in JP-DL. However, unlike CBF, all BS’s cooperate in sharing the data and thus act as a single transmitter in downlink. The data is jointly processed and transmitted simultaneously from the cooperating BS’s. The fourth one is Joint Processing Uplink (JP-UL). Like CBF and JP-DL, the CSI is shared among cells and all precoders and decoders are jointly designed in JP-UL. However, unlike CBF or JP-DL, all BS’s cooperate in sharing the data and thus act as a single receiver in uplink. The data is received and then jointly processed by the cooperating BS’s. The fifth one is Joint Processing Single User (JP-SU). Like CBF, JP-DL and JP-UL, the CSI is shared among cells and all precoders and decoders are jointly designed in JP-UL. However, unlike CBF, JP-DL or JP-UL, all receivers cooperate in sharing the data and thus act as a single receiver and all transmitters cooperate in sharing the CSI and data and thus act as a single transmitter. The data is jointly processed and transmitted simultaneously. It is also received and then jointly processed. The employing of CBF or JP is expected to improve the performance of the cell edge UE’s.

MIMO linear transceiver designs are needed to improve the performance of each of these configurations. To be adaptive in practice, a need for a universal transceiver design applicable to all configurations arises in general MTMR systems. Much work is currently being done but only a few (e.g., see [1-4]), have been published for the transceiver designs of these configurations under different criteria. Considered in this paper is the minimum mean square error (MMSE) design which is not only optimum in the MMSE sense but also near optimum in some other senses (such as maximum capacity and minimum bit error rate (BER)). Thus, MMSE designs provide a performance benchmark for joint transceiver designs based on other criteria—they show what kinds of gains are possible and what the performance order (among various CoMP configurations) is regardless of design criteria. Before discussing the new work, it is beneficial to have some background on what work has already been done on MMSE transceiver designs when perfect CSI is available.

A closed form design subject to the total power constraint for single user MIMO systems is derived in [5]. Unfortunately, this closed form design cannot be extended to the multiuser case. For the multiuser uplink configuration, the transmit covariance optimization approach (TCO.A) provides numerical solutions for both the per-user [6,7] and per-antenna [8] power...
constraints. It is a convex approach and obtains optimum solutions. However, it does not allow the numbers of data streams to be pre-specified. Fortunately, our generalized iterative approach (GIA) for the uplink [8,9], which can deal with arbitrary linear equality power constraints, does. Interestingly enough, it is shown in [8] that the GIA is equivalent to the DCOA and obtains optimum solutions when the TCOA is applicable and the transmit covariance matrices obtained from the MMSE designs are full rank.

For the downlink configuration, iterative approaches (e.g., [10]) and a dual uplink approach [11,12] are employed to provide numerical MMSE designs for multiuser MIMO systems subject to the total power constraint. The extension to deal with the per-antenna and per-cell power constraints is achieved by an iterative approach using a second order cone programming (SOCP) [2], our GIA for the downlink [13,14], and our decoder covariance optimization approach (DCOA) [14]. The iterative approach (using a SOCP) and the DCOA are on two extremes with the GIA in the middle. On one extreme is the iterative approach (using a SOCP) which can deal with arbitrary number of data streams but can only guarantee local optimality. On the other is the DCOA which cannot deal with arbitrary number of data streams but can always guarantee global optimality. In the middle is the GIA. It can deal with arbitrary number of data streams and guarantee local optimality like the iterative approach (using a SOCP). But, it is shown in [14] that the GIA is equivalent to the DCOA and obtains optimum solutions when the DCOA is applicable and the decoder covariance matrices obtained from the MMSE designs are full rank.

However, to the best of our knowledge, no work related to joint MMSE transceiver designs for general Network MIMO systems has been published. In this paper, our GIA [8,9,13,14] is extended to provide joint transceiver design for general 3MTMR MIMO systems including the above mentioned five CoMP configurations. There are three main contributions of this paper: one, a single formulation is created to take care of the different CoMP configurations and power constraints thus enables a unified framework for transceiver design of general Multi-antenna Transmission and Multi-receiver (MTMR) systems; two, the GIA is extended from [8,9,13,14] to deal with the universal MMSE transceiver design for general MTMR systems including the five CoMP configurations (it can deal with arbitrary source covariance matrices and allows for tradeoff between diversity and multiplexing gains as well); three, performance comparison of different configurations for cell edge UE’s are provided thus giving the benchmark for joint transceiver designs based on other criteria. (Without loss of generality, we consider in this paper a special case for the CBF and Non-CoMP configurations where each BS is associated with one UE). Since the main focus of this paper is the performance benchmark, the information exchange required for different CoMP configurations will not be discussed here.

Notations are as follows. All boldface letters indicate vectors (lower case) or matrices (upper case). $A^*$, $A^T$, $\text{tr}(A)$, $\langle A \rangle$, stand for the Hermitian, inverse, trace and expectation of $A$, respectively. span($A$) represents the subspace spanned by the columns of $A$. Matrix $I_n$ signifies an identity matrix with rank $n$. $\text{diag}([\ldots])$ denotes the diagonal matrix with elements $[\ldots]$ on the main diagonal. $A*B$ denotes the element-wise product of $A$ and $B$. $CN(\mu, \sigma^2)$ denotes a complex normal random variable with mean $\mu$ and variance $\sigma^2$.

II. FORMULATION

A. Network MIMO Systems

Consider a Network MIMO system with $C$ composite transmitters and $K$ composite receivers. Here, depending on which CoMP configuration is under consideration, a composite transmitter (receiver) can represent a UE, a BS, a set of cooperating UE’s or a set of cooperating BS’s. In other words, a composite transmitter (receiver) can refer to a localized unit (such as a single BS or a single UE) or a distributed unit (such as a set of multiple BS’s or a set of multiple UE’s).

Let $L$, $L \geq C$, denote the total number of localized transmitters. Let $\tau_c$ and $t_c$ denote the numbers of antennas at the $n^{th}$ localized transmitter and the $c^{th}$ composite transmitter respectively. Thus, $t_c = \sum_{i=1}^{C} t_i = \sum_{i=1}^{\tau_c} t_i$ where $t$ is the total number of transmit antennas in the system. Similarly, Let $R$, $R \geq K$, denote the total number of localized receivers. Let $\gamma_i$ and $r_i$ denote the numbers of antennas at the $i^{th}$ localized receiver and the $l^{th}$ composite receiver respectively. Thus, $r = \sum_{i=1}^{R} r_i = \sum_{i=1}^{\gamma_i} r_i$ where $r$ is the total number of receive antennas in the system. For convenience, we will refer a composite transmitter (composite receiver) as a transmitter (receiver) in the rest of this paper.

Let $H_n$ denote the channel matrix from the $c^{th}$ transmitter to the $i^{th}$ receiver. At the $c^{th}$ transmitter, let $s_n$ and $F_n$ denote the transmitted data and the precoder for the $i^{th}$ receiver, respectively. Furthermore, let $\Phi_{bc} = <s_n s_n^* >$ and $G_{bc}$ be, respectively, the source covariance matrix and the decoder for $s_n$. When the $c^{th}$ transmitter has no data to transmit to the $i^{th}$ receiver, $s_n = 0$, $\Phi_{bc} = 0$, $F_n = 0$ and $G_{bc} = 0$. When it does, $\Phi_{bc}$ is positive definite and $F_n$ and $G_{bc}$ must be determined in the joint precoder and decoder design.

In this system, there may be multiple clusters where each cluster jointly designs (full CSI for this cluster is known) the MIMO processors for its own transmitters and receivers but does so independently of the other clusters. Let $D$ and $S$ define one such cluster; $D$ being the set of transmitter indices in the cluster and $S$ being the set of receiver indices in the cluster. At the $i^{th}$ receiver, $i \in S$, the received signal is thus

$$y_i = \sum_{c \in D} H_n \sum_{j \in S} F_j s_j + n_i , \quad n_i = a_i + i$$

where $n_i$, $a_i$ and $i$ are the noise plus interference vector, the noise vector and the interference vectors, respectively, at the $i^{th}$ receiver. The interference is from all of the transmitters who do not belong to $D$. How many clusters there are and what are their structures will depend on the configuration of the system. In this paper, the following five configurations are considered. The single formulation in (1) is employed to unify different CoMP configurations thus enable a unified framework to take care of the MMSE transceiver design for general MTMR MIMO systems with arbitrary linear power constraints.

Configuration I. JP-UL:
In JP-UL, there are \( C \) transmitters (i.e., \( C \) UE’s) but only one receiver (consisting of \( R \) cooperating BS’s). Therefore, \( C=L \) and \( K=1 \). All of the transmitters want to transmit data to the receiver. Furthermore, a central processing unit knows all of the channels and performs the system-wide transceiver design. Thus,
\[
D = \{1,2,...,C\}, \quad S = \{1\}, \quad C > 1, \quad \mathbf{n}_i = \mathbf{a}, \quad \mathbf{i}_i = 0, \quad i \in S. \tag{2a}
\]

**Configuration II. JP-DL:**
In JP-DL, there are \( K \) receivers (i.e., \( K \) UE’s) but only one transmitter (consisting of \( L \) cooperating BS’s). Therefore, \( K=R \) and \( C=1 \). The transmitter wants to transmit data to all of the receivers. Furthermore, a central processing unit knows all of the channels and performs the system-wide transceiver design. Thus,
\[
D = \{1\}, \quad S = \{1,2,...,K\}, \quad K > 1, \quad \mathbf{n}_i = \mathbf{a}, \quad \mathbf{i}_i = 0, \quad i \in S. \tag{2b}
\]

**Configuration III. JP-SU:**
In JP SU, there is only one transmitter (\( C=1 \)) and only one receiver (\( K=1 \)). For the uplink scenario, the transmitter consists of \( L \) cooperating UE’s and the receiver consists of \( R \) cooperating BS’s. On the other hand, for the downlink scenario, the transmitter consists of \( L \) cooperating BS’s and the receiver consists of \( R \) cooperating UE’s. Furthermore, a central processing unit knows the channel and performs the system-wide transceiver design. Thus,
\[
D = \{1\}, \quad S = \{1\}, \quad \mathbf{n}_i = \mathbf{a}, \quad \mathbf{i}_i = 0, \quad i \in S. \tag{2c}
\]
This configuration is not practical but can be used to derive the mean square error (MSE) or BER performance upper bound (not only for all JP configurations but also for all other CoMP configurations).

**Configuration IV. Non-CoMP:**
In Non-CoMP, without loss of generality, each BS is associated with one UE. So, there are multiple pairs of transceivers. Each pair knows only the channel matrix between its transmitter and receiver. This enables pairwise transceiver design to be performed. At each receiver, the signals transmitted by transmitters other than the desired one are considered as interference. Thus, a system with \( C \) transceivers consists of a single cluster and the \( i^{th} \) one being
\[
D = \{1\}, \quad S = \{1\}, \quad \mathbf{n}_i = \mathbf{a} + \mathbf{i}_i, \quad \mathbf{i}_i = \sum_{i=1}^{C} \mathbf{H}_i \mathbf{F}_i \mathbf{s}_i, \quad i \in S. \tag{2d}
\]

**Configuration V. CBF:**
The CBF configuration is the same as Non-CoMP except that here, all channels are known to a central processing unit. This enables system-wide transceiver design to be performed. Thus, in a system with \( C \) transceivers (\( C=K \)) pairs,
\[
D = \{1,2,...,C\}, \quad S = \{1,2,...,C\}, \quad \mathbf{n}_i = \mathbf{a}, \quad \mathbf{i}_i = 0, \quad i \in S. \tag{2e}
\]
Note that in JP-UL, JP-DL, JP-SU and CBF, there is only one cluster, one \( D \) and \( S \) in the system but that in Non-CoMP, there are \( C \) of them.

**B. Problem Formulation**
For a given cluster and thus a given \( D \) and \( S \), the following is the problem formulation. Define the MSE with respect to the \( i^{th} \) receiver and the \( c^{th} \) transmitter, \( i \in S, c \in D \), as
\[
\eta_{ic} = tr < (\mathbf{G}_i \mathbf{y}_i - \mathbf{s}_i) (\mathbf{G}_i \mathbf{y}_i - \mathbf{s}_i)^\ast > \tag{3}
\]
When the \( c^{th} \) transmitter has no data for the \( i^{th} \) receiver, \( \eta_{ic} \), as to be expected, is zero. Define the sum MSE \( \eta \) as
\[
\eta = \sum_{c \in D} \eta_{ic} \tag{4}
\]
Note that in Non-CoMP, for the \( c^{th} \) cluster, \( \eta = \eta_{ic} \). We will jointly choose \( \{\mathbf{F}_i, \mathbf{G}_i\}_{i \in S, c \in D} \) to minimize the sum MSE \( \eta \)
\[
\{\mathbf{F}_i, \mathbf{G}_i\}_{i \in S, c \in D} = \arg \min \{\eta\} \tag{5}
\]
subject to either the per-antenna power constraint at the \( c^{th} \) transmitter
\[
\mathbf{I}_c = \left( \sum_{a \in \mathcal{A}} \mathbf{F}_a \mathbf{\Phi}_a \mathbf{F}_a^\ast \right) \preceq \text{diag}(P_{c1},...,P_{ct},) \quad c \in D. \tag{6a}
\]
or the total power constraint at the \( n^{th} \) localized transmitter (a UE or BS) of the \( c^{th} \) transmitter
\[
\text{tr}\left[ \mathbf{Q}_n \right] = \text{tr} \left( \sum_{a \in \mathcal{A}} \mathbf{F}_a \mathbf{\Phi}_a \mathbf{F}_a^\ast \right) \leq P_{\text{mac}}, n \in J_c, c \in D, \tag{6b}
\]
where \( J_c \) denotes the set of all cooperating localized transmitters that form the \( c^{th} \) transmitter. When the \( c^{th} \) transmitter is just a localized transmitter (a UE or BS), \( \mathbf{Q}_n = \mathbf{I}_c \) in (6b). When the \( c^{th} \) transmitter consists of multiple localized transmitters (multiple UE’s or BS’s), \( \mathbf{Q}_n \) in (6b) is a \( t \times t \) matrix whose entries are all equal to zero except for the diagonal elements corresponding to the antennas of the \( n^{th} \) localized transmitter. The values of these non-zero diagonal elements are equal to one.

To solve (5) subject to (6a) or (6b), one can use the method of Lagrange multipliers to set up the augmented cost function
\[
\xi = \eta + \sum_{c \in D} \text{tr}\left[ \mathbf{A}_c \left( \sum_{a \in \mathcal{A}} \mathbf{F}_a \mathbf{\Phi}_a \mathbf{F}_a^\ast - \mathbf{P}_c \right) \right], \tag{7}
\]
where \( \mathbf{A}_c \) is an unknown diagonal matrix, representing the Lagrange multipliers. For the per-antenna power constraint at the \( c^{th} \) transmitter in (6a),
\[
\mathbf{A}_c = \text{diag}(\lambda_{c1},...\lambda_{ct}), \quad \mathbf{P}_c = \text{diag}(P_{c1},...,P_{ct}), \quad c \in D. \tag{8a}
\]
For the total power constraint at the \( n^{th} \) localized transmitter of the \( c^{th} \) transmitter in (6b), define
\[
\mathbf{A}_n = \mathbf{I}_{n_c} \lambda_{nc}, \quad \mathbf{P}_n = \mathbf{I}_{n_c} P_{nc} \tau_{nc}, \quad \forall n \in J_c, \quad \forall c \in D. \tag{8b}
\]

**III. GIA**
The GIA for the joint MMSE transceiver designs in uplink [8,9] and downlink [13,14] is extended to deal with the transceiver design in general MTMR MIMO systems subject to either the per-antenna or total power constraints per UE or BS. The extension is nontrivial because the precoder(s), decoder(s) and Lagrange multipliers are coupled in a highly nonlinear manner and have to be solved numerically by an iterative procedure. In the proposed approach, closed form expressions for the Lagrange multipliers corresponding to the power constraints at the precoder(s) are obtained to improve the computational efficiency and accuracy.
Define the noise covariance matrix and the noise plus interference covariance matrix at the $i^{th}$ receiver as $\Phi_{ni} = \langle a_i a_i^H \rangle$ and $\Phi_{ni} = \langle n_i n_i^H \rangle$, respectively. Note that $\Phi_{ni}$ is assumed known. Thus, except for the Non-CoMP configuration where $\Phi_{ni}$ is not equal to $\Phi_{ni}$ and needs to be estimated, $\Phi_{ni}$ is equal to $\Phi_{ni}$ in all other four configurations and is therefore also assumed known.

After some math manipulations, (3) becomes

$$\text{tr} \left( - \Phi_{ni} H_i F_i \Phi_{ni} - \Phi_{ni} F_i^H G_i^* \right) + \text{tr} \left( \sum_{k \in K} H_{ik} \sum_{j \in J} F_{jk} \Phi_{nj} F_{jk}^H \right) = 0,$$

or

$$\text{tr} \left( - H_i G_i^* + \Phi_{ni} \right) + \text{tr} \left( \sum_{k \in K} H_{ik} \Phi_{nj} \sum_{j \in J} F_{jk} F_{jk}^H \right) = 0.$$  \hfill (9)

A. MMSE Decoders and Precoders

For a given set of precoders $\{F_{ik}\}_{i \in S, k \in D}$, the well known MMSE decoder for the data transmitted from the $c^{th}$ transmitter to the $i^{th}$ receiver is:

$$G_i = \Phi_{ni} F_i^* H_i^* M_i.$$  \hfill (10)

$$M_i = \left[ \sum_{k \in D} H_{ik} \sum_{j \in J} F_{jk} \Phi_{nj} F_{jk}^H \right]^{-1}.$$  \hfill (11)

Substituting (10) into (9), the cost function $\eta$ in (4) is reduced (its explicit dependence on $\{G_{ik}\}_{i \in S, k \in D}$ is removed) to

$$\eta = \sum_{i \in S} \sum_{k \in D} \text{tr} \left( - \Phi_{ni} F_i^* H_i^* M_i + \Phi_{ni} F_i^* - P_r \right).$$  \hfill (12)

On the other hand, for a given set of decoders $\{G_{ik}\}_{i \in S, k \in D}$ and Lagrange multipliers $\{\Lambda_{ik}\}_{i \in S, k \in D}$, setting the gradient of $\xi$ in (7) with respect to $F_{ik}$ equal to zero yields the MMSE precoder for the data transmitted from the $c^{th}$ transmitter to the $i^{th}$ receiver:

$$F_{ic} = N_i H_i^* G_i^*, N_i = \left[ \sum_{k \in D} H_{ik}^* G_i^* G_{jk} H_{jc} + \Lambda_{ic} \right]^{-1}.$$  \hfill (13)

B. Lagrange Multipliers

To obtain an explicit expression for the Lagrange multiplier $\Lambda_{ic}$, set the gradient of (12) with respect to $F_{ic}$ equal to zero and then left multiply the resulting equation by $F_{ic}$. Once this is done for each $i \in S$, sum them all up to obtain the following equation

$$\sum_{i \in S} \sum_{k \in D} F_{ik} \Phi_{nj} F_{ik}^H = B_c,$$  \hfill (14)

where

$$B_c = \sum_{i \in S} \sum_{k \in D} F_{ik} \Phi_{nj} F_{jk}^H M_{jk}.$$  \hfill (15)

Utilizing (6a) with equality, we have, for the per-antenna power constraint,

$$\Lambda_c = \lambda_c \left( \frac{1}{\lambda_c} + B_c \right).$$  \hfill (16a)

Utilizing (6b) with equality, we have, for the total power constraint per UE or BS,

$$\lambda_c = P_n^* r \left( Q_c ^* B_c \right), \quad n \in J_c.$$  \hfill (16b)

C. GIA

With the explicit expression for the Lagrange multipliers in hand, a novel GIA can be developed using the MMSE decoders in (10) and the MMSE precoders in (13), and the Lagrange multipliers in (16a) or (16b). The GIA consists of the following three steps in each iteration:

Step 1: Given $\{F_{ik}\}_{i \in S, k \in D}$, obtain $\{G_{ik}\}_{i \in S, k \in D}$ using (10).

Step 2: Given $\{G_{ik}\}_{i \in S, k \in D}$, obtain $\{\Lambda_{ik}\}_{i \in S, k \in D}$ using (16a) or (16b).

Step 3: Given $\{G_{ik}\}_{i \in S, k \in D}$ and $\{\Lambda_{ik}\}_{i \in S, k \in D}$, obtain $\{F_{ik}\}_{i \in S, k \in D}$ using (13).

Since the MSE has a lower bound at zero and each step actually enforces one of the Karush-Kuhn-Tucker conditions of the MMSE problem, the GIA can converge quickly to a local minimum at low powers. At high transmit powers, a scaling initialization (scaling the MMSE MIMO precoders and decoders given by the GIA at lower powers) is very effective and efficient. Note that the GIA is applicable to all configurations in Section II. A. It can also deal with arbitrary source covariance matrices $\{\Phi_{cm}\}_{i \in S, k \in D}$, thus allowing $m_{ci}$, the number of data streams intended from the $c^{th}$ transmitter to the $i^{th}$ receiver, to be pre-specified for $i \in S, c \in D, s_k \neq 0$. Since the numbers of data streams can be pre-specified, the GIA allows for tradeoff between diversity and multiplexing gains.

IV. NUMERICAL RESULTS

A. Numerical Setup

Table I. The Different Setups

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup</td>
<td>1a</td>
<td>1b</td>
<td>2a</td>
</tr>
<tr>
<td>$L$</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$C$</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$t$</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$r$</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$m_{ici}$</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$m$</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

(K: number of receivers; $r$: number of antennas of the $i^{th}$ receiver; $t$: total number of transmit antennas; 15$\times$5$\times$5)

Let the entries of $H_{ik}$ be i.i.d. $CN(0,1)$ for all $i \in S, k \in D$, so the possible interfering channels in Non-CoMP and CBF are as strong as the desired channels, and thus all UE’s are at cell edge. Also let $\Phi_{mi} = l_m, i \in S$ and $\Phi_{mi} = l_m$ for all $i \in S, k \in D, s_k \neq 0$. In Non-CoMP, the noise plus interference covariance matrix at the $i^{th}$ receiver, $\Phi_{ni}$ can be calculated exactly as

$$\Phi_{ni} = \sum_{l \in [1,\ldots,m]} P_{bl} \lambda_c + \Phi_{ni}.$$  \hfill (16a)

Let the per-antenna power

$$\Lambda_c = \lambda_c \left( \frac{1}{\lambda_c} + B_c \right).$$  \hfill (16a)
constraint for the $c^h$ transmitter be equal to $P_{i}$, (see (6a)) and let the total power constraint $P_{\text{max}}$ for the $n^h$ localized transmitter (a UE or BS) of the $c^h$ transmitter, $n \in J$, and $c \in D$, be equal to $\tau_{n}P$ (see (6b)). Therefore, the total transmission power from the $n^h$ localized transmitter of the $c^h$ transmitter is $\tau_{n}P$ under both the per-antenna and total power constraints.

All setups used in numerical simulations are defined in Table I. For each configuration (I-V), there may be multiple setups. For example, for JP-UL, setups 1a and 1b are exactly the same except for the values of $m_{c}$ (the number of data streams per UE) and $m$ (the total numbers of data streams). Note that setups 4a and 4b can correspond to either Non-CoMP or CBF. The difference is that, if a central processing unit has all the CSI of the system, setups 4a and 4b correspond to CBF; otherwise, they correspond to Non-CoMP.

B. Performance Comparison of Different CoMP Configurations

To understand the impact of different levels of cooperation on performance in Network MIMO systems, we compare the performance of all five configurations defined in Section II. A. Out of the five configurations, Non-CoMP has the lowest level of cooperation; its transmitters do not share their data, its receivers do not share their received signals, and the transmitter, receiver pairs do not jointly perform their transceiver designs. The second lowest is CBF. This is because the only difference between it and Non-CoMP is that it jointly performs the system-wide transceiver designs. Next come JP-UL and JP-DL. In them, the system-wide transceiver design is also done jointly. Furthermore, the receivers jointly decode in JP-UL and the transmitters jointly transmit in JP-DL. Lastly, JP-SU has the highest level of cooperation. Actually, it has the highest possible level of cooperation; the system-wide transceiver design is done jointly, the receivers jointly decode, and the transmitters jointly transmit.

In order to compare the five configurations, we study two groups of setups: group A consists of setups 1a, 2a, 3a, 4a (Non-CoMP) and 4a (CBF), and group B consists of setups 1b, 2b, 3b, 4b (Non-CoMP) and 4b (CBF). The total number of transmit and receive antennas are the same for all of the setups. The same power constraints are considered for each of them as well. The differences between the groups lie in the number of data streams (per UE); all setups in group A have two data streams per UE (four data streams transmitted in total) while all setups in group B have one data stream per UE (two data streams transmitted in total). Fig. 1 shows the MSE and raw BER (of uncoded BPSK modulated bits) results derived in groups A and B. All the MSE and BER results are obtained by averaging over 20 channel realizations. The results of setup 4b (Non-CoMP) under the per-antenna power constraint are not presented here because they are not always feasible.

Before comparing the results of groups A and B, let’s compare the individual setups within each group first. Firstly, observe that in both groups, the performance order of the five configurations is exactly the same as the level of cooperation order. As the level of cooperation increases (as one implements joint system-wide transceiver design, cooperation among the receivers, and/or cooperation among the transmitters), the performance also improves. Secondly, observe that in both groups, although JP-SU gives an upper bound on the achievable performance, JP-UL and JP-DL come very close to it. Lastly, observe that there is a relationship between the performances of the two power constraints and the configuration numbers. In general, the use of the per-antenna power constraint instead of the total power constraint per UE or BS may result in performance degradation due to the loss of freedom in assigning different power to different transmit antennas. Here though, there is almost no degradation in MSE for JP-UL, JP-DL and JP-SU. However, minor degradation for Non-CoMP and noticeable degradation for CBF are observed. This is due to (at least in part) the ability of the power constraints to meet with equality. In JP-UL, JP-DL and JP-SU, the equality power constraint is usually met. On the other hand, in Non-CoMP and CBF, it is not so rare that equality is not satisfied. When the per-antenna power constraint does not meet with equality, less power is used than with the total power constraint resulting in a large performance gap.

With that done, let’s now compare the results of groups A and B. The setups of groups A and B only differ in the numbers of data streams (per UE). Thus, the first observation is that decreasing the numbers of data streams increases the performance. The second observation is that CBF is actually able to achieve similar MSE performances with the higher level of cooperation configuration (JP-UL, JP-DL and JU-SU) when each transmitter transmits 1 data stream and the transmit power is high. The last observation, somewhat related to the
first, is that the performances of Non-CoMP and CBF are more much dependent on the number of data streams than JP-UL, JP-DL and JP-SU.

The difference in the BER’s of Non-CoMP and CBF between the two groups is remarkable and can be explained as follows. In group A, the \( c^{th} \) receiver, \( c=1,2 \), needs \( \mathbf{G}_c \mathbf{H}_c \mathbf{F}_c \) to be full rank (and thus, \( \mathbf{G}_c, \mathbf{H}_c, \) and \( \mathbf{F}_c \) to be all full rank) in order to successfully receive its 2 data streams. This is quite feasible since \( \mathbf{H}_c \) is a physical channel and thus, very likely to be full rank. The problem arises if \( \mathbf{G}_c \mathbf{H}_c \mathbf{F}_c \) is full rank for both receivers (i.e., for \( c=1,2 \)). In this case, span(\( \mathbf{G}_c \mathbf{H}_c \mathbf{F}_c \)) = span(\( \mathbf{G}_c \mathbf{H}_c \mathbf{F}_c \)), \( k \neq c \), i.e., the interference and desired signal span the same vector space. Thus, the interference has not been removed by the precoders and decoders. Actually, it cannot be removed as long as both receivers insist on successfully receiving all of their data streams and the \( \mathbf{H}_{ck} \), \( k \neq c \), are full rank. Thus, if the interference is significant, as is likely at the cell edge, the performance will suffer greatly. On the other hand, it is possible in group B for both pairs to successfully receive each of their data streams and null out the interference. This is because span(\( \mathbf{H}_c \mathbf{F}_c \)) is not necessarily equal to span(\( \mathbf{H}_k \mathbf{F}_k \)), \( c=1,2 \), \( k \neq c \). In CBF, the precoders of neighboring cells (for \( k \neq c \)) can be chosen to try to steer \( \mathbf{H}_c \mathbf{F}_c \) away from \( \mathbf{H}_k \mathbf{F}_k \) and the \( c^{th} \) decoder can be chosen to null out \( \mathbf{H}_c \mathbf{F}_c \), \( k \neq c \). In Non-CoMP, the \( c^k \) pair does not know \( \mathbf{H}_c \mathbf{F}_c \), \( k \neq c \), but it does know \( \mathbf{F}_c \). It can therefore use its perfect knowledge of \( \mathbf{F}_c \) to design \( \mathbf{F}_c \) and \( \mathbf{G}_c \).

V. CONCLUSION

In this paper, a unified MTMR framework and a novel iterative approach, the GIA, are proposed for jointly designing MMSE transceivers of each cluster in Network MIMO systems. The formulation and the GIA are very flexible and powerful. They can deal with general MTMR configurations and linear power constraints. They can also cope with different numbers of data streams and therefore allows for tradeoff between diversity and multiplexing gains. Five CoMP configurations (JP-UL, JP-DL, JP-SU, CBF and Non-CoMP) are considered as examples. The performances of cell edge UE’s in these five CoMP configurations subject to different linear power constraints and different numbers of data streams are compared so as to provide a benchmark for joint transceiver designs based on other criteria. It is obvious that higher level of cooperation will yield better system performances. Thus, JP-SU is the best, JP-UL and JP-DL are next, CBF is after the JP’s, and Non-CoMP is the worst. However, it is remarkable that both JP-UL and JP-DL essentially provide the same MSE and BER performances as JP-SU which provides the performance upper bound for general MTMR systems. That means full cooperation at either transmitters or receivers is almost as good as full cooperation at both transmitters and receivers.

The performances of Non-CoMP and CBF greatly depend on the number of data streams (per UE). When the number of data streams of each UE is the same as its number of antennas, the MSE and BER performances of CBF are much worse than those of JP-UL, JP-DL and JP-SU. This is due to the fact that there are not enough degrees of freedom in designing the transceivers for the CBF to suppress the ICI under this circumstance. However, When the number of data streams per UE is less than (exactly, half of) its number of antennas, the MSE and BER performances of CBF becomes comparable to those of JP-UL, JP-DL and JP-SU, especially when the transmit power is high. This is due to the fact that there are enough degrees of freedom for the CBF to suppress the ICI now.

When the number of data streams of each UE is the same as its number of antennas, the MSE and BER performances of Non-CoMP are not acceptable for practical applications at all. This is due to the fact that Non-CoMP has no cooperation among transmitters or among receivers and there is no mechanism for Non-CoMP to suppress the ICI under such a circumstance. However, when the number of data streams of each UE is less than its number of antennas, it is surprising to see that the MSE and BER performances of Non-CoMP become acceptable. This is due to the fact that the covariance of interference can be predicted and there are enough degrees of freedom for Non-CoMP to suppress (to a certain extent) the ICI in such a situation.

REFERENCES