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Research Article

Joint Full- and Half-Duplex Communication Strategy for MIMO Interference Channels

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Although a full-duplex (FD) communication in K-links MIMO systems suffers from both self-interference and interuser interference, the bidirectional exchange of information between nodes on each of the K-links in FD significantly enhances the capacity of the wireless channel. On the other hand, a half-duplex (HD) communication is not affected by self-interference but faces the interuser interference. In order to take full advantages of the FD and HD communication modes, this article proposes a joint full- and half-duplex (FuHaDu) communication strategy for MIMO interference channels whereby K MIMO links capacity is enhanced, while both self-interference and interuser interference are reduced. Specifically, the proposed joint FuHaDu model is based on Rosen's gradient projection method for maximising the weighted sum rate (WSR) of optimal transmitter and receiver filters. The computer simulation results show that the joint FuHaDu strategy enhances the spectral efficiency when compared to the purely HD and FD conventional approaches. The results further reveal that channel capacity doubles as the number of antennas is increased from 2 × 2 to 4 × 4. The most significant capacity performance is noted with the 4 × 3 MIMO configuration for the HD, FD, and FuHaDu strategies.

1. Introduction

Today's explosive demand for high data rates and proliferation of massive number of users for wireless services have already compelled for modern communications technologies that exploit finite spectrum and energy resources more efficiently [1, 2]. Half-duplex (HD) communication modes and other techniques that emulate full-duplex communication over a half-duplex communication link, such as Time-Division Duplex (TDD) and Frequency-Division Duplex (FDD) wireless MIMO systems, employ two orthogonal channels to transmit and receive signals. However, they cannot achieve the maximal spectral and energy efficiency [3]. Thus, the full-duplex (FD) wireless MIMO communication systems enabling the simultaneous transmission and reception at the same time in the same frequency band have considerably gained tremendous interest in academia [4, 5]. This is because the FD communication modes can potentially double each link capacity and can increase the efficiency of radio resources targeted by the next generation wireless communication systems [3]. Based on the benefits of FD over the HD communication modes, the FD relaying technologies have been investigated in [6] for effective mitigation of the effects of multipath fading, pathloss, and shadowing as well as enhancement of the quality of service (QoS) of the users at the edge of the cells. In addition to relay nodes, FD communication technology has been considered for the deployment of small cells which provide improved cellular coverage due to low transmit powers, short transmission distances, and low mobility [7]. A small cell network where an FD base station (BS) serves multiple uplink (UL) and downlink (DL) users simultaneously has been considered in [4, 8]. The FD communication modes have also been witnessed in cognitive and foraging radios as promising technologies for enhancing the spectrum and energy efficiencies of the fixed spectrum allocation policies [1, 9–11].

Many recent papers on FD bidirectional systems consider a single pair of nodes, exchanging information simultaneously [12–14]. Cirik et al. [3] have studied FD systems under multiple pair of nodes, that is, FD MIMO interference channels. Their study has been motivated by the recent interest migration from point-to-point MIMO and MIMO downlink channels to the MIMO interference channels modelling huge practical applications of the Internet of Things [15]. In fact, a study on the performance of cellular communication systems (open spectrum, multicell systems, etc.) where each cell causes interference to other cells can be carried out by focusing on MIMO interference channels [16]. However, the limiting factor on the performance of FD systems is the strong self-interference at the front end of the receiver created by the signal leakage from the transmitter antennas of a FD node to its own receiver antennas. Kang and Cho [17] consider a FD amplify-and-forward (AF) relay that suffers from the problem of self-interference in a MIMO wireless channel. In their investigation, they derive the optimal transformation matrix that maximises the mutual information under average power constraint at the relay output. In particular, the capacity of the channel without a direct path is derived and it is shown that the relay maximises the throughput as if there is no interference from the relay itself. When the proposed MIMO wireless channel model is compared to the channel with a HD relay having the same average transmission power, the FD relay outperforms a HD relay and numerical results show that this result also holds for MIMO channels approximately.

There exists wireless communication systems which consist of both a cognitive radio and MIMO technology with the aim to achieve higher spectral efficiency [18]. The MIMO technology provides spatial multiplexing by using multiple transmit and receive antennas instead of a single pair. It has therefore proven to be capable of tremendously improving communication data rates capabilities in more than one current application ranging from sensor networks to cellular systems. However, the use of multiple antennas comes with its own challenges and the intralink and cross channel interference between the multiple transmissions remains one of the main challenges faced by MIMO technologies. Indeed, the advent of MIMO technologies has shifted the focus of the wireless channel modelling from a *fading channel* to an *interference channel*. The latter approach pays much more attention to the multiplicative channel impairments such as interference, while the fading channel modelling mainly considers the additive effect of noise on the transmitted signal. Therefore, handling interference at both the transmitter and the receiver design level, in which the FD and HD communication architectures are considered, has become the purpose of many research works [16]. It has also been evident that little success has been witnessed in the recent past with seperate FD and HD communication modes, especially in terms of minimising both self-interference and interuser interference [3]. In our current work, the main idea is to tap into the potentials of both FD and HD models with a view of enhancing the spectral efficiency by interleaving them on a single K-links MIMO channel. Specifically, we apply Rosen's gradient projection and restorations method to maximise the sum rates for MIMO interference channels [19]. To the best of our knowledge, there is no previous studies that applied Rosen's gradient projection optimisation method to jointly model the full- and half-duplex (FuHaDu) communication for MIMO interference channels.

The rest of the paper is organised as follows. Section 2 discusses the related work. Section 3 presents the system model of the proposed joint FuHaDu communication strategy. In Section 4, the joint FuHaDu algorithm is outlined. Sections 5 and 6 provide results and conclusions of the paper, respectively.

2. Related Work

Most existing MIMO technologies have been so far entirely HD [20] or entirely FD [3]. Moreover, most of them have been either Time-Division Duplex (TDD) or Frequency-Division Duplex (FDD). This means that despite the increase in channel capacity provided by MIMO technologies either most of them have simply provided possibility for only using half capacity of a link as they have not been able to allow transmission and reception to occur concurrently or they have evaluated the impact of using a FD communication for all the K-links.

In [4], the authors devise a beamforming scheme for a FD system, in which a FD capable BS communicates with multiple HD users in the downlink (DL) and uplink (UL) channels simultaneously. The authors consider the problem of joint spectral efficiency (SE) maximisation of DL and UL transmissions under some power constraints. First, the design problem is formulated as a rank constrained optimisation one, and then the rank relaxation technique is applied. However, the relaxed problem is still nonconvex. To solve this problem they propose two iterative algorithms, one based on the concept of the Frank-Wolfe (FW) algorithm and the other based on the framework of sequential parametric convex approximation (SPCA) method. The idea of both proposed methods is to approximate the nonconvex problem by a convex formulation in each iteration. While the first design algorithm sticks to a determinant maximisation (MAXDET) problem solvers, the second one offers more flexibility in choosing optimisation software and can take advantage of many state-of-the-art semidefinite program (SDP) solvers. They run the two algorithms in parallel until they converge and then select the better solution. The numerical results show that the FD transmission improves spectral efficiency significantly.

The authors in [21] note that only a few contributions focus on optimising bounds on the capacity of the MIMO relay channels. For instance, in [22], it is shown that Gaussian input distributions maximises the cut-set-bound (CSB) and the achievable decode-and-forward (DF) rate for the FD relay channel and an upper bound on the CSB that is loose in general is then provided. Suboptimal lower bounds are also given based on a point-to-point transmission (source to destination) and the cascaded relay channel (source to relay, relay to destination). While the achievable rates are shown to improve on the lower bounds of [22], Gerdes and Utschick [21] demonstrate the solutions of convex optimisation problems.

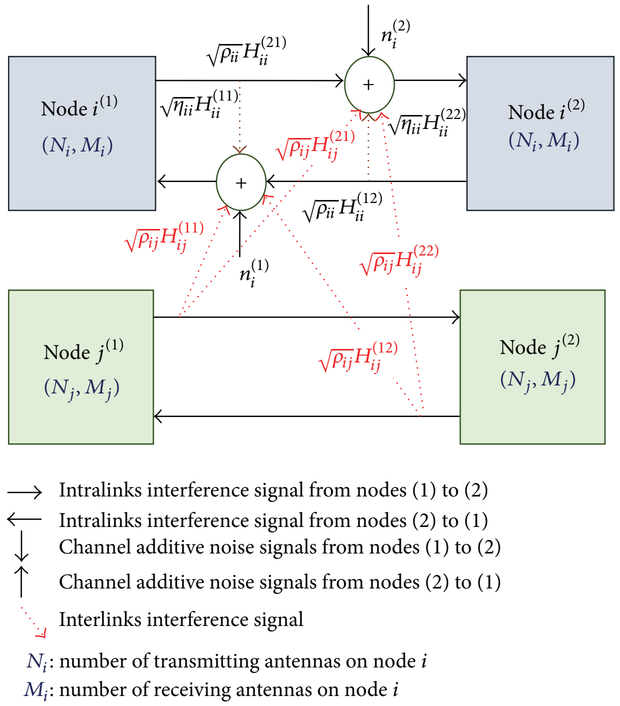

Figure 1: Channel behaviour analysis of a FD 2-link MIMO.

They extend these results to the HD relay channel where a feasible HD constraint is imposed on all nodes and verify that the expressions resulting from those derivations are only upper bounds to the optimal solutions

The authors in [3] develop a low complexity algorithm to compute the maximum weighted sum rate (WSR) of a K-link FD MIMO interference channel, where each link has two FD nodes exchanging information simultaneously. The nodes in each pair suffer from self-interference due to operating in FD mode and interuser interference due to simultaneous transmission at all links. Two types of realistic power constraints are considered. One is a power constraint on the sum power of the system. The other is a power constraint on the power at each radio node. The authors in [3] allude the fact that, under either constraint, the problem is nonconvex and hard to solve; thus the WSR problem can be turned into a much-easier-to-solve weighted minimum mean squared error (WMMSE) problem for broadcast channels. The authors then implement the distributed MIMO interference channels strategy for the FD communication models beyond those proposed for HD models [23]. Moreover, they show that the proposed algorithm is not only applicable to FD MIMO interference channels, but also to FD cellular systems in which a base station (BS) operating in FD mode serves multiple UL and DL users operating in half-duplex (HD) mode, simultaneously. Simulation results demonstrate that the proposed FD system outperforms the baseline HD systems under moderate interference levels of self-interference and interuser interference levels. In particular, the authors in [3] consider the channel model, depicted in Figure 1, in which different channel impairments at each link are considered.

Here, N_i and M_i are the numbers of transmit and receive antennas on link i, respectively. Notation $\sqrt{\rho_{ii}}$ represents the average attenuation of the channel on link i as derived from the channel's average power gain ρ_{ii}. In general, $H_{km}^{(ab)}$ is the channel matrix component from the links k to m, between the transmitting node b and the receiving node a, that is, $H_{ii}^{(12)}$. Finally, $n_i^{(1)}$ and $n_i^{(2)}$ are the distortion Additive White Gaussian Noise (AWGN) signals at node 1 and node 2 on link i, respectively.

Based on interference scenario in Figure 1, the authors in [3] have formulated a nonconvex optimisation problem in terms of the WSR maximisation under either individual or sum power constraints as follows:

$$\begin{aligned} &\underset{U_i^{(b)}}{\text{Max}} && \sum_{i=1}^{K}\sum_{a=1}^{2}\operatorname{tr}\left\{\mu_i^{(a)} I_i^{(a)}\right\} \\ &\text{Subject to:} && \operatorname{tr}\left\{U_i^{(b)}\left(U_i^{(b)}\right)^H\right\} \leq P_i^{(b)}, \quad \forall (i,b) \qquad (1) \\ &\text{or subject to:} && \sum_{i=1}^{K}\sum_{a=1}^{2}\operatorname{tr}\left\{U_i^{(b)}\left(U_i^{(b)}\right)^H\right\} \leq P_T^{(b)}, \end{aligned}$$

where $U_i^{(b)}$ is the precoding matrix of the transmitter's data stream's signal vector x_i which is used as the optimisation variable of the problem as derived in [3]. K is the number of MIMO links considered and it varies from as little as 2 links to more links. a represents the considered block of nodes which could be the transmitting or receiving block as FD (bidirectional) communication modes. Notation tr represents the computation of the trace of a matrix, while $\mu_i^{(a)}$ denotes the weight values which are always positive values ($\mu_i^{(a)} \geq 0$). $I_i^{(a)}$ is the lower bound of the achievable rate of node $i^{(a)}$ under Gaussian signaling as determined by a study in [24] which analyses the maximum achievable (limited) data rates in K-links MIMO as a result of the limited Dynamic Range (DR) of the input circuitry. Finally, P_T and $P_i^{(b)}$ are the total (sum) available power of the system and individual available powers for all nodes b, respectively.

However, the performance of FD MIMO systems is usually limited due to the strong self-interference at the front end of the receive antenna. This self-interference results in the combination of the signal received from a transmitting antenna on a different node and the leaked signal from the transmitting antenna of the node itself as both radios happen to be switched on at the same time [3]. Moreover, designing a transmit filter is not the only existing method or approach for minimising (reducing) self-interference at the transmitter. Thus, our work contributes to [3, 25] by introducing an adaptive mixed FD and HD, which takes into account the complementary advantages of separate FD [3] and HD [25] in order to reduce effects of self-interference at the transmitters of a communication system.

Some research works, both theoretical [26] and experimental [27], have been performed for reducing self-interference by smart antenna designs, for instance. Most of these smart antenna designs are based on antenna beamforming and target achieving with as minimum self-interference

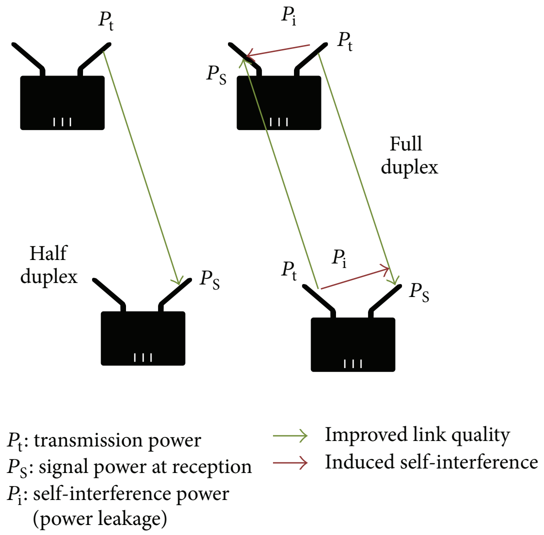

FIGURE 2: Effect of transmit power increase on MIMO channel interference.

as possible. This approach is usually referred to as the spatial domain self-interference suppression technique [13]. The operation of a K-links MIMO in FD mode is conditional to achieving an acceptable level of self-interference cancellation at the transmitter. This is normally done by means of a well-designed transmit filter aimed at minimising the effect of self-interference as much as possible [28]. The increase in transmit power for the HD MIMO mode results in improving the quality of the link, while, for the FD mode, it results in improving the quality of the link and at the same time causes an increase in self-interference as illustrated in Figure 2.

In [29], the exploitation of both spatial and temporal freedoms of the source covariance matrices of MIMO links has been used in studying the sum rate maximisation problem for FD bidirectional MIMO channels for slow and fast fading channels. A WSR maximisation, signal-to-leakage-plus-noise maximisation (SLNR), total transmission power minimisation, and distributed sum rate maximisation problems for bidirectional FD systems have also been studied in [29]. Furthermore, WSR maximisation for FD systems under multiple pairs of nodes or FD MIMO interference channels has been considered in [3]. This approach has brought into play the doubling of the link capacity but it has suffered from a very strong self-interference at each link.

To the best of our knowledge, no MIMO approach has proposed the use of hybrid links (both FD and HD) as a strategy to enhance the overall channel capacity of the system. Therefore, in a quite unique manner, this work taps into the potential of the FD MIMO approach to double channel capacity while alleviating the counter effect of its intrauser (intralink) interference by interleaving FD links with HD links. This approach is proposed under the hypothesis that the interleaving of the FD and HD MIMO subsystems could be the best possible scenario of achieving maximum channel capacity in a multiple links MIMO system at least at the network architectural point of view.

From a robustness point of view, for the formulated constrained optimisation problem, the choice of Rosen's gradient projection method for channel capacity maximisation for the proposed FuHaDu MIMO channels is more computationally effective than the previously proposed solutions for the entirely HD MIMO channels [20, 21, 25]. The robustness is justified by a faster convergence rate than the alternative channel capacity optimisation methods when the size of self-interfering links increases as demonstrated in [3, 25]. Furthermore, the FuHaDu strategy minimises the effect of self-interference exhibited in entirely FD strategy [3, 13, 17, 25] and thereby demonstrating a superior channel capacity. However, the convergence rate or computational complexity exhibited by the FuHaDu strategy is relatively comparable to that of the entirely FD strategy for a small size of the K-links [13, 17]. The reason is that the cumulative number of iterations required to ensure convergence of the optimisation procedure is directly proportional to the K size of the transceiver links and the M size of the MIMO channels [3].

Based on the fact that, in the case of MIMO interference channels, the half-duplex suffers from low data rates due to its single link capacity and based on the fact that the full-duplex also suffers from self-interference which considerably limits its channel capacity, the current paper proposes an enhancement strategy of the channel capacity in the presence of self-interference and interuser interferences by introducing a joint FuHaDu strategy using Rosen's gradient projection method.

3. System Model for a Joint Full- and Half-Duplex (FuHaDu) Multilinks Based MIMO Channels

This section presents the proposed joint full- and half-duplex (FuHaDu) multilinks based MIMO interference channels. The channel impairments involved in the joint FuHaDu multilinks based MIMO interference channels are identified, analysed, and discussed. Channel gains are derived and then considered in the design of the transceiver interference cancellation filters. By noting that the total interference cancellation is not feasible, an optimisation problem with the objective that maximises the capacity of the MIMO interference channels is formulated subject to feasible power constraints.

Suppose we consider the system of FD MIMO interference channels in [3] and proceed to interleave it with HD MIMO systems such that there are two nodes on each link. That is, each FD link has two neighbouring HD links. Two types of feasible power constraints are considered, namely, the sum power constraints and individual power constraints. It is assumed that channel impairments which will normally affect a signal $x_i^{(a)}$ transmitted from a node a on a link i are the "*transmitter distortion*" as well as the "*receiver distortion*" signals. These distortion signals are random by nature and are caused by designs of nonideal amplifiers, oscillators, Analog-to-Digital Converters (ADCs), and Digital-to-Analog Converters (DACs) of transceivers. A study in [30] has shown experimentally that the transmitter and receiver distortion signals can be modelled as AWGN ($n_i^{(1,2)}$) with zero-mean and different variances. Considering a transmission from

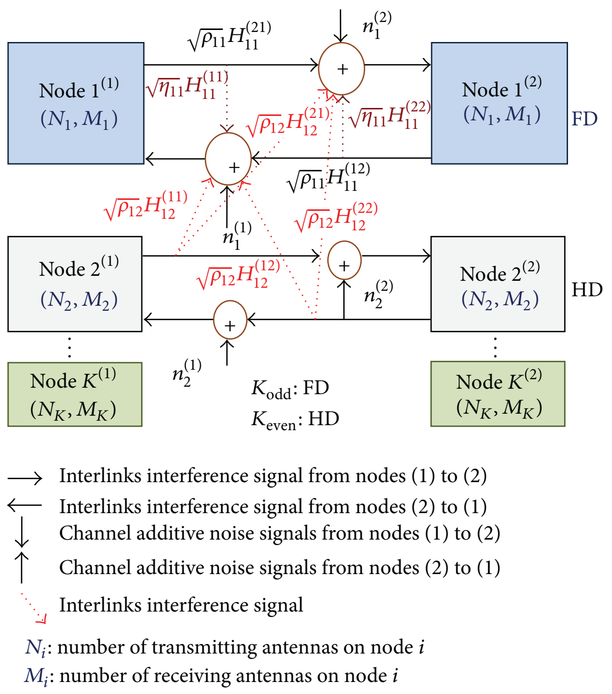

Figure 3: Joint FuHaDu K-links based MIMO channels.

node 1 to node 2 on link i in Figure 3, the variance of the transmitter and receiver distortions is, respectively, given as follows:

$$\begin{aligned}\operatorname{Var}\left(n_i^{(1)}\right) &= \delta \times E_{\text{Tx}},\\ \operatorname{Var}\left(n_i^{(2)}\right) &= \gamma \times E_{\text{Rx}},\end{aligned} \tag{2}$$

where δ and γ are constant values multiplying the randomly varying energy of the transmitted and the received signals E_{Tx} and E_{Rx}, respectively. In addition, by considering the joint FuHaDu communication model depicted in Figure 3, the system reveals that for K-links MIMO channels, there will be $K/2$ FD links and $K/2$ HD links when K is even or when K is odd and then $(K + 1)/2$ and $(K - 1)/2$ FD and HD links, respectively. If we further assume that data streams are transmitted from node $i^{(a)}$ and they first go through a transmit filter $V_i^{(a)}$ also referred to as the *precoding matrix* then they can be represented using a Gaussian distributed and zero-mean random vector as

$$x_i^{(a)} = U_i^{(a)} d_i^{(a)}, \tag{3}$$

where $d_i^{(a)}$ is the complex, zero-mean of the independently, identically distributed (i.i.d) transmitted data streams at node $i^{(a)}$. $x_i^{(a)}$ is $N_i \times 1$ signal vector transmitted by node $i^{(a)}$ and $U_i^{(a)}$ is the precoding matrix of the data stream's signal vector x_i^a of the transmitter on node (a) of i_{th} link.

During transmission, the transmitted signal $x_i^{(a)}$ will be modified by the different channel impairments such as self-interference, interuser interference, and AWGN $(n_i^{(a)})$. The AWGN signals at the transmitter and receiver can be modelled in terms of their respective covariance matrices c_i^a and e_i^a as follows:

$$\begin{aligned}c_i^a &\sim CN\left(0, \delta \operatorname{diag}\left(U_i^{(a)}\left(U_i^{(a)}\right)^H\right)\right),\\ e_i^a &\sim CN\left(0, \gamma \operatorname{diag}\left(\psi_i^{(a)}\right)\right),\\ &\qquad \text{where } \psi_i^{(a)} = \operatorname{Cov}\left(\mu_i^{(a)}\right).\end{aligned} \tag{4}$$

It can be noted that $\mu_i^{(a)}$ is the undistorted received signal. That is, it is equivalent to the received signal with no receiver's distortion e_i^a added to it. Moreover, a receiving antenna of a node b on the same FD link i has the transmitted signal $x_i^{(a)}$ throughout the wireless channel in the presence of both self-interference and interuser interference. The FD received signal y on link i of the transmitted signal $x_i^{(a)}$ is given from Figure 3 as follows:

$$\begin{aligned}y_{\text{FD}i}^{(a)} &= \sqrt{\rho_i}H_{ii}^{(ab)}\left(x_i^b + c_i^b\right) + \sqrt{\eta_{ii}}H_{ii}^{(aa)}\left(x_i^{(a)} + c_i^{(a)}\right)\\ &\quad + \sum_{j\neq i}^{K}\sum_{k=1}^{2}\sqrt{\left(n_{ij}\right)}H_{ij}^{(ak)}\left(x_j^{(k)} + c_j^{(k)}\right) + e_i^{(a)} + n_i^a\\ &\qquad \forall i \in \{1, 2, \ldots, K\},\ (a, b) \in \{1, 2\},\ a \neq b.\end{aligned} \tag{5}$$

Similarly, the signal which is received by a node on a HD link $j = 2$, as in Figure 1, for example, will not consist of any self-interference effects as provided by the following:

$$\begin{aligned}y_{\text{HD}i}^{(a)} &= \sqrt{\rho_i}H_{ii}^{(ab)}\left(x_i^b + c_i^b\right)\\ &\quad + \sum_{j\neq i}^{K}\sum_{k=1}^{2}\sqrt{\left(n_{ij}\right)}H_{ij}^{(ak)}\left(x_j^{(k)} + c_j^{(k)}\right) + e_i^{(a)} + n_i^a\\ &\qquad \forall i \in \{1, 2, \ldots, K\},\ (a, b) \in \{1, 2\},\ a \neq b.\end{aligned} \tag{6}$$

Thus, the undistorted received signal $\mu_i^{(a)}$ using the received signals $y_{\text{FD}i}^{(a)}$ and $y_{\text{HD}i}^{(a)}$ in both cases (FD in (5) and HD in (6). resp.) becomes

$$\mu_{\text{FD}i}^{(a)} = y_{\text{FD}i}^{(a)} - e_i^a, \tag{7}$$

$$\mu_{\text{HD}i}^{(a)} = y_{\text{HD}i}^{(a)} - e_i^a. \tag{8}$$

It is important to note that the difference between (7) and (8) is the value of the received signals $y_{\text{FD}i}^{(a)}$ and $y_{\text{HD}i}^{(a)}$ as clearly depicted by (5) and (6), respectively. The received signal on the half-duplex link does not comprise any self-interference component unlike the one of the full-duplex link that comprises both the self-interference and the interuser interference components.

In order to design optimal transmit and receive filters for both joint FuHaDu links, it is important to know the threshold signals for both modes beforehand. Since the self-interference signal component occurs at the transmit filters which means that it occurs before transmission into wireless channels, this could be measured and therefore can be assumed to be known by the transmitter. The self-interference received signals $\widetilde{y}_{\mathrm{FD}i}^{(a)}$ and $\widetilde{y}_{\mathrm{HD}i}^{(a)}$ for FD and HD are given by filtering $\sqrt{\eta_{ii}}H_{ii}^{(aa)}x_i^{(a)}$ off from (5) and (6) to have

$$\begin{aligned}
\widetilde{y}_{\mathrm{FD}i}^{(a)} &= y_{\mathrm{FD}i}^{(a)} - \sqrt{\eta_{ii}}H_{ii}^{(aa)}x_i^{(a)} = \sqrt{\rho_i}H_{ii}^{(ab)}x_i^{(b)} + z_{\mathrm{FD}i}^{(a)}, \\
\widetilde{y}_{\mathrm{HD}i}^{(a)} &= y_{\mathrm{FD}i}^{(a)} - \sqrt{\eta_{ii}}H_{ii}^{(aa)}x_i^{(a)} = \sqrt{\rho_i}H_{ii}^{(ab)}x_i^{(b)} + z_{\mathrm{HD}i}^{(a)}.
\end{aligned} \tag{9}$$

From (9), it should further be noted that unlike self-interference signals known by the transmitter filters prior to the transmit filters design, the interuser interference signals and the noise components which are also part of the received signal in both the joint FuHaDu and the entirely FD communication modes are known and random. Such random components $z_{\mathrm{FD}i}^{(a)}$ and $z_{\mathrm{HD}i}^{(a)}$ can then be computed according to

$$\begin{aligned}
z_{\mathrm{FD}i}^{(a)} = {} & \sqrt{\rho_i}H_{ii}^{(ab)}c_i^{b} + \sqrt{\eta_{ii}}H_{ii}^{(aa)}c_i^{(a)} + e_i^{(a)} + n_i^{(a)} \\
& + \sum_{j\neq i}^{K}\sum_{k=1}^{2}\sqrt{(n_{ij})}H_{ij}^{(ak)}\left(x_j^{(k)} + c_j^{(k)}\right),
\end{aligned} \tag{10}$$

$$\begin{aligned}
z_{\mathrm{HD}i}^{(a)} = {} & \sqrt{\rho_i}H_{ii}^{(ab)}c_i^{b} + e_i^{(a)} + n_i^{(a)} \\
& + \sum_{j\neq i}^{K}\sum_{k=1}^{2}\sqrt{(n_{ij})}H_{ij}^{(ak)}\left(x_j^{(k)} + c_j^{(k)}\right).
\end{aligned} \tag{11}$$

Note from (9), (10), and (11) that the lower bounds of achievable rates of a node $i^{(a)}$ under Gaussian signaling for the FD (as systematically derived in [24]) and the HD links, respectively, will then become

$$\begin{aligned}
I_{\mathrm{FD}i}^{(a)} = \log_2 \Bigg| & I_{M_i} \\
& + \rho_i H_{ii}^{(ab)}U_i^{(b)}\left(U_i^{(b)}\right)^{H}\left(H_{ii}^{(ab)}\right)^{H}\left(\sum_{\mathrm{FD}i}^{(a)}\right)^{-1}\Bigg|,
\end{aligned} \tag{12}$$

$$\begin{aligned}
I_{\mathrm{HD}i}^{(a)} = \log_2 \Bigg| & I_{M_i} \\
& + \rho_i H_{ii}^{(ab)}U_i^{(b)}\left(U_i^{(b)}\right)^{H}\left(H_{ii}^{(ab)}\right)^{H}\left(\sum_{\mathrm{HD}i}^{(a)}\right)^{-1}\Bigg|.
\end{aligned} \tag{13}$$

Here, I_{M_i} is a $M_i \times M_i$ identity matrix and $(\sum_{\mathrm{FD}i}^{(a)})$ and $(\sum_{\mathrm{HD}i}^{(a)})$ are the covariance matrices of $z_{\mathrm{FD}i}^{(a)}$ and $z_{\mathrm{HD}i}^{(a)}$, respectively. These can be expanded mathematically by incorporating channel impairments as follows:

$$\begin{aligned}
\sum_{\mathrm{FD}i}^{(a)} \approx {} & \rho_i\delta H_{ii}^{(ab)}\operatorname{diag}\left(U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right)\left(H_{ii}^{(ab)}\right) \\
& + \eta_{ii}\delta H_{ii}^{(aa)}\operatorname{diag}\left(U_i^{(a)}\left(U_i^{(a)}\right)^{H}\right)\left(H_{ii}^{aa}\right)^{H} \\
& + \gamma\rho_i\operatorname{diag}\left(H_{ii}^{(ab)}U_i^{(b)}\left(U_i^{(b)}\right)^{H}\left(H_{ii}^{(ab)}\right)^{H}\right) \\
& + \gamma\eta_{ii}\operatorname{diag}\left(H_{ii}^{(aa)}U_i^{(a)}\left(U_i^{(a)}\right)^{H}\right) \\
& + \sum_{j\neq i}^{K}\sum_{c=1}^{2}\eta_{ij}\left[H_{ij}^{(ac)}\left(U_i^{(c)}\left(U_i^{(c)^{H}}\right) + \delta\operatorname{diag}\left(U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right)\right)\right] \\
& + \sum_{j\neq i}^{K}\sum_{c=1}^{2}\gamma\eta_{ij}\operatorname{diag}\left(H_{ij}^{(ac)}U_j^{(c)}\left(U_j^{(c)}\right)\left(H_{ij}^{(ac)}\right)^{H}\right) + I_{M_i}, \\
\sum_{\mathrm{HD}i}^{(a)} \approx {} & \rho_i\delta H_{ii}^{(ab)}\operatorname{diag}\left(U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right)\left(H_{ii}^{(ab)}\right) \\
& + \gamma\rho_i\operatorname{diag}\left(H_{ii}^{(ab)}U_i^{(b)}\left(U_i^{(b)}\right)^{H}\left(H_{ii}^{(ab)}\right)^{H}\right) \\
& + \sum_{j\neq i}^{K}\sum_{c=1}^{2}\eta_{ij}\left[H_{ij}^{(ac)}\left(U_i^{(c)}\left(U_i^{(c)^{H}}\right) + \delta\operatorname{diag}\left(U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right)\right)\right] \\
& + \sum_{j\neq i}^{K}\sum_{c=1}^{2}\gamma\eta_{ij}\operatorname{diag}\left(H_{ij}^{(ac)}U_j^{(c)}\left(U_j^{(c)}\right)\left(H_{ij}^{(ac)}\right)^{H}\right) + I_{M_i}.
\end{aligned} \tag{14}$$

By using the derived lower bound of achievable rate of node $i^{(a)}$ in (12) and (13), the WSR optimisation problem of the joint FuHaDu strategy can be formulated as follows:

$$\begin{aligned}
& \underset{(U_{\mathrm{FD}i}^{(b)}+U_{\mathrm{HD}i}^{(b)})}{\mathrm{Max}} && \sum_{i=1}^{K}\sum_{a=1}^{2}\operatorname{tr}\left\{\mu_i^{(a)}\left(I_{\mathrm{FD}i}^{(a)} + I_{\mathrm{HD}i}^{(a)}\right)\right\} \\
& \text{Subject to:} && \operatorname{tr}\left\{U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right\} \leq P_i^{(b)}, \quad \forall (i,b) \\
& \text{or subject to:} && \sum_{i=1}^{K}\sum_{a=1}^{2}\operatorname{tr}\left\{U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right\} \leq P_T^{(b)},
\end{aligned} \tag{15}$$

where $U_i^{b} = U_{\mathrm{FD}i}^{b} + U_{\mathrm{HD}i}^{b}$ and their definitions have been outlined in the appendix. We note that the nonconvexity property of the WSR maximisation problem presents difficulty in trying to find an optimal solution. In that case, the objective function can then be transformed into a simpler-to-solve convex problem formulation, namely, the WMMSE minimisation problem as shown in the following:

$$\begin{aligned}
& \underset{U_i^{(b)}}{\mathrm{Min}} && \sum_{i=1}^{K}\sum_{a=1}^{2}\operatorname{tr}\left\{W_i^{(a)}\left(\log_2\left|\left(E_{\mathrm{FD}i}^{(a)}\right)^{-1}\left(E_{\mathrm{HD}i}^{(a)}\right)^{-1}\right|\right)\right\} \\
& \text{Subject to:} && \operatorname{tr}\left\{U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right\} \leq P_i^{(b)}, \quad \forall (i,b) \\
& \text{or subject to:} && \sum_{i=1}^{K}\sum_{a=1}^{2}\operatorname{tr}\left\{U_i^{(b)}\left(U_i^{(b)}\right)^{H}\right\} \leq P_T^{(b)},
\end{aligned} \tag{16}$$

where $W_i^{(a)} = (\mu_i^{(a)}/\ln 2)(E_i^{(a)})^{-1}$, $I_{\mathrm{FD}i}^{(a)} = \log_2|(E_{\mathrm{FD}i}^{(a)})^{-1}|$, and $I_{\mathrm{HD}i}^{(a)} = \log_2|(E_{\mathrm{HD}i}^{(a)})^{-1}|$. Therefore, $I_{\mathrm{FD}i}^{(a)}+I_{\mathrm{HD}i}^{(a)} = \log_2|(E_{\mathrm{FD}i}^{(a)})^{-1}|+\log_2|(E_{\mathrm{HD}i}^{(a)})^{-1}| = \log_2|(E_{\mathrm{FD}i}^{(a)})^{-1}(E_{\mathrm{HD}i}^{(a)})^{-1}|$ as depicted in (16).

The key parameters of the system model as derived in the present section are the lower bounds of achievable rates of a node $i^{(a)}$ under Gaussian signaling for the FD and the HD links, respectively, $I_{\mathrm{HD}i}^{(a)}$ & $I_{\mathrm{FD}i}^{(a)}$. These two key system model parameters are functions of the channel matrix model between a transmitting antenna on node (a) and a receiving antenna on node (b) both on the same link (i) and on different links (i) and (j), therefore modelling the intralink interference and the interlinks interference, respectively. The other very important and nonnegligible system model parameter that has also been considered is the additive noise channel impairment as experienced in both directions on each specific link. It is important to note that, although inspired from the model in [3], the system model developed for the FuHaDu strategy is quite specific in a sense that the change in the architecture if the MIMO system changes from being either entirely HD or entirely FD to being mixed comes with totally different channel impairment considerations which is even the actual motivation for this work.

The change from WSR maximisation problem to WMMSE minimisation problem is justified by the fact that both share the same Karush-Kuhn-Tucker (KKT) conditions [31]. Thus, the corresponding optimum receive filters at a node $i^{(a)}$ for both joint FuHaDu communication modes based on WMMSE minimisation in (12) can be obtained as follows [3]:

$$\begin{aligned} r_{\mathrm{FD}i}^{(a)*} &= \sqrt{\rho_i}\left(U_i^b\right)^H \left(H_{ii}^{ab}\right)^H \\ &\quad \cdot \left(\rho_i H_{ii}^{ab} U_i^b \left(U_i^b\right)^H \left(H_i^{ab}\right)^H + \sum_{\mathrm{FD}i}^{(a)}\right)^{-1}, \\ r_{\mathrm{HD}i}^{(a)*} &= \sqrt{\rho_i}\left(U_i^b\right)^H \left(H_{ii}^{ab}\right)^H \\ &\quad \cdot \left(\rho_i H_{ii}^{ab} U_i^b \left(U_i^b\right)^H \left(H_i^{ab}\right)^H + \sum_{\mathrm{HD}i}^{(a)}\right)^{-1}. \end{aligned} \tag{17}$$

4. Solving the Formulated FuHaDu Optimisation Problem

This section presents the optimisation algorithm selected for solving the WMMSE minimisation problem derived in the previous section. In particular, Rosen's gradient projection method [19] has been applied to solve the formulated joint FuHaDu communication strategy for the MIMO interference channels. The main idea is that Rosen's gradient projection method simply projects the search direction into the subspace tangent to the active constraints as illustrated in Figure 4. This method reduces the main difficulty caused by the nonlinearity of the constraints, in which the one-dimensional search typically moves away from the constraint boundary. It achieves this gain by prescribing a restoration move to bring optimisation variable back to the constraint boundaries after the one-dimensional search is over [19]. Moreover, the computation of Rosen's gradient projection is far less demanding in convex optimisation formulations and only requires the product of the gradient by a projection matrix [31].

Here, the notations $(U_i^b)_n$ and $(U_i^b)_{(n+1)}$ are n^{ieme} and $(n+1)^{ieme}$ optimal transmit filters on link i node b. $(\overline{U}_i^b)_n$ is the projection of $(U_i^b)_n$ on the search direction axis. $g_i((U_i^b)_n)$ is the individual or even the sum power constraint as these two have been proven to yield more or less the same results in [3].

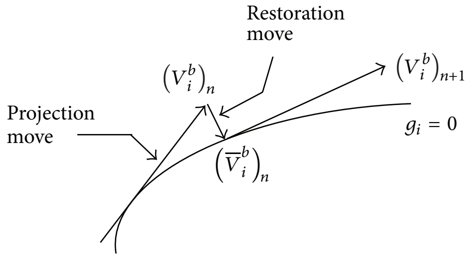

Figure 4: Rosen's gradient projection and restoration concepts.

By invoking the optimisation problem in (11), the objective function $f(U_i^{(b)})$ can be writen as $f(U_i^{(b)}) = \sum_{i=1}^{K}\sum_{a=1}^{2} \operatorname{tr}\{W_i^{(a)}(\log_2|(E_{\mathrm{FD}i}^{(a)})^{-1}(E_{\mathrm{HD}i}^{(a)})^{-1}|)\}$. It should be noted that the gradient projection algorithm is a modified version of the steepest descent algorithm, in which only solutions that lie in a closed bounded domain are valid [19]. Based on Figure 4, the gradient projection algorithm for solving the WMMSE minimisation problem (11) of the FuHaDu communication modes for the MIMO interference channels is outlined as follows.

Rosen's gradient projection WSMMSE minimisation algorithm (FuHaDu strategy) is as follows.

(1) Set the iteration number $n = 0$.

(2) Start with an arbitrary initial complex transmit filter (precoding matrix) $(U_i^b)_0$ of size $(N_i \times d_i)$, such that $i : 1 \to K$ and $b \in \{1, 2\}$.

(3) Find a search direction S_n as $S_n = -\Delta f_n$ where $f_n = -\Delta f((U_i^{(b)})_n)$.

(4) Determine the optimal step length λ_n^* in the search direction S_n and get the next iteration optimal transmit filter $(U_i^b)_{(n+1)}$ using the following: $(U_i^b)_{(n+1)} = (U_i^b)_n + (\lambda_n^* \times \Delta f_n)$.

(5) Update $n = n + 1$. Update the corresponding receive filters $r_{\mathrm{FD}i}^{(a)*}$ and $r_{\mathrm{HD}i}^{(a)*}$ using (13).

(6) Repeat steps (3) and (4) until convergence, or else up until a predefined number of iterations N is reached.

5. Performance Evaluation

The performance evaluation of this study has been conducted using discrete-event based computer simulations. The key simulation setup parameter values are captured in Table 1.

By using the setup in Table 1, the different conducted simulations yield the results in Figure 5.

It can be noticed from Figure 5 that, at low SNR, the FD model outperforms the joint FuHaDu strategy in terms of spectral efficiency but, as SNR is increased, the joint FuHaDu strategy exhibits better performance. However, as SNR reaches higher values, the performance of two models seems to converge towards a maximum WSR of approximately

Table 1: Simulation parameters.

Parameter	Value	Description
d_i	800	Transmission data streams size
K	5	Number of MIMO links
$N_i = M_i$	2, 3, 4	Number of transmitters/receivers per node
$\gamma = \delta$	−40 dB	Receiver and transmitter distortion parameters
μ	1	Positive WSR weight coefficient Dichotomous method step length optimisation

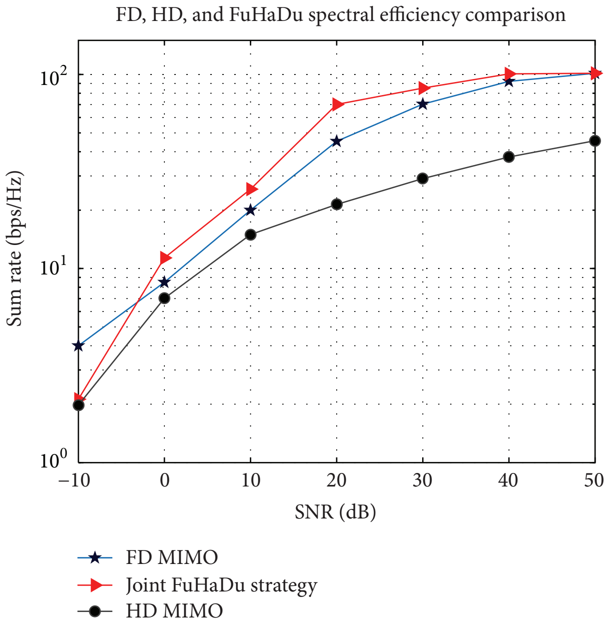

Figure 5: Spectral efficiency performance comparison between FD, HD, and the joint FuHaDu strategy with SNR variation.

100 bits/s/Hz. In addition, it can be noticed that the HD MIMO mode performs poorly in terms of spectral efficiency when compared to the FD. Therefore, the performance of the HD MIMO mode is worse compared to the one of the proposed joint FuHaDu strategy.

Figure 6 shows that the adaptive FuHaDu strategy achieves better convergence rate than with HD MIMO strategy. However, no much significant convergence rate has been achieved by the FuHaDu MIMO strategy when compared to the entirely FD MIMO strategy. This convergence speed of the FuHaDu strategy as compared to the FD strategy is numerically evaluated to 1.3014% on average. Another interesting observation is that after the 6th iteration of Rosen's gradient projection algorithm both FD and joint FuHaDu strategies show spectral efficiency performance that is quite steady. However, the HD multilinks based MIMO strategy exhibits a much slower convergence towards maximum spectral efficiency than that of the FD MIMO and the proposed joint FuHaDu strategy. In addition, it can be noted that the maximum achievable channel capacity of the HD MIMO is much lower than that of the FD and the joint FuHaDu strategy. Although the computational complexity performance of Rosen's gradient projection algorithm while solving the formulated FuHaDu channel capacity optimisation method is not very significant, the FuHaDu approach still exhibits significant improvement of the overall system's channel capacity when compared with the entirely FD approach. This means that the primary goal of this work is still achieved with the extra advantage provided by the solution method in terms of computational complexity. However, it is also important to note that the convergence speed and spectral efficiency performance of the FuHaDu system as compared to the HD MIMO system is quite significant.

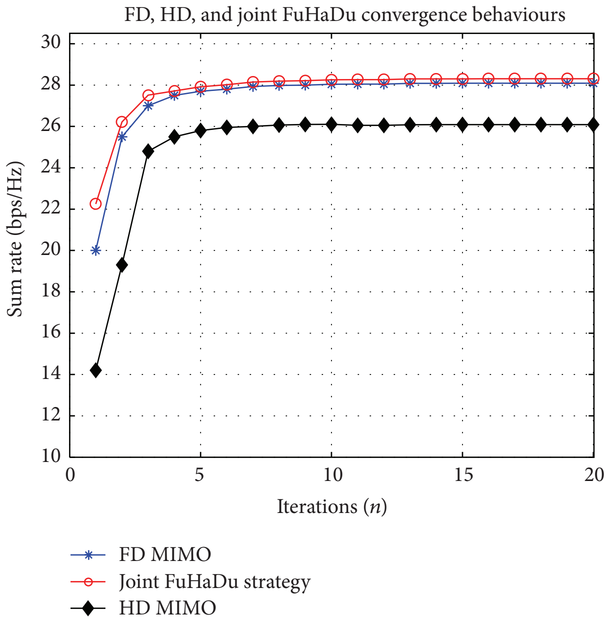

Figure 6: Convergence comparison between FD and joint FuHaDu strategy WSR maximisation.

Figure 7 clearly shows that spectral efficiency increases as the SNR increases. The aim is to investigate the effect of increasing the number of both the transmit and receive antennas on spectral efficiency performance. Clearly, as the number of antennas increases from 2 to 3 and then to 4, the spectral efficiency of the joint FuHaDu strategy is considerably improved to a point of doubling at a SNR of 40 dB (i.e., Figure 7).

The bar graph in Figure 8 clearly indicates that the joint FuHaDu strategy achieves better channel capacity performance than the FD and HD MIMO for all the possible nine considered antennas configurations when operated at a SNR of 40 dB. It can be furthermore observed that for each N_t (varying from 2 to 4) transmitting antenna, better channel capacity performance is observed when the number of receiving antennas is equal to 3 as compared to when the number of receiving antennas is equal to 2 and 4. This is because the configurations with 3 receiving antennas require less total power than the ones with 4 receiving antennas for the same number of transmitting antennas 2, 3, and 4. Since, we still

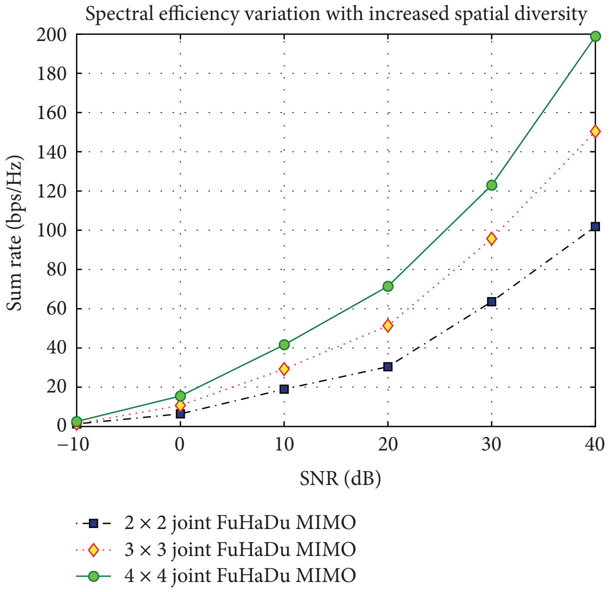

FIGURE 7: Spectral efficiency variation with increased SNR and spatial diversity.

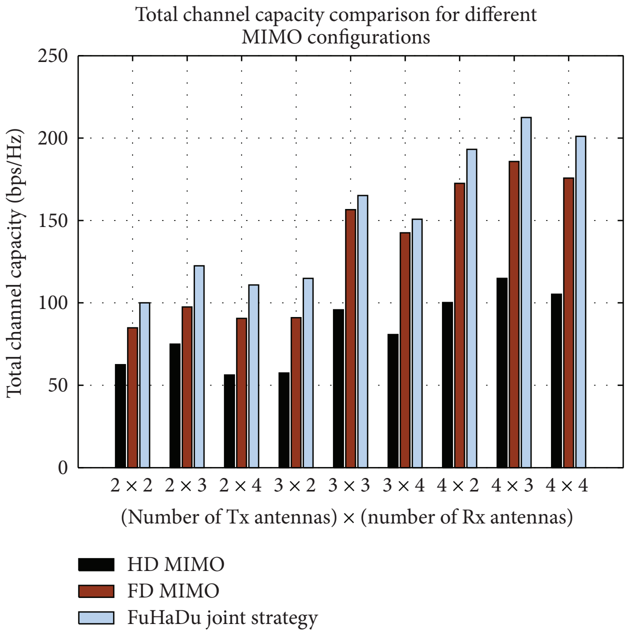

FIGURE 8: Total channel capacity for different MIMO antennas configurations at a SNR of 40 dB.

have the same number of transmitting antennas, theoretically there should not be any significant difference in data rates between the configurations with 3 receiving antennas and the ones with 4 receiving antennas. The assumption in this case is that the decoding of the transmitted signals is properly handled and that the used antennas have a gain of unity (isotopic antennas). This is a theoretical assumption because, in practice, it becomes quite complex to decode the received signals when the number of receiving antennas is less than the one of transmitting antennas as it is the case for the 4 × 3 configuration and also because an isotopic antenna is not practical.

In addition, the results in Figure 8 show that the higher the number of transmitter antennas, the higher the spectral efficiency. As expected, it is shown that the 4×4 MIMO antennas configuration strategies double the spectral efficiency achieved by the 2 × 2 MIMO antennas configuration and the proposed joint FuHaDu strategy achieves the most significant performance.

6. Conclusion

In this work, the possibility for developing a joint full- and half-duplex (FuHaDu) communication strategy in K-links based MIMO interference channels has been explored. The FuHaDu concept involved different channel impairments such as interference (both self-interference and interuser interference) and the distortions at the transmitter and the receiver. The numerical results demonstrate that the proposed joint FuHaDu communication strategy for the MIMO interference channels is more spectrally efficient when compared to the entireley full-duplex (FD) and entirely half-duplex (HD) systems. The impact of the joint FuHaDu strategy on the achievable channel capacity with respect to the increase in the number of antennas has also been investigated. The obtained results show that the more transmit antennas used in FuHaDu strategy translates to the higher channel capacity achieved.

Furthermore, the spectral performance test results depicted in Figures 5, 7, and 8 demonstrate the superiority of the FuHaDu strategy against separate FD and HD strategies provided in existing literature. Such performance is attributed to the (i) exploitation of the functional benefits of hybridising the FD and HD MIMO channels in order to resolve interuser and self-interference problems as well as (ii) exploitation of a relative fast convergence nonlinear optimisation technique (i.e., Rosen's gradient projection method) in order to lower the computational complexity.

It is left for further work emanating from this study to undertake an in-depth robustness analysis of the FuHaDu as compared to the entirely FD strategies and also to apply the joint FuHaDu strategy to the next generation multitier based cellular systems such as the 5G, whereby the complex interference evolutions will include cochannel and intertier channels in addition to the self-interference and interuser interference of the joint FuHaDu communication modes.

Appendix

The expressions for determining the WSR transmit filters $U^b_{\mathrm{FD}i}$ and $U^b_{\mathrm{HD}i}$ can be extended as follows:

$$\begin{aligned} U^b_{\mathrm{FD}i} &= \alpha_{\mathrm{FD}i}\overline{U}^b_{\mathrm{FD}i}, \\ U^b_{\mathrm{HD}i} &= \alpha_{\mathrm{HD}i}\overline{U}^{1,2}_{\mathrm{HD}i}, \end{aligned} \tag{A.1}$$

respectively.

Here, the squares of the scaling parameters $\alpha_{\mathrm{FD}i}$ and $\alpha_{\mathrm{HD}i}$ are directly proportional to the total power P_T and are defined as

$$\alpha_{\mathrm{FD}i} = \sqrt{\frac{P_T}{\sum_{i=1}^{k}\sum_{b=1}^{2} \operatorname{tr}\left\{\overline{U}_{\mathrm{FD}i}^{b}\left(\overline{U}_{\mathrm{FD}i}^{b}\right)^{H}\right\}}},$$
$$\alpha_{\mathrm{HD}i} = \sqrt{\frac{P_T}{\sum_{i=1}^{k} \operatorname{tr}\left\{\overline{U}_{\mathrm{HD}i}^{1,2}\left(\overline{U}_{\mathrm{HD}i}^{1,2}\right)^{H}\right\}}} \tag{A.2}$$

and the unweighted transmit filter on the full-duplex links $\overline{U}_{\mathrm{FD}i}^{b}$ is obtained as

$$\overline{U}_{\mathrm{FD}i}^{b} = \sqrt{\rho_i}\left(X_{\mathrm{FD}i}^{(b)} + \frac{\sum_{i=1}^{K}\sum_{a=2}^{K} \operatorname{tr}\left\{B_{\mathrm{FD}i}^{(a)}\right\}}{P_T} I_{N_i}\right)^{-1} \cdot \left(H_{ii}^{(ab)}\right)^{H}\left(\mathrm{Rx}_{\mathrm{FD}i}^{(a)}\right)^{H} W_i^{(a)}, \tag{A.3}$$

where $\mathrm{Rx}_{\mathrm{FD}i}^{(a)}$ is the minimum mean squared error (MMSE) receiver filter applied at node $i^{(a)}$ on the full-duplex link i and computed as

$$\mathrm{Rx}_{\mathrm{FD}i}^{(a)} = \sqrt{\rho_i}\left(U_{\mathrm{FD}i}^{b}\right)^{H}\left(U_{\mathrm{FD}i}^{b}\right)^{H}\left(H_{ii}^{(ab)}\right)^{H} \cdot \left(\rho_i H_{ii}^{(ab)} U_{\mathrm{FD}i}^{b}\left(U_{\mathrm{FD}i}^{b}\right)^{H}\left(H_{ii}^{(ab)}\right)^{H} + \sum_{\mathrm{FD}i}^{(a)}\right)^{-1}, \tag{A.4}$$

where $B_{\mathrm{FD}i}^{(a)} = (\mathrm{Rx}_{\mathrm{FD}i}^{(a)})^{H} W_i^{(a)} \mathrm{Rx}_{\mathrm{FD}i}^{(a)}$ and $X_{\mathrm{FD}i}^{(b)}$ is the signal received at node b on a full-duplex link i as a result of a transmission from another node a on the same full-duplex link i.

Similarly, the unweighted transmit filter on the half-duplex links $\overline{U}_{\mathrm{HD}i}^{b}$ is obtained as follows:

$$\overline{U}_{\mathrm{HD}i}^{b} = \sqrt{\rho_i}\left(X_{\mathrm{HD}i}^{(b)} + \frac{\sum_{i=1}^{K} \operatorname{tr}\left\{B_{\mathrm{HD}i}^{(1,2)}\right\}}{P_T} I_{N_i}\right)^{-1} \cdot \left(H_{ii}^{(ab)}\right)^{H}\left(\mathrm{Rx}_{\mathrm{HD}i}^{(1,2)}\right)^{H} W_i^{(1,2)}. \tag{A.5}$$

Here, $\mathrm{Rx}_{\mathrm{HD}i}^{(1,2)}$ is the minimum mean squared error (MMSE) receiver filter applied at node $i^{(1,2)}$ on the full-duplex link i either transmitting (1) or receiving (2) and computed as

$$\mathrm{Rx}_{\mathrm{HD}i}^{(1,2)} = \sqrt{\rho_i}\left(U_{\mathrm{HD}i}^{b}\right)^{H}\left(U_{\mathrm{FD}i}^{b}\right)^{H}\left(H_{ii}^{(ab)}\right)^{H} \cdot \left(\rho_i H_{ii}^{(ab)} U_{\mathrm{HD}i}^{b} {U_{\mathrm{FD}i}^{b}}^{H}\left(H_{ii}^{(ab)}\right)^{H} + \sum_{\mathrm{HD}i}^{(1,2)}\right)^{-1}, \tag{A.6}$$

where $B_{\mathrm{HD}i}^{(1,2)} = (\mathrm{Rx}_{\mathrm{HD}i}^{(1,2)})^{H} W_i^{(1,2)} \mathrm{Rx}_{\mathrm{HD}i}^{(1,2)}$ and $X_{\mathrm{HD}i}^{(b)}$ is the signal received at node b on a half-duplex link i as a result of a transmission from another node a on the same half-duplex link i.

Further details on the derivation of (A.3) and (A.5) by using the *complementary slackness conditions* of the optimisation problem in (16) on the gradient of the Lagrangian function (matrix of partial first derivatives of the Lagrangian function with respect to *alpha*), $\overline{U}_{\mathrm{FD}i}^{b}$, and $\overline{U}_{\mathrm{HD}i}^{b}$ are provided in [3].

Abbreviations

A^H:	The complex conjugate of a matrix A throughout the modelling process
a:	The transmitting node
b:	The receiving antenna
i:	i_{th} link
HD:	Half-duplex
FD:	Full-duplex
FuHaDu:	Full- and half-duplex.

Competing Interests

The authors declare that they have no competing interests.

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