Full-Duplex Transmission Optimization for Bi-directional MIMO links with QoS Guarantees

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Abstract—We consider a bi-directional Full-Duplex (FD) Multiple-Input Multiple-Output (MIMO) communication system in which nodes are capable of performing transmitter (TX)-Receiver (RX) digital precoding/combining and multi-tap analog cancellation, and have individual Signal-to-Interference-plus-noise Ratio (SINR) requirements. We present an iterative algorithm for the TX powers minimization that includes closed-form expressions for the TX/RX digital beamformers at each algorithmic iteration step. Our representative simulation results demonstrate that the proposed algorithm can reduce residual Self-Interference (SI) due to FD operation to below $-110$ dB, which is the typical noise floor level for wireless communications. In addition, our design outperforms relevant recent solutions proposed for 2-user MIMO systems (the so called MIMO X channel) in terms of both power efficiency and computational complexity.

Index Terms—Full-duplex MIMO, Beamforming (BF), self-interference cancellation, power minimization, optimization.

I. INTRODUCTION

Motivated by the exponentially increasing demand for higher information rate under limited wireless resources, and propelled by recent advances in radio frequency (RF) hardware, in-band Full-Duplex (FD) radio has emerged as a key technology for future wireless applications from fifth generation (5G) mobile communication systems to Internet of Things (IoT) [1]–[3].

Practical communication in FD mode requires dedicated solutions to mitigate the Self-Interference (SI) caused by leakage of TX signals into the Receiver (RX) chain, due to the close proximity between transmitter (TX) and RX antennas [4], [5]. Ironing out this fundamental issue of FD technology is one of the main research topics in this field, motivating various authors to contribute with several SI cancellation techniques for FD systems [1], [6]–[8].

Thanks to the added Degrees of Freedom (DoF) afforded by multiple antennas, bi-directional FD radio systems with high spectral efficiency can be designed exploiting MIMO technology [9]–[12]. In particular, hybrid MIMO SI suppressing techniques combining analog and digital cancellers have been proposed for FD radios [13]–[16] which proved very effective from a theoretical standpoint. From a practical implementation standpoint, however, it has been recently demonstrated in real-world experiments that such MIMO approaches are not devoid of its own technical challenges [1], [17], [18], one of which is the excessive cost incurred by the use of large numbers of antennas.

One approach to keep the hardware cost of hybrid MIMO SI suppressing techniques for FD radios under control is to reduce the number of antennas while introducing temporal DoFs by means of Tap Delay Line (TDL) processing in order to maintain the DoF required to achieve the desired performance [19]. In [19], for instance, a joint hybrid TX-RX BF design with limited hardware costs was proposed, in which the sum rate of a system with one MIMO TX-RX BF communicating with two MIMO Half-Duplex (HD) nodes was optimized.

In this paper, we contribute to the area of effective and feasible SI canceller designs for MIMO FD radios as follows. First, we combine the joint hybrid TX-RX approach of [19] with the analog cancellation technique referred to as multi-tap analog canceller previously presented in [20]. The result is a new multi-tap hybrid (analog and digital) TX-RX MIMO FD SI cancellation scheme, in which the number of hardware components for analog cancellation becomes independent of the number of antennas. Secondly, instead of maximizing the sum rate (which is of less practical interest), we formulate our problem to minimize the TX power while guaranteeing (when possible) prescribed Quality of Service (QoS) targets defined in terms of maximum Signal-to-Interference-plus-noise Ratio (SINR). Thirdly and finally, we present a low-complexity solution to the latter problem in which the TX employs Maximum Ratio Transmission (MRT) with powers optimized in closed-form via a Perron-Frobenius (PF) method, while the RX maximizes the SINR by computing corresponding closed-form RX BF vectors from a Rayleigh Quotient (RQ), iteratively. Our results show that our algorithm can outperform the similar methods previously proposed for 2-user MIMO systems in terms of both power efficiency and computational complexity.

II. SYSTEM MODEL

Consider the two-way FD MIMO communication system illustrated in Figure 1. This system consists of two node in which each equipped with $M$ TX and $N$ receive antennas. Both nodes are assumed to TX and receive simultaneously to/from one another in the same resource unit.
A generic $k$-th node, with $k \in \{1, 2\}$, is assumed to employ the digital TX precoding vector $v_k \in \mathbb{C}^{M \times 1}$ and the digital RX BF vector $u_k \in \mathbb{C}^{1 \times N}$, as well as the multi-tap analog cancellation matrix $C_k \in \mathbb{C}^{N \times M}$ [19], [20]. It is capable of performing TX-RX digital BF and analog SI cancellation with the aim at suppressing SI and maximizing rate simultaneously. Finally, in order to model practical limitations, it is assumed that the TXted signal at the $k$-th node has a power upper bound, such that $\text{Tr} (v_k^H v_k^H) = P_k \leq P_{\text{max}}$. Referring to Figure 1, let $H_k \in \mathbb{C}^{N \times M}$ and $H_{kk} \in \mathbb{C}^{N \times M}$ be the intended channel matrix between the two nodes and the SI channel matrix at the $k$-th node, respectively, with $k \neq \ell \in \{1, 2\}$. It is also assumed throughout this paper that each node has full knowledge of the Channel State Information (CSI) of both the communication links and their own SI link. Extension to imperfect CSI knowledge is left for future work.

From all the above, the received signal at the $k$-th node after applying analog SI cancellation can be written as

$$y_k = H_{\ell k} v_\ell s_\ell + (H_{kk} - C_k) v_k s_k + n_k \quad (1)$$

where the multi-tap analog cancellation matrix $C_k$ consists of $N_{\text{tap}}$ non-zero components and $M N - N_{\text{tap}}$ zeros, $n_k \sim \mathcal{C}\mathcal{N}(0, \sigma^2 I_N)$ denotes the complex Additive White Gaussian Noise (AWGN) vector under the assumption that $n_k$ is independent from the TXted signal $s_k$, and $H_{kk} \triangleq H_{kk} - C_k$ is the SI channel matrix after performing the considered analog cancellation.

After digital down conversion and combining by the RX BF vector $u_k$, the estimated signal $\hat{s}_\ell$ corresponding to the intended signal $s_\ell$ at the $k$-th node can be expressed as

$$\hat{s}_\ell = u_k y_k = u_k H_{\ell k} v_\ell s_\ell + u_k H_{kk} v_k s_k + u_k n_k \quad (2)$$

Similarly, the received signal and symbol estimate at node $\ell \neq k$ after analog cancellation and RX BF are given, respectively, by

$$y_\ell = H_{\ell k} v_k s_k + H_{\ell \ell} v_\ell s_\ell + n_\ell, \quad (3)$$

$$\hat{s}_k = u_\ell y_\ell = u_\ell H_{\ell k} v_k s_k + u_\ell H_{\ell \ell} v_\ell s_\ell + u_\ell n_\ell \quad (4)$$

where $n_\ell \sim \mathcal{C}\mathcal{N}(0, \sigma^2 I_N)$ is the AWGN vector that is assumed independent from the TXted symbol $s_k$.

Assuming that unit power information signals $s_k$ and $s_\ell$ are used, the average SINR estimates at the two nodes in Figure 1 can be, respectively, written as

$$\gamma_k = \frac{|u_k H_{\ell k} v_\ell|^2}{|u_k H_{kk} v_k|^2 + \sigma^2} \quad \text{and} \quad \gamma_\ell = \frac{|u_\ell H_{\ell k} v_\ell|^2}{|u_\ell H_{\ell \ell} v_\ell|^2 + \sigma^2}, \quad (5)$$

where we assume that the channel matrices in equation (5) are constant for a number of signal transmissions and the RX combining vector $u_k, \forall k$ has a unit norm, i.e., $|u_k|^2 = 1$.

### III. QoS-Guaranteed Transmissions

Signal processing techniques for the joint TX-RX linear precoding/combining and adaptive TX power allocation with the aim of maximizing data rate while suppressing the residual SI power level have been proposed in the past [21], [22] demonstrating the feasibility of two-way FD MIMO systems.

Maximizing data rate is, however, not typically required by actual users, which instead tend to perceive the quality of a communication system by comparing it to a given level of expectation dictated by the intended application. We therefore consider instead the TX-RX beamformer optimization problem aiming at minimizing the individual TX powers while satisfying individual target SINR requirements:

$$\min_{v_k, v_\ell} \quad \sum_{k=1}^{2} ||v_k||^2 \quad \text{s.t.} \quad \gamma_k \geq \Gamma_k \quad \forall k, \quad (6a)$$

$$\min_{P_1, P_2} \quad \sum_{k=1}^{2} P_k \quad \text{s.t.} \quad \gamma_k \geq \Gamma_k \quad \forall k. \quad (7b)$$

The optimization problem described by equation (7) is well-known to be non convex due to the SINR constraints [23], although approximate solutions can be obtained for it with basis on convex optimization algorithms, such as interior point methods if the constraint can be convexified [24]. In addition to the losses due to convex relaxation, such solutions tend also to be computationally demanding. Therefore, we propose instead a low complexity alternating minimization method based on closed-form expressions of the optimal TX powers $P_1$ and $P_2$.

In order to obtain the desired closed-form expressions for $P_1$ and $P_2$, notice that from equation (5) and (7) we readily obtain

$$P_2 |u_1 H_{21} \bar{v}_2|^2 \geq \Gamma_1 \left( P_1 |u_1 \tilde{H}_{11} \bar{v}_1|^2 + \sigma^2 \right), \quad (8a)$$

$$P_1 |u_2 H_{12} \bar{v}_1|^2 \geq \Gamma_2 \left( P_2 |u_2 \tilde{H}_{22} \bar{v}_2|^2 + \sigma^2 \right). \quad (8b)$$
The latter inequalities can be re-expressed in matrix form as:

\[(I - \Gamma M)p \geq \sigma^2 \Gamma m,\]

where we define the TX power vector \(p \triangleq [P_1, P_2]^T\) and the auxiliary matrices \(\Gamma, M\) and \(m\) respectively by:

\[
\Gamma = \begin{bmatrix}
0 & \Gamma_2 \\
\Gamma_1 & 0
\end{bmatrix},
\]

\[
M = \begin{bmatrix}
u_1 H_{11} \bar{v}_1^2 & 0 \\
u_1 H_{21} \bar{v}_1^2 & 0
\end{bmatrix},
\]

\[
m = \begin{bmatrix}
u_1 H_{21} \bar{v}_2 \nu_1 H_{21} \bar{v}_2 & 0
\end{bmatrix}^T.
\]

Taking advantage of the PF theorem [25] and the fact that \(\Gamma M\) is a non-negative matrix, the optimal TX power vector \(p^*\) can be computed in closed form as:

\[p^* = \sigma^2 (I - \Gamma M)^{-1} \Gamma m.\]

### B. Optimal BF Design for SINR Maximization

With possession of a closed-form optimal solution to the TX power vector \(p\) as per equation (11), as well as given analog cancellation matrix \(C_k\) for each node as discussed in [19], [22], we seek optimal BF designs for \(v_k\) and \(u_k\) for each node, such that the average SINR at each node is maximized, while minimizing the effect of the SI. Taking into account the fact that the role of TX-RX beamformers is to minimize the effect of SI while maximizing the downlink rate, we consider the MRT TX beamformer with perfect CSI known at the nodes, such that the instantaneous SINR at each node is maximized under the assumption that the SI power level can be significantly reduced after processing by the proposed optimal RX combiner.

1) Design of RX Combiner \(u_k\) for \(k\):

The role of the RX combining vector \(u_k\) at the \(k\)-th node is to maximize the power of the signal from the \(k\)-th node, while suppressing the interference-plus-noise signal. In other words, the RX BF vector \(u_k\) must be designed so as to maximize the ratio between the power of the intended signal and that of interference-plus-noise term of equation (2), which can be mathematically expressed as:

\[
\max_{\|u_k\|^2 = 1} \frac{\Delta Q_{u_k}}{\|u_k \| H_{kk} v_k \nu_k^H H_{kk}^H u_k^H + \sigma^2 I} u_k^H \equiv w_{u_k}.
\]

which holds a generalized RQ structure, such that the optimal solution to \(u_k\) is obtained by [26]

\[u_k^* = \text{eig}_{\text{max}} \left(W_{u_k}^{-1} Q_{u_k}\right)^H.
\]
For the modeling practical situations, the multi-tap analog canceller is assumed to be subjected to amplitude imperfection uniformly distributed between $-100$ dB and 0.01dB and phase noise uniformly distributed between $-0.065^\circ$ and $0.065^\circ$ [19], [20].

In all figures that follow, we compare the proposed TX power minimization method in Algorithm 1 with 100 maximum iterations against the conventional Zero-Forcing (ZF) TX precoder, in which the proposed PF power optimization is applied. In addition, by noticing that the considered bi-directional FD MIMO corresponds to a special form of the MIMO X channel, we deploy relevant algorithms [28]–[30] targeting at TX-RX BF design yielding sum rate maximization. Particularly, our considered system is a MIMO X channel having $H_{21}$ and $H_{12}$ as the intended channels and $H_{11}$ and $H_{22}$ as the interference channels, having possibly larger powers than the intended ones.

**TABLE I: Run time comparisons for different methods.**

| Methods   | ZF  | RQ-RQ | Rec | Proposed |
|-----------|-----|-------|-----|----------|
| Average run time [s] | 0.0025 | 0.0028 | 0.1309 | 0.0022 |

First, average TX power comparisons of the proposed algorithm for different target rates $\log_2(1 + \Gamma_k)/k$ is shown in Figure 2, where ZF-RQ, RQ-RQ [30] and the Reconfigurable sum rate maximization algorithm [28] are employed as a benchmark. In order to fairly compare those algorithms, we adopt an alternating recalculation between TX-RX BF for each algorithms until convergence or maximum number of iterations reached. It is shown in Figure 2 that the proposed method can decrease the TX power by about $-4.5$dB compared to the conventional ZF-RQ, RQ-RQ methods and about $-0.8$dB compared against the Reconfigurable method.

Secondly, Figure 3 outlines that the interference cancellation performance in terms of residual SI power levels after processing by the RX BF are compared for the different TX-RX BF schemes. From Figure 2 and 3, one can notice that although the ZF method can perfectly suppress the effect of SI at the RX baseband, the proposed method can outperform the other schemes due to the fact that not only the residual SI level of the proposed method is suppressed below the noise floor level but also it aims at maximizing the data rate performance. In other words, the other methods devote too much available DoFs to suppressing SI power level at the RX baseband.

Thirdly, the TX power outage probability of the proposed method for different available TX powers $P_{\text{max}}$ with target data rate fixed at $R_k = R_\ell = 8$ [bps/Hz] is compared with the outage performance of the other conventional methods in Figure 4, where we define the TX power outage probability as $P(\min(P_k, P_\ell) > P_{\text{max}})$. Lastly, the average run time comparisons until the convergence for each different algorithms are depicted in TABLE I, where we take an average from 500 channel realizations. From Figure 2, 3 and 4 and Table I, it can be observed that the proposed method can has much fast convergence rate compared with the Reconfigurable method and outperform the conventional ZF and RQ TX BF methods in terms of the TX power outage probability performance.

**V. Conclusion**

In this paper, we considered bi-directional FD MIMO communications systems with limited number of analog canceller taps and designed TX-RX BF vectors with the goal to minimize TX power under SINR constraints. The proposed TX power minimization BF design was investigated in terms of system performance and complexity, and the PF TX power minimization approach was jointly offered with the proposed beamformers. Simulation results demonstrate the capability of our proposed algorithm to suppress the SI level to below $-110$dB which is the typical noise floor for wireless communications, while maximizing the downlink rate, and consequently, it minimizes the average TX power for different target data rate.

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