# Reducing Self-interference in Full Duplex Transmission by Interference Exploitation

Mahmoud T. Kabir, Muhammad R. A. Khandaker, and Christos Masouros
Dept. of Electronic and Electrical Engineering
University College London,
Gower Street, London, WC1E 7JE, United Kingdom
Email: kabir.tukur.15@ucl.ac.uk, m.khandaker@ucl.ac.uk, c.masouros@ucl.ac.uk

***Abstract*—In this paper, we consider the power minimization problem in a multi-user full-duplex communication system by employing a multi-objective optimization problem via the weighted Tchebycheff method. We propose to exploit the multi-user interference by using the knowledge of the data symbols and channel state information at the full-duplex base station. Simulation results show that significant power savings can be obtained, which leads to substantial reduction of the self-interference power in the full-duplex systems.**

## I. Introduction

The rapid growth and continuous need for improved spectrum-efficiency in wireless links has brought FD at the forefront of research attention. By allowing simultaneous transmission and reception, FD has the potential to drastically improve the spectral efficiency of the HD communication networks [1], [2].

The major challenge in FD communication systems is the strong loop-back self-interference (SI) that exists from the transmit antennas to the receive antennas of the wireless transceiver. Several self-interference cancellation techniques have been proposed in the literature [1], [3], [4] and [5]. [6] presented an experiment-based characterization of passive suppression and active SI cancellation mechanisms in FD systems. The authors characterization of total and individual cancellation mechanisms, based on extensive experimentation shows that a total average cancellation of 74dB can be achieved. In [7], a digital SI cancellation technique was proposed that could mitigate the SI to ∽3dB higher than the receiver noise floor, which results in up to 76% rate improvement compared to conventional half-duplex systems at 20dBm transmit power values. Overall, with the above mentioned literature, we can observe that the SI cannot be completely cancelled in FD systems [3], [7].

Many of the works on FD build upon existing beamforming solutions in the literature, that have been extensively developed for the downlink channel. Several optimization based beamforming designs have been proposed in the literature subject to quality-of-service constraints [8]. Interference exploitation (IE) was first introduced in the realm of CDMA in [9], [10]. In [11] and [12], it was shown that with the knowledge of the users' data symbols and the CSI, the interference can be classified into constructive and destructive interference. The authors extended their work in [13], [14] showing that tremendous gains can be achieved by exploiting the constructive interference based on symbol level optimization for PSK modulation and for QAM modulation in [15]. Accordingly, IE has been extended to multiple scenarios including cognitive radio, and massive MIMO amongst others [16]–[19]. However, these findings are all based on MISO HD systems.

Recently, a considerable number of work have focused on power efficiency and green communications owing to the global initiative to reduce $CO_2$ emissions of communication systems and also due to the rapidly increasing cost of energy [13], [20]–[23]. The authors in [22] investigated the power efficient resource allocation for a MU-MIMO FD system. They proposed a multi-objective optimization problem (MOOP) to study the total uplink and downlink transmit power minimization problems jointly via the weighed Tchebycheff method. They extended their work to a robust and secure FD systems model in the presence of roaming users (eavesdroppers) in [23]. Accordingly, in this work we aim to further reduce the power consumption in FD MU-MIMO wireless communication systems by adopting the concept of constructive interference in the literature to the downlink channel for generic PSK modulation. Constructive interference is yet to be explored in the realm of FD communication systems, where FD brings unique opportunities to be explored with respect to existing works on IE. By exploiting interference constructively, useful signal power from interference, we can provide a truly power efficient resource allocation for a FD MU-MIMO system and this presents us with the unique opportunity to significantly reduce the strong loop-back SI in the FD system.

## II. System Model

We consider a FD multiuser communication system as shown in Fig. 1. The system consists of a FD radio BS with $N$ antennas serving $K$ HD downlink users and $J$ HD uplink users. Each user is equipped with a single antenna to reduce hardware complexity. Let $\mathbf{h}_i \in \mathbb{C}^{N\times 1}$ be the channel vector between the FD radio BS and the *i-th* downlink user, and $\mathbf{f}_j \in \mathbb{C}^{N\times 1}$ be the channel vector between the FD radio BS and the *j-th* uplink user. We denote the transmit signal vector from the FD radio BS to the *i-th* downlink user as

$$\mathbf{t}_i = \mathbf{w}_i d_i, \tag{1}$$

where $\mathbf{w}_i \in \mathbb{C}^{N\times 1}$ and $d_i$ denote the beamforming vector and the unit data symbol for the *i-th* downlink user, respectively.

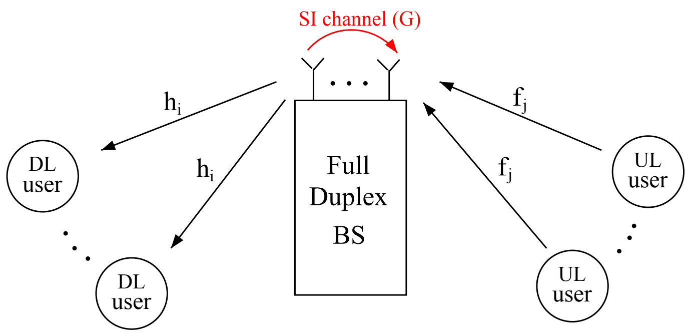


Fig. 1. System model with a FD radio BS with $N$ antennas, $K$ HD downlink users and $J$ HD uplink users.

The received signal at the *i-th* downlink user is:

$$y_i = \underbrace{\mathbf{h}_i^H \mathbf{t}_i}_{\text{desired signal}} + \underbrace{\sum_{k\neq i}^{K} \mathbf{h}_i^H \mathbf{t}_k + n_i}_{\text{interference plus noise}}, \tag{2}$$

where $n_i \sim \mathcal{CN}\left(0, \sigma_i^2\right)$ represents the additive white Gaussian noise AWGN at the *i-th* downlink user. For each time slot the FD radio BS transmits $K$ independent unit data symbols $d$ simultaneously at the same frequency to the $K$ downlink users. The first term in (2) represents the desired signal while the second term is the multiuser interference signal. The received signal from the $J$ uplink users at the FD radio BS is:

$$\mathbf{y}^{BS} = \sum_{j=1}^{J} \sqrt{P}_j \mathbf{f}_j x_j + \underbrace{\mathbf{G}\sum_{k=1}^{K} \mathbf{t}_k}_{\text{residual self-interference}} + \mathbf{z}, \tag{3}$$

where $P_j$ and $x_j$ denotes the uplink transmit power and the data symbol from the *j-th* uplink user, respectively. The vector $\mathbf{z} \sim \mathcal{CN}(0, \sigma_N^2)$ represents the additive white Gaussian noise AWGN at the FD radio BS. The matrix $\mathbf{G} \in \mathbb{C}^{N\times N}$ denotes the self-interference (SI) channel at the FD radio BS. In the literature, different SI mitigation techniques have been proposed [3], [4] to reduce the effect of self-interference. In order to isolate our proposed scheme from the specific implementation of a SI mitigation technique, since the SI cannot be cancelled perfectly in FD systems due to limited dynamic range at the receiver even if the SI channel is known perfectly [3], [23], we model the residual SI after cancellation as $\left(\mathbf{G}\sum_{k=1}^{K} \mathbf{t}_k\right)$ as in [22], [23]. Accordingly, the first term of (3) represents the desired signal from the *j-th* uplink user and the second term represents the residual SI.

Before we formulate the problem, we first define the signal-to-interference ratio (SINR) at the *i-th* downlink user and at the FD radio BS respectively as

$$\text{SINR}_i^{DL} = \frac{\mid \mathbf{h}_i^H \mathbf{w}_i \mid^2}{\sum_{k\neq i}^{K} \mid \mathbf{h}_i^H \mathbf{w}_k \mid^2 + \sigma_i^2}, \tag{4}$$

$$\text{SINR}_j^{UL} = \frac{P_j \mid \mathbf{f}_j^H \mathbf{u}_j \mid^2}{\sum_{n\neq j}^{J} P_n \mid \mathbf{f}_n^H \mathbf{u}_j \mid^2 + \sum_{k=1}^{K} \mid \mathbf{u}_j^H \mathbf{G}\mathbf{w}_k \mid^2 + \sigma_N^2 \|\mathbf{u}_j\|^2}, \tag{5}$$

where $\mathbf{u}_j \in^{N\times 1}$ is the receive beamforming vector for detecting the received symbol from the *j-th* uplink user. To reduce complexity, we assume a zero-forcing receiver at the BS. Hence, the receive beamformer for the *j-th* uplink user is given as

$$\mathbf{u}_j = (\mathbf{r}_j \mathbf{F}^{\dagger})^H, \tag{6}$$

where $\mathbf{r}_j = [\underbrace{0,\ldots,0}_{j-1},1,\underbrace{0,\ldots,0}_{J-j}]$, $\mathbf{F}^{\dagger} = (\mathbf{F}^H\mathbf{F})^{-1}\mathbf{F}^H$,$^{\dagger}$ denotes the pseudo-inverse operation and $\mathbf{F} = [\mathbf{f}_1, \ldots, \mathbf{f}_J]$.

## III. Conventional Power Minimization Problem

In this section, we study the conventional power minimization (PM) problem where all the interference are treated as undesired signals. We first formulate the downlink and uplink power minimization problems, which aim to minimize the total downlink and uplink transmit power, respectively, subject to the downlink users SINR and uplink users SINR. Then we formulate a multi-objective PM problem that aims to investigate the two system's objectives (downlink and uplink) jointly.

*Problem 1: Total Downlink Transmit PM Problem*

The downlink PM problem for FD optimization is typically formulated as [22], [23]:

$$\begin{aligned} \mathcal{P}1: \quad & \min_{\mathbf{w}_i, P_j} \quad \sum_{i=1}^{K} \|\mathbf{w}_i\|^2 \\ \text{s.t.} \quad & A1: \frac{\mid \mathbf{h}_i^H \mathbf{w}_i \mid^2}{\sum_{k\neq i}^{K} \mid \mathbf{h}_i^H \mathbf{w}_k \mid^2 + \sigma_i^2} \geq \Gamma_i^{DL}, \forall i, \\ & A2: \frac{P_j \mid \mathbf{f}_j^H \mathbf{u}_j \mid^2}{I_j + \sigma_N^2 \|\mathbf{u}_j\|^2} \geq \Gamma_j^{UL}, \forall j, \end{aligned} \tag{7}$$

where, $I_j = \sum_{n\neq j}^{J} P_n \mid \mathbf{f}_n^H \mathbf{u}_j \mid^2 + \sum_{k=1}^{K} \mid \mathbf{u}_j^H \mathbf{G}\mathbf{w}_k \mid^2$, we define $\Gamma_i^{DL}$ and $\Gamma_j^{UL}$ as the minimum required SINRs for the *i-th* downlink user and the *j-th* uplink user, respectively. This problem aims to minimize the total downlink transmit power with no regards to the consumed uplink transmit power. This problem is non-convex and it is commonly solved via semidefinite relaxation as in [22], [23].

*Problem 2: Total Uplink Transmit PM Problem*

The uplink PM problem for FD optimization is typically formulated as [22], [23]:

$$\begin{aligned} \mathcal{P}2: \quad & \min_{\mathbf{w}_i, P_j} \quad \sum_{j=1}^{J} P_j \\ \text{s.t.} \quad & A1: \frac{\mid \mathbf{h}_i^H \mathbf{w}_i \mid^2}{\sum_{k\neq i}^{K} \mid \mathbf{h}_i^H \mathbf{w}_k \mid^2 + \sigma_i^2} \geq \Gamma_i^{DL}, \forall i, \\ & A2: \frac{P_j \mid \mathbf{f}_j^H \mathbf{u}_j \mid^2}{I_j + \sigma_N^2 \|\mathbf{u}_j\|^2} \geq \Gamma_j^{UL}, \forall j, \end{aligned} \tag{8}$$

This problem unlike problem $\mathcal{P}1$ aims to minimize the total uplink transmit power with no regards to the consumed downlink transmit power. Problem $\mathcal{P}2$ is non-convex and it is commonly solved via semidefinite relaxation as in [22], [23].

*Problem 3: Multi-objective PM Problem*

This formulation combines the two objectives of problem $\mathcal{P}1$ and $\mathcal{P}2$ since both objectives are very important to both the users and system operator. The multi-objective optimization is employed when there is need to study jointly the trade-off between two desirable objectives via the concept of Pareto optimality. A point is said to be Pareto optimal if there is no other point that improves any of the objectives without decreasing the others [24]. [24] did a survey of multi-objective optimization methods in engineering. By using the weighted Tchebycheff method [24] which can achieve the complete Pareto optimal set with lower computational complexity, the multi-objective PM problem for FD optimization is typically formulated as [22], [23],

$$\begin{aligned}\mathcal{P}3: \quad & \min_{\mathbf{w}_i, P_j} \max_{a=1,2} \{\lambda_a (Q_a^* - Q_a(\mathbf{w}_i, P_j))\} \\ \text{s.t.} \quad & A1: \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum_{k\neq i}^K |\mathbf{h}_i^H \mathbf{w}_k|^2 + \sigma_i^2} \geq \Gamma_i^{DL}, \forall i, \\ & A2: \frac{P_j |\mathbf{f}_j^H \mathbf{u}_j|^2}{I_j + \sigma_N^2 \|\mathbf{u}_j\|^2} \geq \Gamma_j^{UL}, \forall j,\end{aligned} \tag{9}$$

where $Q_a$ and $Q_a^*$ denote the objective and the optimal objective value of the *a-th* optimization problem, respectively. The variable $\lambda_a \geq 0$, $\sum \lambda_a = 1$, specifies the priority given to the *a-th* objective i.e. for a given $\lambda_1 = 0.8$ means 80% priority is given to the objective of problem $\mathcal{P}1$ and 20% priority to the objective of problem $\mathcal{P}2$. By varying $\lambda_a$ we can obtain the complete Pareto optimal set. Problem $\mathcal{P}3$ is a non-convex problem due to the SINR constraints A1 and A2, and it is commonly solved via semidefinite relaxation as in [22], [23].

## IV. Power Minimization Problem based on Constructive Interference

In this section, we study the PM optimization problems based on constructive interference. With prior knowledge of the CSI and users' data symbols for the downlink users, the instantaneous interference can be exploited rather than suppressed [13]. To be precise, constructive interference is the interference that pushes the received signal further into the detection region of the constellation and away from the detection threshold [13]. This concept has been thoroughly studied in the literature for PSK modulation. We refer the reader to [13], [20] for further details of this topic. Motivated by this idea, here, we apply this concept to the PM problems in Section III for PSK modulation. We note that constructive interference is only applied to the downlink users and not the uplink users following that only the prior knowledge of the CSI and users' data symbols for the downlink users are available at the BS. Nevertheless, we show in the following that power savings can be obtained for both uplink and downlink transmission, by means of the MOOP design.

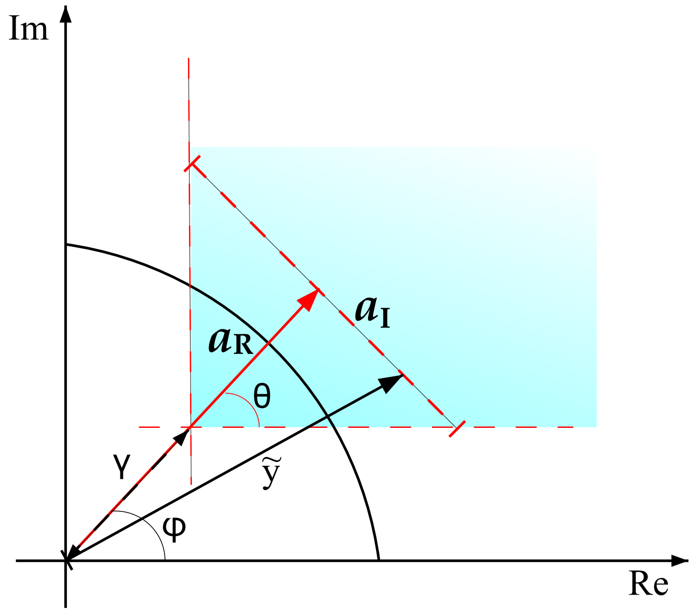


Fig. 2. Constructive interference region for a QPSK constellation point

To illustrate this concept, we provide a geometric illustration of the constructive interference regions for a QPSK constellation in Fig. 2. We can define the total transmit signal vector as

$$\sum_{k=1}^K \mathbf{w}_k d_k = \sum_{k=1}^K \mathbf{w}_k e^{j(\phi_k - \phi_i)} d_i, \tag{10}$$

where $d_i = de^{\phi_i}$ is the desired symbol for the *i-th* downlink user. Therefore, the received signal (2) without noise at the *i-th* downlink user can be defined as

$$\begin{aligned}\widetilde{y}_i &= \mathbf{h}_i^H \sum_{k=1}^K \mathbf{w}_k d_k, & (11)\\ &= \mathbf{h}_i^H \sum_{k=1}^K \mathbf{w}_k e^{j(\phi_k - \phi_i)} d_i. & (12)\end{aligned}$$

Accordingly, since the interference contributes constructively to the received signal, it has been shown in [12] that the downlink SNR at the *i-th* downlink user (4) can be rewritten as

$$SNR_i^{DL} = \frac{\left|\mathbf{h}_i^H \sum_{k=1}^K \mathbf{w}_k d_k\right|^2}{\sigma_i^2}. \tag{13}$$

Without loss of generality, by taking user 1 as reference the instantaneous transmit power for a unit symbol is

$$P_{total} = \left\|\sum_{k=1}^K \mathbf{w}_k e^{j(\phi_k - \phi_1)}\right\|^2. \tag{14}$$

As detailed in [13], the shaded area in Fig. 2 is the region of constructive interference. If the received signal without noise $\widetilde{y}_i$ falls within this region, then interference has been exploited constructively. The angle $\theta = \pm\frac{\pi}{M}$ determines the maximum angle shift of the constructive interference region for a

$$\mathcal{P}4: \quad \min_{\mathbf{w}_k, P_j} \quad \left\|\sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_1)}\right\|^2$$
$$\text{s.t.} \quad B1: \left|Im\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right)\right| \leq \left(Re\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right) - \sqrt{\Gamma_i^{DL}\sigma_i^2}\right)\tan\theta, \forall i, \tag{16}$$
$$B2: \frac{P_j \left|\mathbf{f}_j^H \mathbf{u}_j\right|^2}{\sum_{n\neq j}^{J} P_n \left|\mathbf{f}_n^H \mathbf{u}_j\right|^2 + \sum_{k=1}^{K}\left|\mathbf{u}_j^H \mathbf{G}\mathbf{w}_k e^{j(\phi_k-\phi_1)}\right|^2 + \sigma_N^2\|\mathbf{u}_j\|^2} \geq \Gamma_j^{UL}, \forall j.$$

modulation order $M$, $a_I$ and $a_R$ are the imaginary and real parts of the received signal $\widetilde{y}_i$ without the noise, respectively. The detection threshold is determined by $\gamma = \sqrt{\Gamma_i^{DL}}\sigma_i$.

Therefore, by applying these definitions and basic geometry from Fig. 2 it can be seen that for the received signal to fall in the constructive region of the constellation we need to have $a_I \leq (a_R-\gamma)\tan\theta$. Accordingly, we can define the downlink SINR constraint that guarantees constructive interference at the *i-th* downlink user by

$$\left|Im\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right)\right| \leq \left(Re\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right) - \sqrt{\Gamma_i^{DL}\sigma_i^2}\right)\tan\theta. \tag{15}$$

*1) Total Downlink Transmit PM Problem:* Based on the analysis above, we can modify the SINR constraints for the downlink users to accommodate CI. The optimization problem for the total downlink transmit PM is expressed in $\mathcal{P}4$, where the total downlink transmit power is minimized subject to constraint B1, which guarantees constructive interference for the downlink users for minimum required SINR $\Gamma_i^{DL}$ while the constraint B2 guarantees the minimum required SINR $\Gamma_j^{UL}$ for the uplink users. Unlike its conventional counterpart $\mathcal{P}1$, it can be seen that $\mathcal{P}4$ is convex due to the substitution of the conventional downlink SINR constraint with the CI SNR constraints and can be tackled with standard solvers.

*2) Total Uplink Transmit PM Problem:* On the other hand, we formulate the uplink transmit PM problem by minimizing the total uplink transmit power with no regards to the downlink transmit power.

$$\mathcal{P}5: \min_{\mathbf{w}_i, P_j} \sum_{j=1}^{J} P_j$$
$$\text{s.t.}\ B1: \left|Im\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right)\right| \leq \left(Re\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right) - \sqrt{\Gamma_i^{DL}\sigma_i^2}\right)\tan\theta, \forall i,$$
$$B2: \frac{P_j \left|\mathbf{f}_j^H \mathbf{u}_j\right|^2}{I_j^{PSK} + \sigma_N^2\|\mathbf{u}_j\|^2} \geq \Gamma_j^{UL}, \forall j, \tag{17}$$

where, $I_j^{PSK} = \sum_{n\neq j}^{J} P_n \left|\mathbf{f}_n^H \mathbf{u}_j\right|^2 + \sum_{k=1}^{K}\left|\mathbf{u}_j^H \mathbf{G}\mathbf{w}_k e^{j(\phi_k-\phi_1)}\right|^2$.

Again, it can be seen that the above problem is convex and can be tackled with standard solvers.

*3) Multi-objective PM Problem:* By adapting the downlink SINR constraints in $\mathcal{P}3$, we can further obtain the MOOP for interference exploitation in the FD scenario under study as

$$\mathcal{P}6: \min_{\mathbf{w}_i, P_j, t} \quad t$$
$$\text{s.t.}\ B1: \left|Im\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right)\right| \leq \left(Re\left(\mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k e^{j(\phi_k-\phi_i)}\right) - \sqrt{\Gamma_i^{DL}\sigma_i^2}\right)\tan\theta, \forall i,$$
$$B2: \frac{P_j \left|\mathbf{f}_j^H \mathbf{u}_j\right|^2}{I_j^{PSK} + \sigma_N^2\|\mathbf{u}_j\|^2} \geq \Gamma_j^{UL}, \forall j,$$
$$B3: \lambda_a\left(Q_a^* - Q_a(\mathbf{w}_i, P_j)\right) \leq t, \forall a \in \{1,2\}, \tag{18}$$

where $t$ is an auxiliary variable.

It can be observed that, due to the substitution of the conventional downlink SINR constraint with the CI SNR constraints, this formulation unlike the conventional problem in $\mathcal{P}3$ is convex and thus can be optimally solved using standard convex softwares like CVX [25].

## V. Results

In this section, we investigate the performance of our proposed CI-based MOOP approach through simulations. We model all channels as independent and identically distributed Rayleigh fading. Systems with QPSK and 8PSK modulations are considered while it is clear that the benefit extends to higher order modulation. For comparison in every scenario, we compare the proposed technique, constructive interference (CI) with the conventional case i.e. where interference is treated as harmful signal [22], [23].

### A. Average Transmit Power versus QoS

In Fig. 3, we study the average power consumption of the uplink and downlink users for different minimum required downlink SINR ($\Gamma^{DL}$). We assume a minimum required uplink SINR $\Gamma^{UL} = 0dB$ for all uplink users and we select $\lambda_1 = 0.9$ and $\lambda_2 = 0.1$. It can be observed that both the uplink and downlink power consumption increases with increase in $\Gamma^{DL}$. This is because an increase in the downlink

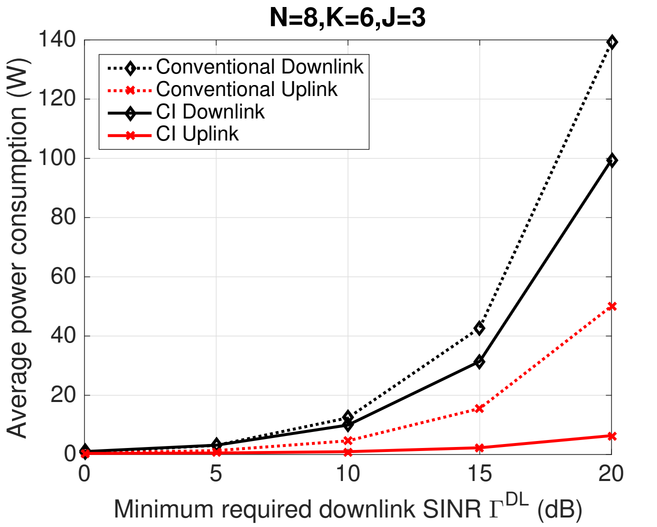


Fig. 3. Average power consumption versus minimum required downlink SINR when $\lambda_1 = 0.9, \lambda_2 = 0.1$ and $\Gamma^{UL} = 0$dB for QPSK modulation

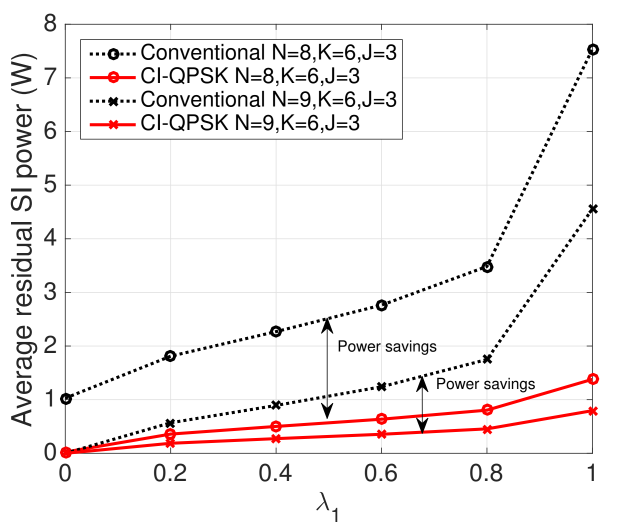


Fig. 4. Average residual SI power versus $\lambda_1$ when $\Gamma^{UL} = 5$dB and $\Gamma^{DL} = 10$dB

SINR requirement translates to increase in downlink transmit power and hence increase in the SI power. Therefore, the uplink users have to transmit with a higher power to meet their QoS requirement ($\Gamma^{UL}$). Besides, power savings of up to 86% can be seen for the uplink users and for the downlink users, power savings of about 28% can be seen, respectively, for the proposed CI approach compared with the conventional approach.

### *B. Residual SI Power*

In addition to the power savings of the proposed approach, we can observe that though CI is applied to only the downlink users, more power savings is achieved by the uplink users. This is because with CI the total downlink transmit power is reduced and this directly reduces the residual SI power at the FD BS. This is shown in Fig. 4, which shows the average residual SI power when $\lambda_1$ is varied from 0 to 1 (remember $\lambda_a$

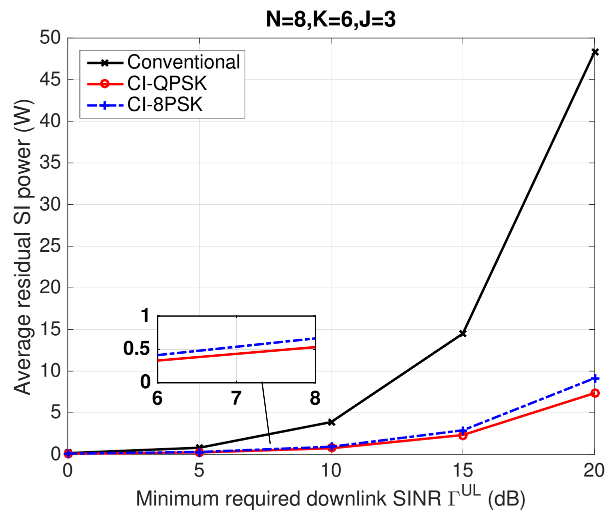


Fig. 5. Average residual SI power versus minimum required downlink SINR when $\lambda_1 = 0.9, \lambda_2 = 0.1$ and $\Gamma^{UL} = 5$dB

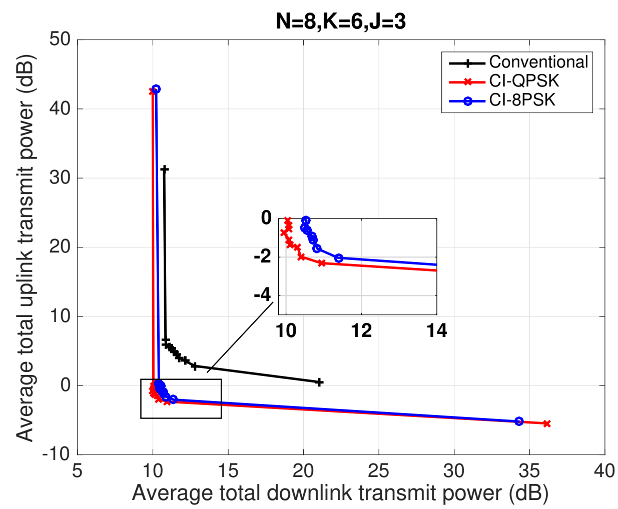


Fig. 6. Average system object trade-off region achieved by the proposed scheme versus the conventional scheme $\Gamma^{UL} = 0$dB and $\Gamma^{DL} = 10$dB

specifies the priority given to the *a-th* objective). Accordingly, we can see a constant increase in power savings as more priority is given to the downlink users and it reaches a maximum at $\lambda_1 = 1$, when 100% of the priority is given to the downlink users. The figure also shows that less power savings is achieved as the number of antennas at the BS is increased.

Furthermore, in Fig. 5, we show how the average residual SI power varies with the downlink QoS constraint ($\Gamma^{DL}$) for $\lambda_1 = 0.9$ and $\lambda_2 = 0.1$ when $\Gamma^{UL} = 5$dB for QPSK and 8PSK modulations. Power savings of up to 82% can be seen. These two results highlight one of the key advantages of the proposed approach over conventional approaches.

### *C. Uplink-Downlink Power Trade-off*

In Fig. 6, we investigate the trade-off between the downlink and uplink total transmit power for the case of $N = 8, K = 6, J = 3$ antennas. The trade-off region is obtained by solving problem $\mathcal{P}3$ and $\mathcal{P}6$ for the conventional and CI case, respectively, for $0 \leq \lambda_a \leq 1, a \in (1, 2)$ with a step size of $0.1$. We assume $\Gamma^{DL} = 10dB$ and $\Gamma^{UL} = 0dB$ for all downlink and uplink users, respectively. It can be seen from the plot that there is a trade-off between the two objectives (downlink and uplink) i.e. an increase in one leads to a decrease in the other and vice versa. Thus, for QPSK modulation, power savings of about 7dB and 2dB can be seen for the uplink and downlink users, respectively. And for 8PSK modulation, we have power savings of about 6dB and 1.8dB for the uplink and downlink users, respectively. This is due to the fact that, with the proposed approach, interference is exploited constructively rather than suppressed as in conventional approaches.

## VI. Conclusion

In this paper, we studied the application of the interference exploitation concept to a multi-user system with a FD radio BS. We formulated a convex Multi-Objective optimization problem (MOOP) via the weighted Tchebycheff method. Simulation results reveal significant power savings compared to the conventional approaches, and most importantly, how our approach leads to substantial reduction in the self-interference power.


## Acknowledgment

The author would like to thank the Federal Republic of Nigeria and the Petroleum Technology Development Fund (PTDF) for funding his PhD.


## References


[1] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," *ACM SIGCOMM Computer Communication Review*, vol. 43, no. 4, pp. 375–386, 2013.

[2] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings of the sixteenth annual international conference on Mobile computing and networking*. ACM, 2010, pp. 1–12.

[3] B. P. Day, A. R. Margetts, D. W. Bliss, and P. Schniter, "Full-duplex mimo relaying: Achievable rates under limited dynamic range," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 8, pp. 1541–1553, 2012.

[4] D. Bharadia and S. Katti, "Full duplex mimo radios," *Self*, vol. 1, no. A2, p. A3, 2014.

[5] T. Riihonen, S. Werner, and R. Wichman, "Mitigation of loopback self-interference in full-duplex mimo relays," *IEEE Transactions on Signal Processing*, vol. 59, no. 12, pp. 5983–5993, 2011.

[6] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Transactions on Wireless Communications*, vol. 11, no. 12, pp. 4296–4307, 2012.

[7] E. Ahmed and A. M. Eltawil, "All-digital self-interference cancellation technique for full-duplex systems," *IEEE Transactions on Wireless Communications*, vol. 14, no. 7, pp. 3519–3532, 2015.

[8] M. Bengtsson and B. Ottersten, "Handbook of antennas in wireless communications," *Optimal and Suboptimal Transmit Beamforming: Boco Raton, FL: CRC*, 2001.

[9] E. Alsusa and C. Masouros, "Adaptive code allocation for interference management on the downlink of ds-cdma systems," *IEEE transactions on Wireless communications*, vol. 7, no. 7, 2008.

[10] C. Masouros and E. Alsusa, "Two-stage transmitter precoding based on data-driven code-hopping and partial zero forcing beamforming for mc-cdma communications," *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, 2009.

[11] ——, "Dynamic linear precoding for the exploitation of known interference in mimo broadcast systems," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1396–1404, 2009.

[12] C. Masouros, "Correlation rotation linear precoding for mimo broadcast communications," *IEEE Transactions on Signal Processing*, vol. 59, no. 1, pp. 252–262, 2011.

[13] C. Masouros and G. Zheng, "Exploiting known interference as green signal power for downlink beamforming optimization," *IEEE Transactions on Signal Processing*, vol. 63, no. 14, pp. 3628–3640, 2015.

[14] C. Masouros, M. Sellathurai, and T. Ratnarajah, "Vector perturbation based on symbol scaling for limited feedback miso downlinks," *IEEE Transactions on Signal Processing*, vol. 62, no. 3, pp. 562–571, 2014.

[15] A. Li and C. Masouros, "Exploiting constructive mutual coupling in p2p mimo by analog-digital phase alignment," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1948–1962, 2017.

[16] F. A. Khan, C. Masouros, and T. Ratnarajah, "Interference-driven linear precoding in multiuser miso downlink cognitive radio network," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 6, pp. 2531–2543, 2012.

[17] P. V. Amadori and C. Masouros, "Constant envelope precoding by interference exploitation in phase shift keying-modulated multiuser transmission," *IEEE Transactions on Wireless Communications*, vol. 16, no. 1, pp. 538–550, 2017.

[18] ——, "Interference-driven antenna selection for massive multiuser mimo," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 8, pp. 5944–5958, 2016.

[19] ——, "Large scale antenna selection and precoding for interference exploitation," *IEEE Transactions on Communications*, 2017.

[20] K. L. Law and C. Masouros, "Constructive interference exploitation for downlink beamforming based on noise robustness and outage probability," in *Acoustics, Speech and Signal Processing (ICASSP), 2016 IEEE International Conference on*. IEEE, 2016, pp. 3291–3295.

[21] M. Alodeh, S. Chatzinotas, and B. Ottersten, "Constructive multiuser interference in symbol level precoding for the miso downlink channel," *IEEE Transactions on Signal processing*, vol. 63, no. 9, pp. 2239–2252, 2015.

[22] Y. Sun, D. W. K. Ng, and R. Schober, "Multi-objective optimization for power efficient full-duplex wireless communication systems," in *Global Communications Conference (GLOBECOM), 2015 IEEE*. IEEE, 2015, pp. 1–6.

[23] Y. Sun, D. W. K. Ng, J. Zhu, and R. Schober, "Multi-objective optimization for robust power efficient and secure full-duplex wireless communication systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 8, pp. 5511–5526, 2016.

[24] R. T. Marler and J. S. Arora, "Survey of multi-objective optimization methods for engineering," *Structural and multidisciplinary optimization*, vol. 26, no. 6, pp. 369–395, 2004.

[25] M. Grant, S. Boyd, and Y. Ye, "Cvx: Matlab software for disciplined convex programming," 2008.