Transmission Mode Selection Algorithms for Spatially Correlated MIMO Interference Channels

Jin-Sung Kim, Kyoung-Jae Lee, Haewook Park, and Inkyu Lee

***Abstract*—In this paper, we study K-user multiple-input multiple-output (MIMO) interference channels (IC) in the presence of antenna correlations. Although interference alignment (IA) achieves the maximum multiplexing gain, i.e., degrees of freedom (DOF), the actual performance is degraded due to ill-conditioned channels caused by the antenna correlations. To enhance the overall system performance, we thus consider a transmission mode selection scheme which adaptively determines the number of data streams at each transmitter-receiver pair in a distributed fashion using local channel state information (CSI). A filter update process is exploited in order to estimate the performance regarding each transmission mode successively by considering the actual channel conditions as well as signal-to-noise ratio (SNR). Simulation results show that our mode selection scheme enhances the sum rate performance compared to the conventional full data stream transmissions in spatially correlated MIMO IC.**

***Index Terms*—Interference channels, multiple-input multiple-output (MIMO), mode selection.**

I. Introduction

In a wireless network, interference is one of the major factors that limits the overall system performance. Although the capacity region of interference channels (ICs) has been researched for certain cases, general characterization still remains as an open problem. Recently, there has been a series of attempts to analyze the asymptotic system capacity behavior in the IC by means of maximum multiplexing gain or degrees of freedom (DOF) [1]. In order to achieve the maximum DOF, a linear precoding technique named interference alignment (IA) has been proposed [2], [3]. Especially in multiple-input multiple-output (MIMO) systems, the spatial dimension provided by multiple antennas can be exploited for the alignment of the interference.

The original work of MIMO IA in [2] and [3] requires global channel state information (CSI) at each transmitter, which may be difficult to realize in practice. As a result, several methods have been proposed which require local CSI at each node. For example, the authors in [4] proposed an iterative IA which obtains the performance almost identical to that of the original IA by utilizing channel reciprocity (i.e., local CSI) at each node. Also, this iterative IA can be implemented with a general number of $K > 3$-users unlike the original IA. In a real propagation environment where antenna correlations exist, the IA based schemes including [4] exhibit degraded performance due to ill-conditioned channels, and only few works have appeared in the literature to address this issue. A recent work in [5] approximately quantifies received signal-to-noise ratio (SNR) distribution by considering only the transmit antenna correlations with simple zero-forcing (ZF) receivers in the IA.

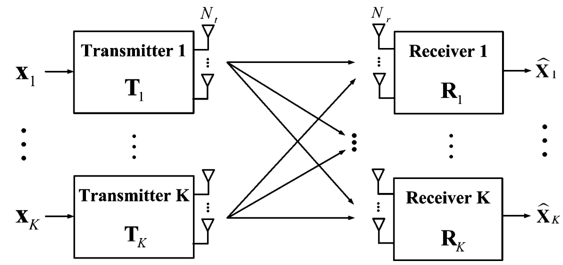

Fig. 1. Schematic diagram of K-user MIMO Interference channel systems.

In this correspondence, to enhance the overall system performance in spatially correlated MIMO IC with the local CSI at each node, we properly adapt the transmission mode which determines the number of data streams at each transmitter-receiver pair in a distributed manner. Using a filter update process, the performance regarding each transmission mode is estimated successively by considering the actual channel conditions as well as the SNR.

In multiuser MIMO downlink channels [6], [7], there also exist several methods adjusting the transmission modes at the transmitter to improve the performance of systems [8], [9]. However, note that multiuser systems are fundamentally different from the IC which includes multiple transmitter-receiver pair. Besides, it is difficult to utilize the results for the multiuser MIMO systems in the scenario of the IC. Simulation results show that the proposed mode selection scheme achieves a notable performance enhancement compared to full data stream transmissions considered in the IA.

The organization of the paper is as follows. Section II presents an interference channel model, and briefly reviews the concept of the IA. In Section III, we introduce our new transmission mode selection algorithm. Section IV compares the sum rate performance of our scheme with the conventional method in various system configurations. Finally, the paper is terminated with conclusions in Section V.

II. System Model

We consider K-user $N_r \times N_t$ MIMO IC shown in Fig. 1 where transmitter i communicates to its corresponding receiver i and interferes with all other receivers $j \neq i$ $(i = 1, \ldots, K)$. In the discrete-time complex baseband MIMO case, the frequency-flat channel from transmitter i to receiver j is modeled by the matrix $\mathbf{H}_{j,i} \in \mathbb{C}^{N_r \times N_t}$ for $i, j = 1, \ldots, K$. In this paper, we apply one widely used MIMO correlation model called "Kronecker model" as $\mathbf{H}_{j,i} = \mathbf{C}_R^{\frac{1}{2}} \overline{\mathbf{H}}_{j,i} \mathbf{C}_T^{\frac{1}{2}}$, where $\mathbf{C}_T \in \mathbb{C}^{N_t \times N_t}$ and $\mathbf{C}_R \in \mathbb{C}^{N_r \times N_r}$ are constant positive-semidefinite matrices standing for correlations among the transmit and receive antennas, respectively, and the entries of $\overline{\mathbf{H}}_{j,i} \in \mathbb{C}^{N_r \times N_t}$ are assumed as independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance $\mathcal{CN}(0, 1)$ [10]. Although we consider the same correlation matrices $\mathbf{C}_T$ and $\mathbf{C}_R$ for every transmitter–receiver pair, our results can be generalized to a network with different correlation values.

When the ith transmitter supports d_i data streams using the transmit precoder $\mathbf{T}_i = [\mathbf{t}_{i,1} \ldots \mathbf{t}_{i,d_i}] \in \mathbb{C}^{N_t \times d_i}$, the received signal vector

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$\mathbf{y}_i \in \mathbb{C}^{d_i \times 1}$ at the ith receiver after the receiver combining $\mathbf{R}_i = [\mathbf{r}_{i,1} \ldots \mathbf{r}_{i,d_i}] \in \mathbb{C}^{N_r \times d_i}$ is expressed as

$$\mathbf{y}_i = \mathbf{R}_i^\dagger \mathbf{H}_{i,i} \mathbf{T}_i \mathbf{x}_i + \mathbf{R}_i^\dagger \sum_{j=1, j\neq i}^{K} \mathbf{H}_{i,j} \mathbf{T}_j \mathbf{x}_j + \mathbf{R}_i^\dagger \mathbf{n}_i \tag{1}$$

where $(\cdot)^\dagger$ stands for conjugate transpose, $\mathbf{x}_i \in \mathbb{C}^{d_i \times 1}$ denotes the transmit symbol vector from transmitter i, and $\mathbf{n}_i \in \mathbb{C}^{N_r \times 1}$ is the additive white Gaussian noise vector observed at receiver i. Here the matrices $\mathbf{T}_i$ and $\mathbf{R}_i$ have unit-norm columns for all i, and the symbols in $\mathbf{x}_i$ are assumed to be independently generated with the total power constraint $\mathbb{E}[\mathbf{x}_i^\dagger \mathbf{x}_i] \leq P$ for all i. Also the entries of $\mathbf{n}_i$ are i.i.d. with zero mean and variance N_0. We assume that receiver i knows its MIMO channels $\mathbf{H}_{i,1}, \ldots, \mathbf{H}_{i,K}$ perfectly based on pilot signals transmitted by each of K transmitters. Also, channel reciprocity is exploited to obtain the local CSI at the transmitters [4].

The IA techniques allow us to achieve the maximum multiplexing gain, or maximum DOF [2]. This implies that the total number of the transmitted data streams $\sum d_i$ can be set to attain a full spatial multiplexing gain without causing interference $\mathbf{R}_i^\dagger \mathbf{H}_{i,j} \mathbf{T}_j$ $(\forall i \neq j)$ in (1) to any of its noncorresponding receivers. However, in practical systems where the antenna correlation exists, this maximum DOF strategy considered in the IA becomes suboptimal especially at the intermediate SNR range. This is because the channels $\mathbf{H}_{i,j}$ $(i, j = 1, \ldots, K)$ become ill-conditioned as the correlation values increase in $\mathbf{C}_T$ and $\mathbf{C}_R$. Consequently, to enhance the overall system performance, we propose an adaptive transmission mode selection scheme suitable for spatially correlated MIMO IC in the following section.

III. Proposed Mode Selection Algorithm

In this section, we describe how to choose the transmission modes corresponding to each transmitter–receiver pair when only the local CSI is available at each node in the interference networks. First, transmitter i applies singular value decomposition (SVD) to its respective channel $\mathbf{H}_{i,i} = \mathbf{U}_i \mathbf{\Sigma}_i \mathbf{V}_i^\dagger$, where $\mathbf{U}_i \in \mathbb{C}^{N_r \times N_r}$ and $\mathbf{V}_i \in \mathbb{C}^{N_t \times N_t}$ denote the left and right singular matrices, respectively, and $\mathbf{\Sigma}_i \in \mathbb{C}^{N_r \times N_t}$ indicates a diagonal matrix containing the singular values. Then, $\mathbf{T}_i$ in (1) is initialized as $\mathbf{T}_i = \mathbf{V}_i$ for all i.

Now, at the ith receiver, the effective channels $\widetilde{\mathbf{H}}_{i,1}, \ldots, \widetilde{\mathbf{H}}_{i,K}$ are obtained through pilot signals, where $\widetilde{\mathbf{H}}_{i,j} = \mathbf{H}_{i,j} \mathbf{V}_j$ for all j. Employing $\mathbf{U}_i$ as a postprocessing filter, which can be obtained from $\widetilde{\mathbf{H}}_{i,i} = \mathbf{U}_i^\dagger \mathbf{\Sigma}_i$, the ith receiver has the effective channels $\mathbf{G}_{i,1}, \ldots, \mathbf{G}_{i,K}$, where $\mathbf{G}_{i,j} = \mathbf{U}_i \widetilde{\mathbf{H}}_{i,j}$ for all j. Specifically, its corresponding channel $\mathbf{G}_{i,i}$ is equivalent to the diagonal matrix $\mathbf{\Sigma}_i$, which is important in describing our proposed method at the next stage. Note that this procedure is made only for determining the transmission mode at receiver i. That is, the actual transmit precoding and receive combining matrices $\mathbf{T}_i$ and $\mathbf{R}_i$ in (1) will be computed after the transmission mode is chosen.

By considering $\mathbf{G}_{i,1}, \ldots, \mathbf{G}_{i,K}$ as the given channels instead of $\mathbf{H}_{i,1}, \ldots, \mathbf{H}_{i,K}$, receiver i now determines the transmission mode under the assumption that other noncorresponding transmitters (i.e., opponents) are maximizing their respective benefits without cooperation. In our proposed algorithm, the ith receiver would "simulate" a filter update process in its mind, and determine a future transmission mode based on this simulation. At each round of our proposed scheme, each node chooses the best response to the filter matrices of others. Consequently, the problem can be solved in a distributed fashion without requiring global CSI.

At each step m $(m = 1, \ldots, m_{\max})$, where $m_{\max}$ denotes the achievable maximum multiplexing gain, i.e., $\frac{m_{\max} = (N_t + N_r)}{(K+1)}$ [11], we estimate the performance of the ith receiver by exploiting a filter update process when m data streams are considered in each transmitter-receiver pair. At the first step $(m = 1)$, to simulate the filter $\mathbf{T}_j = \mathbf{t}_{j,1}$ $(j \neq i)$ in (1) of the jth transmitter at the ith receiver, we first set the benefit F_j for transmittter j by utilizing the definition of signal-to-leakage plus noise ratio (SLNR) [12] regarding the ith receiver as

$$F_j = \frac{P|\mathbf{r}_{j,1}^\dagger \widetilde{\mathbf{H}}_{j,j} \mathbf{t}_{j,1}|^2}{N_0 + P|\mathbf{r}_{i,1}^\dagger \mathbf{G}_{i,j} \mathbf{t}_{j,1}|^2}. \tag{2}$$

By employing this formulation, the jth transmitter can maximize its signal power while minimizing the interference leakage to the ith receiver. To maximize F_j, the transmitter would update its filter $\mathbf{t}_{j,1} \rightarrow \widehat{\mathbf{t}}_{j,1}$ by considering the receive combining vector $\mathbf{r}_{i,1}$ of receiver i as [13]

$$\widehat{\mathbf{t}}_{j,1} = \frac{\mathbf{Q}_j^{-1} \widetilde{\mathbf{H}}_{j,j}^\dagger \mathbf{r}_{j,1}}{\|\mathbf{Q}_j^{-1} \widetilde{\mathbf{H}}_{j,j}^\dagger \mathbf{r}_{j,1}\|} \tag{3}$$

where $\mathbf{Q}_j = N_0 \mathbf{I}_{N_t} + P \mathbf{G}_{i,j}^\dagger \mathbf{r}_{i,1} \mathbf{r}_{i,1}^\dagger \mathbf{G}_{i,j}$. Here, $\mathbf{I}_m$ represents an identity matrix of size m.

Since it is impossible to know $\mathbf{r}_{j,1}$ and $\widetilde{\mathbf{H}}_{j,j}$ in the local CSI scenario when calculating $\widehat{\mathbf{t}}_{j,1}$ in (3), we first assume that $\mathbf{r}_{j,1}$ is determined as maximum ratio combining (MRC) to achieve an upper bound of F_j in (2) as

$$\mathbf{r}_{j,1} = \frac{\widetilde{\mathbf{H}}_{j,j} \mathbf{t}_{j,1}}{\|\widetilde{\mathbf{H}}_{j,j} \mathbf{t}_{j,1}\|}. \tag{4}$$

Now $\widehat{\mathbf{t}}_{j,1}$ in (3) is developed by applying (4) as

$$\widehat{\mathbf{t}}_{j,1} = \frac{\mathbf{Q}_j^{-1} \widetilde{\mathbf{H}}_{j,j}^\dagger \widetilde{\mathbf{H}}_{j,j} \mathbf{t}_{j,1}}{\|\mathbf{Q}_j^{-1} \widetilde{\mathbf{H}}_{j,j}^\dagger \widetilde{\mathbf{H}}_{j,j} \mathbf{t}_{j,1}\|} = \frac{\mathbf{Q}_j^{-1} \mathbf{\Sigma}_j^\dagger \mathbf{\Sigma}_j \mathbf{t}_{j,1}}{\|\mathbf{Q}_j^{-1} \mathbf{\Sigma}_j^\dagger \mathbf{\Sigma}_j \mathbf{t}_{j,1}\|}. \tag{5}$$

To compute (5), we assume that the singular value matrix $\mathbf{\Sigma}_j$ unknown to the ith receiver is the same as $\mathbf{\Sigma}_i$. Although this assumption is suboptimal, we can manipulate our proposed scheme without additional complexity overhead for obtaining $\mathbf{\Sigma}_j$, and a performance loss is also negligible. As a result, the filter $\mathbf{t}_{j,1} \rightarrow \widehat{\mathbf{t}}_{j,1}$ for the jth transmitter is expressed as

$$\widehat{\mathbf{t}}_{j,1} = \frac{\mathbf{Q}_j^{-1} \mathbf{G}_{i,i}^\dagger \mathbf{G}_{i,i} \mathbf{t}_{j,1}}{\|\mathbf{Q}_j^{-1} \mathbf{G}_{i,i}^\dagger \mathbf{G}_{i,i} \mathbf{t}_{j,1}\|}. \tag{6}$$

Now, the ith receiver updates its own filter $\mathbf{R}_i = \mathbf{r}_{i,1}$ in the proposed algorithm by considering the transmit precoding vectors $\mathbf{t}_{j,1}$ $(\forall j \neq i)$ of the opponents at step $m = 1$. To this end, we first set the benefit $\overline{F}_i$ for receiver i to signal-to-interference-plus-noise ratio (SINR) as

$$\overline{F}_i = \frac{P|\mathbf{r}_{i,1}^\dagger \mathbf{G}_{i,i} \mathbf{t}_{i,1}|^2}{N_0 + \sum_{j\neq i} P|\mathbf{r}_{i,1}^\dagger \mathbf{G}_{i,j} \mathbf{t}_{j,1}|^2}. \tag{7}$$

Similar to (3), in order to maximize $\overline{F}_i$, the ith receiver should update its filter $\mathbf{r}_{i,1} \rightarrow \widehat{\mathbf{r}}_{i,1}$ as

$$\widehat{\mathbf{r}}_{i,1} = \frac{\mathbf{Q}_i^{-1} \mathbf{G}_{i,i} \mathbf{t}_{i,1}}{\|\mathbf{Q}_i^{-1} \mathbf{G}_{i,i} \mathbf{t}_{i,1}\|} \tag{8}$$

where $\mathbf{Q}_i = N_0 \mathbf{I}_{N_r} + \sum_{j\neq i} P \mathbf{G}_{i,j} \mathbf{t}_{j,1} \mathbf{t}_{j,1}^\dagger \mathbf{G}_{i,j}^\dagger$.

As it is difficult to derive an exact $\mathbf{t}_{i,1}$ in (8) with only the local CSI, we assume maximum ratio transmission (MRT) in obtaining $\mathbf{t}_{i,1}$ to consider an upper bound of $\overline{F}_i$ in (7) as

$$\mathbf{t}_{i,1} = \frac{\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{i,1}}{\|\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{i,1}\|}. \tag{9}$$

Thus, substituting (9) into (8) results in

$$\widehat{\mathbf{r}}_{i,1} = \frac{\mathbf{Q}_i^{-1}\mathbf{G}_{i,i}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{r}_{\mathbf{i,1}}}{\|\mathbf{Q}_i^{-1}\mathbf{G}_{\mathbf{i,i}}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{r}_{\mathbf{i,1}}\|}. \tag{10}$$

Using (6) and (10), we update the filter of each node iteratively one after another by considering the filters of the other nodes. When all the nodes have maximized their respective benefits without cooperation, interferences among nodes $|\mathbf{r}_{i,1}^{\dagger}\mathbf{G}_{i,j}\mathbf{t}_{j,1}|$ $(\forall j \neq i)$ become constant values. This is because $\mathbf{t}_{j,1}$ and $\mathbf{r}_{i,1}$ converge to the eigenvectors associated with the maximum eigenvalues of $\mathbf{Q}_j^{-1}\mathbf{G}_{i,i}^{\dagger}\mathbf{G}_{i,i}$ and $\mathbf{Q}_i^{-1}\mathbf{G}_{i,i}\mathbf{G}_{i,i}^{\dagger}$, respectively, by carrying out the iterative process. We thus check whether the sum of the interference terms $\sum_{j\neq i}|\mathbf{r}_{i,1}^{\dagger}\mathbf{G}_{i,j}\mathbf{t}_{j,1}|^2$ becomes constant at each iteration in order to observe the convergence. As a result, we estimate the information rate of the ith receiver for step $m=1$ as

$$\begin{aligned} R_1 &= \log_2\left(1+\frac{P|\mathbf{r}_{\mathbf{i,1}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}\mathbf{t}_{\mathbf{i,1}}|^{\mathbf{2}}}{N_0+\sum\limits_{j\neq i}P|\mathbf{r}_{i,1}^{\dagger}\mathbf{G}_{i,j}\mathbf{t}_{\mathbf{j,1}}|^{\mathbf{2}}}\right) \\ &= \log_2\left(1+\frac{P\|\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{i,1}\|^2}{N_0+\sum\limits_{j\neq i}P|\mathbf{r}_{i,1}^{\dagger}\mathbf{G}_{i,j}\mathbf{t}_{\mathbf{j,1}}|^{\mathbf{2}}}\right) \end{aligned} \tag{11}$$

after the convergence where we have used (9) to derive the second equality in (11). Then, we move on to the next step.

At the subsequent steps $m \geq 2$, we repeat the above mentioned process to estimate the performance of the ith receiver under the assumption of m data streams for each node. Considering the filters already determined at the previous steps (i.e., $\mathbf{r}_{i,1},\ldots,\mathbf{r}_{i,m-1}$ and $\mathbf{t}_{j,1},\ldots,\mathbf{t}_{j,m-1}$), the benefit F_j in (2) is now generalized to simulate the filter $\mathbf{t}_{j,m}$ corresponding to the mth data stream of the jth transmitter as

$$F_j = \frac{P|\mathbf{r}_{j,m}^{\dagger}\mathbf{G}_{i,i}\mathbf{t}_{\mathbf{j,m}}|^{\mathbf{2}}}{mN_0+\sum\limits_{p=1}^{m}P|\mathbf{r}_{\mathbf{i,p}}^{\dagger}\mathbf{G}_{\mathbf{i,j}}\mathbf{t}_{\mathbf{j,m}}|^{\mathbf{2}}+\sum\limits_{\mathbf{q=1}}^{\mathbf{m-1}}\frac{\mathbf{P}|\mathbf{t}_{\mathbf{j,q}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}\mathbf{t}_{\mathbf{j,m}}|^{\mathbf{2}}}{\|\mathbf{G}_{\mathbf{i,i}}\mathbf{t}_{\mathbf{j,q}}\|^{\mathbf{2}}}}. \tag{12}$$

In (12), we assume the MRC $\mathbf{r}_{j,l} = \frac{\mathbf{G}_{i,i}\mathbf{t}_{j,l}}{\|\mathbf{G}_{i,i}\mathbf{t}_{j,l}\|}(l=1,\ldots,m-1)$ which coincides with (4). Similar to (6), the update process $\mathbf{t}_{j,m} \rightarrow \widehat{\mathbf{t}}_{j,m}$ for maximizing an upper bound of (12) is yielded as

$$\widehat{\mathbf{t}}_{j,m} = \frac{\mathbf{Q}_j^{-1}\mathbf{G}_{i,i}^{\dagger}\mathbf{G}_{i,i}\mathbf{t}_{j,m}}{\|\mathbf{Q}_{\mathbf{j}}^{-\mathbf{1}}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}\mathbf{t}_{\mathbf{j,m}}\|} \tag{13}$$

where

$$\mathbf{Q}_j = mN_0\mathbf{I}_{N_t}+\sum_{p=1}^{m}P\mathbf{G}_{i,j}^{\dagger}\mathbf{r}_{i,p}\mathbf{r}_{i,p}^{\dagger}\mathbf{G}_{i,j} + \sum_{q=1}^{m-1}\frac{P\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}\mathbf{t}_{\mathbf{j,q}}\mathbf{t}_{\mathbf{j,q}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}}{\|\mathbf{G}_{i,i}\mathbf{t}_{\mathbf{j,q}}\|^{\mathbf{2}}}. \tag{14}$$

Likewise, the benefit $\overline{F}_i$ in (7) is generalized to update the filter $\mathbf{r}_{i,m}$ corresponding to the mth data stream of the ith receiver as

$$\overline{F}_i = \frac{P|\mathbf{r}_{i,m}^{\dagger}\mathbf{G}_{i,i}\mathbf{t}_{i,m}|^2}{mN_0+\sum\limits_{j\neq i}\sum\limits_{p=1}^{m}P|\mathbf{r}_{i,m}^{\dagger}\mathbf{G}_{i,j}\mathbf{t}_{j,p}|^2+\sum\limits_{q=1}^{m-1}\frac{P|\mathbf{r}_{\mathbf{i,m}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{r}_{\mathbf{i,q}}|^{\mathbf{2}}}{\|\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{\mathbf{i,q}}\|^{\mathbf{2}}}} \tag{15}$$

with the assumption of the MRT $\mathbf{t}_{i,l} = \frac{\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{i,l}}{\|\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{r}_{\mathbf{i,l}}\|}(l=1,\ldots,m-1)$ similar to (9).

Following the result in (10), we update $\mathbf{r}_{i,m} \rightarrow \widehat{\mathbf{r}}_{i,m}$ to maximize an upper bound of (15) as

$$\widehat{\mathbf{r}}_{i,m} = \frac{\mathbf{Q}_i^{-1}\mathbf{G}_{\mathbf{i,i}}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{r}_{\mathbf{i,m}}}{\|\mathbf{Q}_{\mathbf{i}}^{-\mathbf{1}}\mathbf{G}_{\mathbf{i,i}}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{r}_{\mathbf{i,m}}\|} \tag{16}$$

where

$$\mathbf{Q}_i = mN_0\mathbf{I}_{N_r}+\sum_{j\neq i}\sum_{p=1}^{m}P\mathbf{G}_{i,j}\mathbf{t}_{j,p}\mathbf{t}_{j,p}^{\dagger}\mathbf{G}_{i,j}^{\dagger} + \sum_{q=1}^{m-1}\frac{P\mathbf{G}_{i,i}\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{i,q}\mathbf{r}_{i,q}^{\dagger}\mathbf{G}_{i,i}\mathbf{G}_{i,i}^{\dagger}}{\|\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{i,q}\|^2}. \tag{17}$$

We can see in (14) and (17) that the predetermined filters $\mathbf{r}_{i,1},\ldots,\mathbf{r}_{i,m-1}$ and $\mathbf{t}_{j,1},\ldots,\mathbf{t}_{j,m-1}$ $(\forall j \neq i)$ are still considered in simulating the current filters $\mathbf{r}_{i,m}$ and $\mathbf{t}_{j,m}$ in our process at the mth step. When the interference $\sum_{j\neq i}|\mathbf{r}_{i,m}^{\dagger}\mathbf{G}_{i,j}\mathbf{t}_{j,m}|^2$ converges to a constant, we stop the filter update.

By utilizing the filters yielded in the proposed algorithm, we now estimate R_m, which represents the information rate attained with m data streams at the ith receiver. Unlike the case of R_1 in (11) where one data stream is transmitted with the maximum symbol power P at each transmitter, power allocation among data streams should be determined to obtain R_m $(m \geq 2)$. Note that the assumption of equal power allocation $\frac{P}{m}$ per symbol is suboptimum in calculating R_m. Therefore, we consider a lower bound of R_m by setting the symbol power of each interfering data stream to the maximum power P, whereas the desired symbol power is $\frac{P}{m}$. As a result, R_m is approximated as (18) at the bottom of the page under the assumption of the MRT at the ith transmitter.

After the mth step, when $R_m > R_{m-1}$, we realize that the transmission mode with m data streams enhances the performance of the ith receiver, and we move on to the next step. Otherwise, when $R_m <$

$$R_m \approx \sum_{s=1}^{m}\log_2\left(1+\frac{\frac{P}{m}\|\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{\mathbf{i,s}}\|^{\mathbf{2}}}{N_0+\sum\limits_{j\neq i}\sum\limits_{p=1}^{m}P|\mathbf{r}_{i,s}^{\dagger}\mathbf{G}_{i,j}\mathbf{t}_{j,p}|^2+\sum\limits_{q=1,q\neq s}^{m}\frac{P|\mathbf{r}_{\mathbf{i,s}}^{\dagger}\mathbf{G}_{\mathbf{i,i}}\mathbf{G}_{\mathbf{i,i}}^{\dagger}\mathbf{r}_{\mathbf{i,q}}|^{\mathbf{2}}}{\|\mathbf{G}_{i,i}^{\dagger}\mathbf{r}_{\mathbf{i,q}}\|^{\mathbf{2}}}}\right) \tag{18}$$

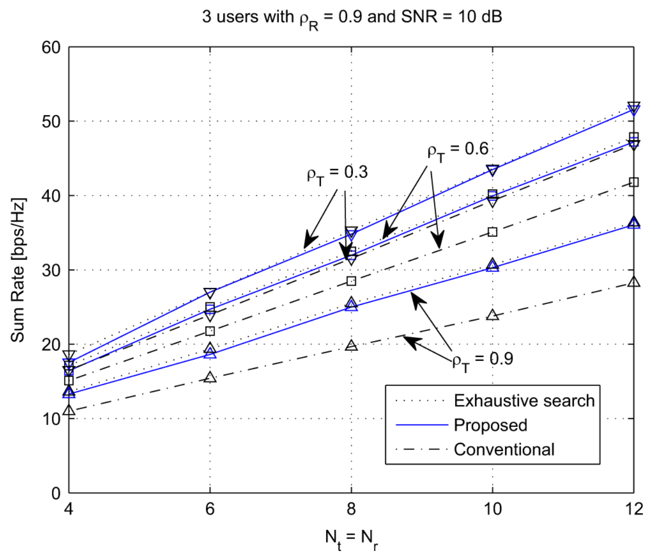

Fig. 2. Sum rate comparison with various numbers of antennas.

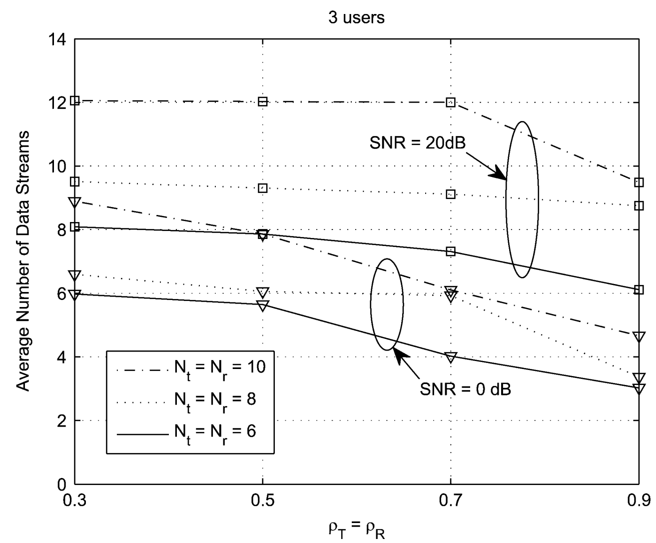

Fig. 3. Transmitted data stream numbers with various correlation coefficients.

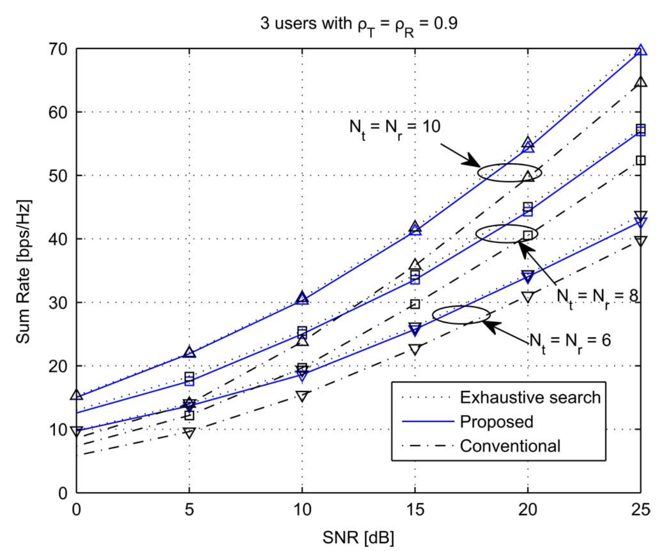

Fig. 4. Sum rate comparison with various SNRs.

R_{m-1}, we conclude that the mth data stream degrades the performance. In this case, we set the number of data streams as $m-1$ for the ith receiver, and do not continue the process. Our proposed scheme is summarized below in Algorithm 1. After all the receivers decide their respective transmission modes, the actual transmit precoding and the receive combining matrices $\mathbf{T}_i$ and $\mathbf{R}_i$ are designed by utilizing the algorithm in [4] suitable for the local CSI scenario.

Algorithm 1: Proposed Algorithm (at Receiver i)

Obtain $\mathbf{G}_{i,1}, \ldots, \mathbf{G}_{i,K}$

Initialize $m = 0$; $R_{-1} = R_0 = 0$; $\mathbf{T}_j = \mathbf{I}_{N_t}$ $(\forall j \neq i)$;

$\mathbf{R}_i = \mathbf{I}_{N_r}$

while $m < m_{\max}$ and $R_{m-1} \leq R_m$,

  $m \leftarrow m+1$; $d_i = m$

  Repeat update with **(13)** and **(16)** until convergence

  Compute R_m in **(18)**

end

if $R_{m-1} > R_m$ **then** $d_i = m-1$

IV. Simulation Results

In this section, we exhibit the performance of the proposed transmission mode selection scheme comparing with the conventional full data stream transmission which attains the maximum DOF in spatially correlated MIMO IC. The SNR is defined as $\frac{P}{N_0}$. For the correlation matrices $\mathbf{C}_T$ and $\mathbf{C}_R$, we utilize the exponential correlation model which defines the (i,j)th component of the correlation matrix as $\rho^{|i-j|}$ with a fixed ρ denoting the correlation coefficient [10]. We define ρ_T and ρ_R as the correlation coefficients for $\mathbf{C}_T$ and $\mathbf{C}_R$, respectively.

Fig. 2 shows a sum rate gain of our scheme over the conventional method for various numbers of antennas with $K = 3$. In this figure, the SNR is set to 10 dB with $\rho_R = 0.9$, which represents high correlations at the receivers. To verify an achievable upper bound of the performance, we also plot the sum rate curves of the optimal transmission mode obtained by exhaustive search of all possible combinations of transmission modes. Note that this exhaustive search is possible only in the global CSI assumption. In Fig. 2, our method exhibits a notable performance enhancement compared to the conventional one with high correlations. Also the gain grows as the numbers of the antennas increase. For instance, the proposed scheme outperforms the conventional method by 20% and 27% in $N_t = N_r = 6$ and 8, respectively, with $\rho_T = 0.9$. A reliable performance can be achieved in our method with only six and eight iterations per receiver on average for $N_t = N_r = 6$ and 8, respectively. We observe in this figure that our proposed scheme utilizing only the local CSI achieves almost identical performance to the exhaustive search which requires global CSI.

Fig. 3 shows the average number of the transmitted data streams $\sum d_i$ in the proposed method with respect to the correlation coefficient. We see in this figure that the transmitted data stream number is reduced as the spatial correlation becomes severe. This phenomenon is analogous to that of point-to-point MIMO systems [14]. Also, we verify that our proposed scheme chooses the data streams adaptively depending on the SNR and the antenna configurations.

Fig. 4 depicts the sum rate curves of various schemes with respect to the SNR in high correlation environments. As can be seen, our proposed method shows about a 3-dB power gain compared to the conventional scheme when $N_t = N_r = 6$ and 8 at the SNR of 10 dB. Besides the performance curve of our scheme is still quite close to that of the

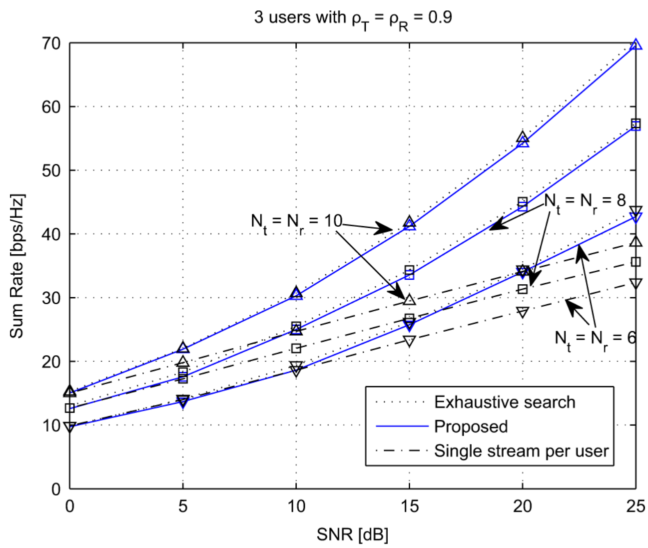

Fig. 5. Sum rate comparison with single data stream transmission per user.

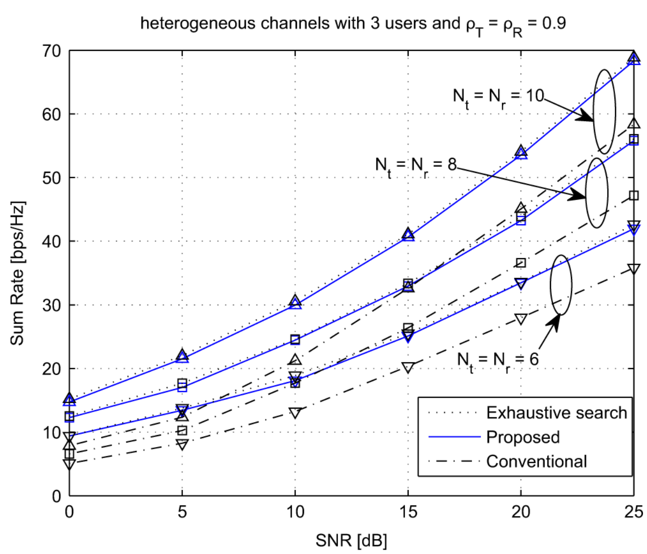

Fig. 6. Sum rate comparison with heterogeneous channels.

exhaustive search regardless of the antenna numbers and the SNRs. We also compare the performance of our method with that of a single data stream transmission per user in Fig. 5. Although the single data stream transmission is near-optimal in highly correlated point-to-point MIMO systems [14], this strategy is not appropriate for obtaining a sufficient spatial multiplexing gain (i.e., DOF) in the MIMO IC. As can be seen in this figure, the proposed scheme shows a significantly better performance especially at high SNR.

Finally, we consider the scenario where the channel gains from different transmitters are heterogeneous due to the presence of pathloss and shadowing. Denoting $\Upsilon_{i,j}$ as the average channel gain regarding $\overline{\mathbf{H}}_{i,j}$ (i.e., $\mathbb{E}[\overline{\mathbf{h}}_{i,j}^{(n)}\overline{\mathbf{h}}_{i,j}^{(n)\dagger}] = \Upsilon_{i,j}\mathbf{I}_{N_r}, \forall n$) [15], we suppose that at each receiver i the channel power $\Upsilon_{i,j}$ $(j \neq i)$ corresponding to the jth transmitter is greater than that of its respective channel $\Upsilon_{i,i}$ as $\Upsilon_{i,j} = 5\,\mathrm{m\,dB}$ and $\Upsilon_{i,i} = 0\,\mathrm{dB}$. Fig. 6 exhibits the performance curves of this case with various antenna numbers and $K = 3$. Again, our proposed scheme shows a performance very close to that of the exhaustive search. Also, this simulation result manifests that our scheme maintains improved performance compared to the conventional method even in heterogeneous channel environments.

V. Conclusion

In this correspondence, we have proposed a new transmission mode selection scheme to enhance the overall system performance in spatially correlated MIMO IC by adjusting the number of data streams at each transmitter-receiver pair. Utilizing a filter update process at each receiver in a decentralized (distributed) fashion, each transmission mode is properly adapted with only the local CSI. The sum rate performance is estimated successively with respect to each transmission mode by considering the actual channel conditions as well as the SNR. We have confirmed through simulations that the proposed mode selection scheme shows a notable sum rate improvement compared to the conventional IA with full data stream transmissions.

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