Joint Interference Alignment and Bi-Directional Scheduling for MIMO Two-Way Multi-Link Networks

A. M. Fouladgar, O. Simeone, O. Sahin, P. Popovski and S. Shamai (Shitz)

Abstract—By means of the emerging technique of dynamic Time Division Duplex (TDD), the switching point between uplink and downlink transmissions can be optimized across a multi-cell system in order to reduce the impact of inter-cell interference. It has been recently recognized that optimizing also the order in which uplink and downlink transmissions, or more generally the two directions of a two-way link, are scheduled can lead to significant benefits in terms of interference reduction. In this work, the optimization of bi-directional scheduling is investigated in conjunction with the design of linear precoding and equalization for a general multi-link MIMO two-way system. A simple algorithm is proposed that performs the joint optimization of the ordering of the transmissions in the two directions of the two-way links and of the linear transceivers, with the aim of minimizing the interference leakage power. Numerical results demonstrate the effectiveness of the proposed strategy.

Index Terms—MIMO, Two-way communications, Scheduling, Interference alignment, Linear precoding.

I. INTRODUCTION

Two-way communication is one of the most common modes of operation for wireless links, particularly for cellular and Device-to-Device (D2D) systems (see Fig. 1). The conventional approach to the design of a system comprising multiple interfering two-way links consists of two separate phases: at first, one fixes a transmission direction independently for each link; and, then, the physical-layer parameters, such as powers or beamforming vectors, are optimized in a centralized or decentralized fashion so as to maximize some system-wide performance criterion. This is, for instance, the standard approach for cellular systems, in which the scheduling of uplink and/or downlink transmissions is performed on a per-cell basis as a preliminary step.

The emerging technique of dynamic Time Division Duplex (TDD) breaks with the conventional approach discussed above in that the switching points between uplink and downlink transmissions in a frame are optimized jointly across all cells based on the current channel conditions [1]–[5]. The key motivation for this paradigm change is the observation that the selection of the duration of the uplink and downlink transmission phases in a cell can have a significant impact on the interference observed by the interfered cells.

With dynamic TDD, the ordering of the transmissions in the two directions of a two-way link is fixed. However, the interference configuration depends significantly on such scheduling decisions. An illustration of bi-directional scheduling is provided in Fig. 2 for two links: in each frame comprising two slots of fixed duration, each link can operate in the left (L) to right (R) direction, i.e., \( L \rightarrow R \), in the first slot and then in the opposite direction, \( R \rightarrow L \), in the second slot, or it can schedule first the \( R \rightarrow L \) direction and then the \( L \rightarrow R \) direction. As in [6], we refer to this binary choice for each link as the interference spin of the link.

Reference [6] studies the optimization of bi-directional scheduling in the presence of fixed switching times for single-antenna links. In this work, instead, we investigate the interplay of multi-antenna transmission and reception with bi-directional scheduling for fixed switching times and a general MIMO two-way multi-link system. This study is motivated by the observation that the choice of the interference spins across the network defines the channel matrices of the interfering channels on which the linear transceivers operate. Therefore, the capability of multiple antennas to mitigate interference depends on the scheduling decisions in a fundamental way. Algorithms are proposed that perform either the separate or the joint optimization of the interference spins and of the linear transceivers, with the aim of minimizing the interference leakage power and hence obtaining enhanced interference alignment solutions in the sense of [7].

Notation: We use lower case fonts for scalars and uppercase bold fonts for vectors and matrices. \( I_d \) represents the \( d \times d \) identity matrix and \( 0_{M \times N} \) is used to indicate the \( M \times N \) zero matrix. \( \text{tr}(A) \) denotes the trace of the matrix \( A \) and

Figure 1. A network of two-way MIMO communication links. Examples include uplink-downlink cellular links and two-way D2D channels.
\[ S_1 = 0: \quad L_1 \rightarrow R \quad R_1 \rightarrow L \quad L_2 \rightarrow R \quad R_2 \rightarrow L \quad \ldots \]
\[ S_2 = 1: \quad R_1 \rightarrow L \quad L_2 \rightarrow R \quad R_2 \rightarrow L \quad L_3 \rightarrow R \quad \ldots \]

Figure 2. Illustration of the definition of interference spin \( S_i \) for each link \( i \). A frame consists of two consecutive slots as shown by bold lines.

\( \mathbf{A}^H \) is the conjugate transpose of matrix \( \mathbf{A} \). \( \rho_{\min}^d(\cdot) \) returns a truncated unitary matrix spanning the space associated with the \( d \) smallest eigenvalues of the argument matrix. \( \mathbb{C}^{M \times N} \) represents the set of complex-valued \( M \times N \) matrices and \( \mathbb{U}^{M \times N} \) represents the set of truncated unitary matrices with \( N \) orthonormal columns. \( X \) is the complement of binary variable \( X \). The indicator function \( 1[\cdot] \) returns one if the argument is true and it returns zero otherwise.

II. SYSTEM MODEL

We consider a wireless network consisting of \( K \) MIMO two-way interfering links. An illustration is shown in Fig. 1 for a scenario with two cellular links and a D2D link. Each two-way link \( k \) is equipped with \( N_{L,k} \) antennas at the left-hand node \( R_k \) and with \( N_{R,k} \) antennas at the right-hand node \( L_k \). Note that the labeling of one end of each link as “right” or “left” is arbitrary. Each link operates using Time Division Duplex (TDD), and two-way communication takes a frame consisting of two successive slots: in the first slot, each kth link may operate either in the direction \( L_k \rightarrow R_k \), so that the \( L_k \) node is the transmitter and the \( R_k \) node is the receiver, or, vice versa, in the direction \( R_k \rightarrow L_k \), and the successive slot is used in the opposite direction. All links are synchronous and are assumed to be always backlogged so that there is a continuous stream of frames.

Based on the discussion above, each link operates in either direction \( L_k \rightarrow R_k \) or \( R_k \rightarrow L_k \) in even slots and in the opposite direction in odd slots. Following [8], we define the order in which the two directions are scheduled as the interference spin or, for short, spin of a link. Specifically, the \( k \)th link is said to have a 0-spin if it operates in the direction \( L_k \rightarrow R_k \) in the odd slots and the direction \( R_k \rightarrow L_k \) in the even slots; otherwise, when it operates in the direction \( R_k \rightarrow L_k \) in the odd slots and in the direction \( L_k \rightarrow R_k \) in the even slots, the \( k \)th link is said to have a 1-spin. We refer to Fig. 2 for an illustration. The spin of the \( k \)th link is denoted by \( S_k \in \{0, 1\} \). In order to simplify the notation, in the following, we set \( N_{L,k} = N_L \) and \( N_{R,k} = N_R \) for all \( k \in K \), although the generalization is straightforward.

A. Signal Model

Referring to Fig. 3 for an illustration of the main definitions, the signal \( y_{R_k} \in \mathbb{C}^{N_R \times 1} \) received by the \( k \)th receiver when active in the \( L_k \rightarrow R_k \) direction is given by

\[
y_{R_k} = \mathbf{H}_{R_k,L_k} \mathbf{x}_{L_k} + \sum_{j \in K \setminus \{k\}} (1[S_j = S_k] \mathbf{H}_{R_k,L_j} \mathbf{x}_{L_j} + 1[S_j \neq S_k] \mathbf{H}_{R_k,R_j} \mathbf{x}_{R_j}) + \mathbf{z}_{R_k},
\]

where the matrices \( \mathbf{H}_{R_k,L_j} \in \mathbb{C}^{N_R \times N_L} \) and \( \mathbf{H}_{R_k,R_j} \in \mathbb{C}^{N_R \times N_R} \) represent the channel responses from the node \( L_j \) to \( R_k \), and from the node \( R_j \) to \( R_k \), respectively; the vectors \( \mathbf{x}_{L_j} \) and \( \mathbf{x}_{R_j} \) are the signals transmitted by the nodes \( L_j \) and \( R_j \), respectively; and the vector \( \mathbf{z}_{R_k} \) is the additive noise, which is distributed as \( \mathbf{z}_{R_k} \in \mathbb{C}^{N_R \times 1} \) and is independent across the link index \( k \). The first term in (1) is the signal received from the desired transmitter while the second term represents the interference from all the other links that have the same spin as link \( k \) and the third accounts for the interference caused by links that have opposite spin. Similarly, the signal \( y_{L_k} \in \mathbb{C}^{N_L \times 1} \) received by the \( k \)th receiver when active in the \( R_k \rightarrow L_k \) direction can be written as

\[
y_{L_k} = \mathbf{H}_{L_k,R_k} \mathbf{x}_{R_k} + \sum_{j \in K \setminus \{k\}} (1[S_j = S_k] \mathbf{H}_{L_k,R_j} \mathbf{x}_{R_j} + 1[S_j \neq S_k] \mathbf{H}_{L_k,L_j} \mathbf{x}_{L_j}) + \mathbf{z}_{L_k},
\]

with analogous definitions.

The channel matrix \( \mathbf{H}_{R_k,L_j} \) and similarly for the other pairs of nodes can be written as \( \mathbf{H}_{R_k,L_j} = \alpha_{R_k,L_j} \mathbf{H}_{R_k,L_j} \), where the parameter \( \alpha_{R_k,L_j} \) models path-loss and shadowing over the link \( R_k \rightarrow L_j \) in both directions \( R_k \rightarrow L_j \) and \( L_j \rightarrow R_k \) and is defined as

\[
\alpha_{R_k,L_j} = \sqrt{\frac{D_{\text{ref}}}{D_{R_k,L_j}}} \cdot \frac{10^{\xi_{R_k,L_j}/10}}, \tag{3}
\]

where \( D_{\text{ref}} \) is a reference distance, \( D_{R_k,L_j} \) is the distance between node \( R_k \) and node \( L_j \), \( \eta \) is the path loss exponent and \( \xi_{R_k,L_j} \) is the log-normal shadowing component, which is distributed as \( \xi_{R_k,L_j} \sim \mathcal{N}(0, \sigma^2) \) and is independent for different pairs of nodes; and \( \mathbf{H}_{R_k,L_j} \) is an \( N_R \times N_L \) channel matrix that accounts for the effect of fast fading on the channel \( L_j \rightarrow R_k \) and is assumed to have i.i.d. \( \mathcal{C}\mathcal{N}(0, 1) \) entries. The channel matrices may or may not be reciprocal, so that, in general we have the inequality \( \mathbf{H}_{R_k,L_j} \neq \mathbf{H}_{L_j,R_k}^H \).

The channel matrices are assumed to be constant for at least a frame. The analysis below will be limited to any period including frames in which the channel matrices remain approximately constant.

When transmitting, nodes \( L_k \) and \( R_k \), first perform channel coding, producing codeword vectors \( \mathbf{s}_{L_k} \in \mathbb{C}^{d_k \times 1} \) and
performs linear equalization with a truncated unitary equalization matrix $U$, and similarly, on receiving the baseband signal $Q$, the transmitted baseband signal is $x_{Lk} = V_{Lk} s_{Lk}$ yielding the transmitted baseband signal

$$x_{Lk} = V_{Lk} s_{Lk} \quad (4)$$

and similarly node $R_k$ performs linear precoding with a truncated unitary precoding matrix $V_{Rk} \in \mathbb{C}^{N_R \times d_k}$ yielding the transmitted baseband signal

$$x_{Rk} = V_{Rk} s_{Rk} \quad (5)$$

On receiving the baseband signal $y_{rk}$, node $R_k$ performs linear equalization with a truncated unitary equalization matrix $U_{Rk} \in \mathbb{C}^{N_R \times d_k}$ yielding the output signal

$$s_{Lk} = U_{Rk}^H y_{rk}, \quad (6)$$

and similarly, on receiving the baseband signal $y_{lk}$, node $L_k$ performs linear equalization with a truncated unitary equalization matrix $U_{Lk} \in \mathbb{C}^{N_L \times d_k}$ yielding the output signal

$$s_{Rk} = U_{Lk}^H y_{lk}. \quad (7)$$

The covariance matrix of the interference signals that affects the equalized signal $s_{Rk}$, is given as

$$Q_{Rx}^{R_k} = U_{Rk}^H \left( \sum_{j \in K \setminus \{k\}} P_j \left[ I | S_j = S_k \right] H_{Rk,Rj} V_{Rj} V_{Lj}^H V_{Lk}^H H_{Rk,ik} \right) U_{Rk}, \quad (8)$$

while for the equalized signal $\hat{s}_{Lk}$ we have

$$Q_{Rx}^{L_k} = U_{Lk}^H \left( \sum_{j \in K \setminus \{k\}} P_j \left[ I | S_j = S_k \right] H_{Lk,Rj} V_{Rj} V_{Lj}^H H_{Lk,Rj}^H \right) U_{Lk}, \quad (9)$$

It is also useful to define the covariance matrix of the overall interference that is caused by node $R_k$ when transmitting as

$$Q_{Rx}^{R_k} = V_{Rk}^H \left( \sum_{j \in K \setminus \{k\}} P_j \left[ I | S_j = S_k \right] H_{Rk,ik} U_{Rj} U_{Lj} H_{Lk,Rj} \right) V_{Rk}, \quad (10)$$

while the covariance matrix of the overall interference that is caused by node $L_k$ when transmitting is given as

$$Q_{Rx}^{L_k} = V_{Lk}^H \left( \sum_{j \in K \setminus \{k\}} P_j \left[ I | S_j = S_k \right] H_{Lk,Rj} U_{Rj} U_{Lj} H_{Lk,Rj} \right) V_{Lk}, \quad (11)$$

Note that the defined interference covariance matrices depend on the interference spin variables $S_k$, $k \in K$, and on the linear precoding and equalization matrices.

### III. Bi-Directional Scheduling and Interference Alignment Optimization

In this section, we propose algorithms that perform the optimization of the interference spins vector $S = [S_1, ..., S_K]$ and of the linear transceivers $U = \{U_{Rk} \}_{k=1}^K$, $\{U_{Lk} \}_{k=1}^K$ and $V = \{V_{Rk} \}_{k=1}^K$, $\{V_{Lk} \}_{k=1}^K$. Following [7], in order to approximate the interference alignment conditions, we adopt as the optimization criterion the interference power leakage. Note that [7] only considers one-way communication links and hence the optimization therein is limited to the linear transceivers. Specifically, we formulate the problem of interest as the minimization of the total received interference leakage power as

$$\min_{S,U,V} \sum_{k \in K} I_{Rx}^{R_k} + I_{Lk}^{Rx}, \quad (12)$$

or, equivalently, as

$$\min_{S,U,V} \sum_{k \in K} I_{Rx}^{L_k} + I_{Lk}^{TX}, \quad (13)$$

where we have the implicit constraints that $S \in \{0, 1 \}^K$ hold and that the matrices $U$ and $V$ be truncated unitary with the mentioned dimensions; moreover, the quantities

$$I_{Rx}^{R_k} = \text{tr} \left( Q_{Rx}^{R_k} \right) \quad \text{and} \quad I_{Rx}^{L_k} = \text{tr} \left( Q_{Rx}^{L_k} \right) \quad (14)$$

measure the received interference power for link $k$ in the two directions, while

$$I_{Rx}^{L_k} = \text{tr} \left( Q_{Rx}^{L_k} \right) \quad \text{and} \quad I_{Lk}^{TX} = \text{tr} \left( Q_{Tx}^{L_k} \right) \quad (15)$$

measure the interference power caused by the transmitters of link $k$ in the two directions.

We observe that it is possible to extend the proposed approach to other performance criteria including the max-SINR method of [7], but this will not be further pursued here. Instead, the focus is on approximating the interference alignment conditions as per the interference leakage minimization (ILM) scheme in [7]. We start by discussing an algorithm that performs the separate optimization of the interference spins and of the linear transceivers in Sec. III-A and then we introduce an algorithm that carries out the joint optimization of interference spins and linear transceivers in Sec. III-B.

#### A. Separate Optimization

A first simple solution is that of first determining the spin variables $S$ and then perform linear transceiver optimization using the ILM algorithm as in [7].

**Spin Optimization:** In order to optimize the spin variables, we propose to solve the problem of (12), or equivalently (13), by setting all precoding and equalization matrices equal to the identity matrix in (8), (11). This optimization can either be carried out by exhaustive search in the space $\{0, 1 \}^K$ or by using the algorithm proposed in [6]. Moreover, in order to minimize the overhead associated to the selection of the vector $S$, one can perform the optimization of $S$ based only on
long-term CSI, namely path loss and log-normal shadowing. This enables the spins to be updated only at the time scale of the long-term fading variability. In this case, problem (12), or (13), is tackled by setting all matrices $U$ and $V$ to the identity matrix and by averaging the interference powers over the fast fading variables. This leads to the problem

$$\min_{\mathbf{S}} \sum_{k \in \mathcal{K}} \left( \sum_{j \in \mathcal{K} \setminus \{k\}} \left( 1 \left[ S_j = S_k \right] \left( \frac{D_{\text{ref}}}{D_{\text{Rx}}(L)} \right)^{\eta} - 10^{\frac{C}{10}} \right) N_L N_R + 1 \left[ S_j \neq S_k \right] \left( \frac{D_{\text{ref}}}{D_{\text{Rx}}(L)} \right)^{\eta} - 10^{\frac{C}{10}} \right) N_R^2 \right)$$

$$+ 1 \left[ S_j = S_k \right] \left( \frac{D_{\text{ref}}}{D_{\text{Rx}}(L)} \right)^{\eta} - 10^{\frac{C}{10}} \right) N_L N_R + 1 \left[ S_j \neq S_k \right] \left( \frac{D_{\text{ref}}}{D_{\text{Rx}}(L)} \right)^{\eta} - 10^{\frac{C}{10}} \right) N_L N_R$$

which can be tackled as explained above.

**Interference Leakage Minimization (ILM):** After finding the optimized spin vector $\mathbf{S} = [S_1, S_2, \ldots, S_K]$ as explained above, the linear transceiver matrices $\mathbf{V}$ and $\mathbf{U}$ can be calculated using the ILM method of [7, Alg. 1] using the optimized spin vector which can be tackled as explained above.

$$\text{Problem (12)}, \text{or long-term CSI, namely path loss and log-normal shadowing.}$$

**Algorithm 1 Interference Leakage Minimization [7]**

1. Start with initial precoding matrices $\mathbf{P}_j$ with $\mathbf{P}_j^H \mathbf{P}_j = \mathbf{I}$ for all $j \in \mathcal{K}$.
2. Begin iteration with setting $i = 1$
3. Compute interference covariance matrix at the receivers $k \in \mathcal{K}$:
   $$Q_k^{\text{RX}} = \sum_{j \in \mathcal{K} \setminus \{k\}} G_{k,j} \mathbf{P}_j \mathbf{P}_j^H G_{k,j}$$
4. Compute the linear equalization matrix at each receiver $k \in \mathcal{K}$:
   $$\mathbf{D}_k = \eta^{d_k}_{\text{min}} (Q_k^{\text{RX}})$$
5. Compute interference covariance matrix for each transmitter $j$ with $j \in \mathcal{K}$:
   $$Q_j^{\text{TX}} = \sum_{k \in \mathcal{K} \setminus \{j\}} G_{k,j} \mathbf{D}_k \mathbf{D}_k^H G_{k,j}$$
6. Compute the linear precoding matrix for each transmitter $j$ with $j \in \mathcal{K}$:
   $$\mathbf{P}_j = \eta^{d_j}_{\text{min}} (Q_j^{\text{TX}})$$

7. If $i > N_{\text{ILM}}$, exit; otherwise $i = i + 1$ and go back to 3.

**B. Joint Optimization**

In this section, we propose a technique that carries out the joint optimization of interference spins and linear transceivers based on full CSI. In order to avoid the exponential complexity of exhaustive search, which scales as $2^K$, the proposed scheme explores a subset of possible spin vectors guided by a simple local search criterion. Specifically, at each step $i$, the algorithm explores a new spin vector $\mathbf{S}(i)$ based on the previous vector $\mathbf{S}(i-1)$ by flipping the spins in $\mathbf{S}(i-1)$ corresponding to the minimum number of links, causing the largest transmitted interference powers. More precisely, we define the set $\mathbf{S}^{(i-1)}$ to include all spin vectors explored up to iteration $(i-1)$ and as $I^{(i-1)}$ the minimum interference leakage power observed up to iteration $(i-1)$ along with the corresponding spin vector $\mathbf{S}^{(i-1)}$. Moreover, we define as $I^{(i)}$ and $I^{(i)}_k$ the interference powers (15) calculated using ILM as discussed in the previous subsection for the current spin vector $\mathbf{S}^{(i)}$.

At each step $i$, we flip the spin variables of the vector $\mathbf{S}^{(i-1)}$ in the order of decreasing caused interference power $I^{(i)}_k = I^{(i)}_k$ until a new spin vector $\mathbf{S}^{(i)} \notin \mathbf{S}^{(i-1)}$.
Algorithm 2 Joint Spin and Linear Transceiver Optimization
1: Initialize the vector \( \mathbf{S}^{(0)} \) and set \( \mathbf{S}_{\text{opt}}^{(0)} = \mathbf{S}^{(0)}, \mathbf{S}^{(-1)} = \emptyset \), and \( I_{\text{opt}}^{(0)} \) to a very large value.
2: Begin step \( i = 1 \).
3: Run two instances of ILM \( \left\{ \left\{ G_{k,j} \right\}_{j=1}^{K}, \left\{ d_{j} \right\}_{j=1}^{K}, \mathcal{N}_{\text{ILM}}, \left\{ P_{j} \right\}_{j=1}^{K}, \left\{ D_{j} \right\}_{j=1}^{K} \right\} \) with \( I_{\text{opt}}^{(0)} \), one instance with \( \mathbf{S}^{(i-1)} \) in lieu of \( \mathbf{S} \) and one with \( \mathbf{S}^{(i-1)} \) in lieu of \( \mathbf{S} \). Calculate the resulting total two-way transmitted interference leakage, i.e., \( I_{k}^{\text{TX}}(i-1) = I_{k}^{\text{RX}}(i-1) + I_{L_{k}}^{\text{TX}}(i-1) \) and receiver interference leakage, i.e., \( I_{k}^{\text{RX}}(i-1) = I_{k}^{\text{RX}}(i-1) + I_{L_{k}}^{\text{RX}}(i-1) \), for all links \( k \in K \).
4: If \( \sum_{k} I_{k}^{\text{TX}}(i-1) + I_{k}^{\text{RX}}(i-1) \leq I_{\text{opt}}^{(i-1)} \), set \( I_{\text{opt}}^{(i)} = I_{\text{opt}}^{(i-1)} \) and \( \mathbf{S}^{(i)} = \mathbf{S}^{(i-1)} \); otherwise, set \( I_{\text{opt}}^{(i)} = I_{\text{opt}}^{(i-1)} \) and \( \mathbf{S}^{(i)} = \mathbf{S}^{(i-1)} \).
5: Update the set of explored spin vectors \( \mathbf{S}^{(i-1)} = \mathbf{S}^{(i-2)} \cup \{ \mathbf{S}^{(i)} \} \).
6: Flip the smallest number of spin variables of the vector \( \mathbf{S}^{(i-1)} \) in the order of decreasing caused interference power \( I_{k}^{\text{TX}}(i-1) + I_{L_{k}}^{\text{TX}}(i-1) \) until a new spin vector \( \mathbf{S}^{(i)} \notin \mathbf{S}^{(i-1)} \) is obtained.
7: If \( i > F \), stop, otherwise set \( i = i + 1 \) and go back to 4.

is obtained. The variables \( \mathbf{S}^{(i)} \), \( I_{k}^{\text{TX}}(i), I_{k}^{\text{RX}}(i), I_{\text{opt}}^{(i)} \) and \( \mathbf{S}_{\text{opt}}^{(i)} \) are updated accordingly based on ILM for the vector \( \mathbf{S}^{(i)} \). We perform a number \( F \) of comparison steps with \( F \leq 2^{K} \).

Remark 1. At each step \( i \), rather than using the largest transmitted interference powers criterion, we could generate a new vector \( \mathbf{S}^{(i)} \) by flipping the spin of the link, or links, with the largest received interference powers, namely \( I_{k}^{\text{RX}}(i-1) + I_{L_{k}}^{\text{RX}}(i-1) \), when using the previous spin vector \( \mathbf{S}^{(i-1)} \). Extensive numerical results, discussed in part in the next section, reveal that the transmitted interference power criterion is generally to be preferred.

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the considered techniques via numerical results. We consider a 100m \( \times \) 100m area in which all the links are located randomly. We set \( \eta = 3 \) and \( \xi = 5dB \) for all links. There are \( K_1 \) shorter-distance links with a transmitter-receiver-distance of \( D_1 = 25m \) and \( K_2 \) longer-distance links with distance of \( D_2 = 50m, \) so that \( K = K_1 + K_2 \). The shorter-distance links may represent D2D connections and the longer-distance links may represent WLAN channels between a device and an access point. In keeping with this interpretation, it is also assumed that both nodes of a shorter-distance link have the same average SNRs at the reference distance \( D_{\text{ref}} = D_1 \) of \( P_L = P_R = 10dB \), while for the longer-distance links we have \( P_L = 30dB \) and \( P_R = 50dB \). Note that the corresponding average SNRs at the distance \( D_2 \) are \( P_L(D_{\text{ref}}/D_2)^{\beta} = 21dB \) and \( P_R(D_{\text{ref}}/D_2)^{\gamma} = 41dB \). The number of antennas and the number of data streams are the same for all the nodes, namely \( N_L = N_R = 4 \) and \( d = 2, \) respectively. The number of ILM iterations is \( N_{\text{ILM}} = 20 \).

![Figure 5](image-url) Figure 5. Average relative interference leakage power (dB) versus the number of comparison steps for the proposed approach and for reference schemes \((K_1 = 3, K_2 = 2, N_L = N_R = 4, d = 2, \) and \( N_{\text{ILM}} = 20)). \)

Fig. 5 illustrates the average interference leakage power versus the number of comparison steps of the proposed Algorithm 2 with \( K_1 = 3 \) and \( K_2 = 2 \). For comparison, we show the performance of exhaustive search, of ILM run on a randomly selected spin vector and of the separate optimization schemes discussed in Sec. IIIA. For Algorithm 2 the spin initialization is done using the result of separate optimization using long-term CSI, i.e., by solving problem (16). The average interference leakage is normalized to the average interference leakage power obtained with random spins. The performance of the proposed techniques is seen to be very close to that of exhaustive search as long as around 10 comparison steps are performed. This is substantially smaller than the required number of comparison steps in exhaustive search, i.e., \( 2^N = 32 \). This advantage is less pronounced if one uses instead the received interference power criterion, as discussed in Remark 1. Moreover, the interference leakage power can be significantly reduced with respect to the considered baseline techniques, e.g., by more than 10dB over a random spin selection. This demonstrates that the interference alignment capabilities of the system are enhanced by the adoption of joint optimization. Finally, we observe that separate optimization based on long-term CSI perfrom very similarly to separate optimization based on full CSI.

Fig. 6 shows the average sum-rate, which is calculated using standard capacity formulas (see, e.g., [7]), versus the number of links \( K_1 \) with \( K_2 = 0 \). The relevant gains of optimizing the
spin vector are confirmed to hold also in terms of achievable two-way rate. Separate optimization is, however, shown to reap most of this advantage, even when using only long-term CSI. Finally, we note that increasing the number of links $K_1$ is at first beneficial as long as interference is manageable, but it leads to a decrease of the rate as soon as the number of links is large enough (here, larger than 9).

V. CONCLUDING REMARKS

In this paper, we have investigated a wireless network with MIMO two-way interfering links that operate using TDD with fixed switching times. We have proposed to optimize the bi-directional schedule, i.e., the order of the transmission directions, along with the linear transceivers, with the aim of minimizing the interference leakage power. Numerical results show that the performance of the proposed technique in terms of interference leakage is very close to that of a scheme based on exhaustive search, but at a substantially lower complexity, and that significant gains can be obtained as compared to a random selection of the interference spins. Interestingly, it is also seen that the interference leakage gains do not necessarily translate into sum-rate gains, for which separate optimization with long-term CSI appear to be sufficient to reap most of the performance advantage. Interesting future work includes the investigation of a distributed version of the proposed scheme.

REFERENCES

[1] B. Yu, S. Mukherjee, H. Ishii, and L. Yang, “Dynamic TDD support in the LTE-B enhanced local area architecture,” in Proc. IEEE Globecom 2012, Anaheim, CA, USA, Dec. 2012.
[2] Z. Shen, A. Khoryaev, E. Eriksson, and X. Pan, “Dynamic uplink-downlink configuration and interference management in TD-LTE,” IEEE Commun. Mag., vol. 50, no. 11, pp. 51–59, Nov. 2012.
[3] V. Venkatasubramanian, M. Hesse, P. Marsch and M. Maternia, “On the performance gain of flexible UL/DL TDD with centralized and decentralized resource allocation in dense 5G deployments,” in Proc. IEEE PIMRC 2014, Washington, DC, USA, Sep. 2014.
[4] A. Dowhuszko, O. Tirkkonen, J. Karjalainen, T. Hettonen and J. Pirskanen, “A decentralized cooperative uplink/downlink adaptation scheme for TDD small cell networks,” in Proc. IEEE PIMRC 2013, London, UK, Sept. 2013.
[5] M. S. El Bamby, M. Bennis, W. Saad and M. Latvaaho, “Dynamic uplink-downlink optimization in TDD-based small cell networks,” in Proc. IEEE INFOCOM 2014, Toronto, Canada, Apr. 2014.
[6] P. Popovski, O. Simeone, J. J. Nielsen and C. Stefanovic, “Interference spin optimization for wireless two-way communications,” submitted.
[7] K. Gomadam, Y. R. Cadambe and S. A. Jafar, “A distributed numerical approach to interference alignment and applications to wireless interference networks,” IEEE Trans. Inf. Theory, vol. 57, no. 6, pp. 3309-3322, Jun. 2011.