Transceiver Optimization in Full Duplex SWIPT Systems with Physical Layer Security

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Abstract. To meet the requirements of energy saving, high security and high speed for the next generation wireless networks, this paper investigates simultaneous wireless information and power transfer (SWIPT) in full duplex systems taking the physical layer security into account. Specifically, we consider a full duplex wireless system where a full duplex base station (FD-BS) communicates with one downlink user and one uplink user simultaneously, and one idle user also scavenges the radio-frequency (RF) energy broadcasted during the communication for future use. Since the idle user has great potential to intercept the downlink information, we assume that FD-BS exploits the artificial noise (AN), which is another energy source to idle user, to prevent it. The imperfect self-interference cancellation at the FD-BS is considered and the zero forcing (ZF) receiver is adopted to cancel the residual self-interference. Then, the optimal transmitter design at FD-BS are derived to maximize the weighted sum rate of downlink secure and uplink transmission, subject to constraints that the transmission power at FD-BS is restricted and the minimal amount of harvested energy at idle user is guaranteed. The perfect full duplex and half duplex schemes are also introduced for comparison. Extensive simulation results are given to verify the superiority of our proposed full duplex scheme.

Keywords: Full duplex system · SWIPT · Physical layer security · Semidefinite program · Convex optimization

1 Introduction

Recently, with the exponential surge of energy consumption in wireless communication, green communications have received much attention from both industry and academic. As a promising technology towards green communications, harvesting the ambient radio-frequency (RF) energy can prolong the lifetime of energy-constrained wireless networks. More importantly, scavenging energy from the far-field RF signal transmission enables simultaneous wireless information and power transfer (SWIPT) [1]. Typically, there exist fundamental tradeoffs between harvested energy and received information rate. Many works focused

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on downlink SWIPT systems where a transmitter serves two kinds of receivers, i.e., information decoding receivers (IRs) and energy harvesting receivers (ERs). Based on this scenario, joint information beamforming for IRs and energy beamforming for ERs were investigated [2,3]. In particular, to meet the different power sensitivity requirements of energy harvesting (EH) and information decoding (ID) (e.g., $-10\,\text{dBm}$ for EH versus $-60\,\text{dBm}$ for ID), a location-based receiver scheduling scheme was proposed in [3], where ERs need to be closer to the transmitter than IRs. This scheme indeed facilitates the energy harvesting at ERs since they always have better channels due to distance-dependent attenuation.

However, this receiver scheduling scheme may also increase the susceptibility to eavesdropping, because that ERs, the potential eavesdroppers, can more easily overhear the information sent to IRs. In traditional communication networks without energy harvesting, this security issue can be addressed from the physical layer perspective, by transmitting additional artificial noise (AN) to degrade the channel of eavesdroppers [4]. When it comes to downlink SWIPT systems, the power stream for energy supply can naturally serve as AN to prevent eavesdropping. Thus, secure communication in downlink systems with SWIPT was studied [5]. In [5], Liu et al. presented a system secrecy rate maximization problem and a weighted sum-harvested-energy maximization problem via the joint design of information and energy beamforming.

Apart from energy saving and high information security, high information speed is also a main objective of next generation wireless communications. To this end, full duplex, which has the potential to double the system spectral efficiency, has aroused researchers' wide concern. The benefits are intuitively brought by allowing signal transmission and reception at the same time and the same frequency. Recently, the strong self-interference (SI) that full duplex systems suffer from can been greatly suppressed via the effective self-interference cancellation (SIC) techniques, such as antenna separation, analog domain suppression and digital domain suppression [6]. Consequently, a majority of researches on full duplex systems have been investigated, including the re-designed SIC [7] and spectral efficiency analysis [8].

In order to meet the requirements of energy saving, high security as well as high speed for the next generation wireless networks, in this paper, we study full duplex SWIPT systems with the physical layer security. Specifically, we consider a full duplex wireless system where the full duplex base station (FD-BS) communicates with one downlink user and one uplink user simultaneously, and one idle user scavenges the RF energy broadcasted during the communication for future use. Since the idle user has the great potential to intercept the downlink information, we assume that FD-BS exploits the artificial noise (AN), which is another energy source to idle user, to prevent it. Similar to full duplex communication systems [8], the proposed secrecy SWIPT full duplex scenario is also subject to the practical issue of imperfect SIC at the FD-BS. To reduce the computational complexity, the optimal transmitter design with the fixed zero forcing (ZF) receiver at FD-BS are derived to maximize the weighted sum rate of downlink secure and uplink transmission, subject to constraints that the transmission power at FD-BS is restricted and the minimal amount of harvested energy at idle user is guaranteed. The objective function of original non-convex optimization is transformed into a linear fractional form by introducing an non-negative parameter. Then, by applying Charnes-Cooper transformation, semi-definite programming (SDP) and the bi-search method, the optimal parameter as well as optimal transmitter design is achieved. Simulation results are given to verify the superiority of our proposed full duplex scheme.

The remainder of the paper is organized as follows. In Sect. 2, system model and problem formulation are introduced. In Sect. 3 we state the ZF receiver based optimal transmitter optimization. Finally, the simulation results are presented in Sect. 4 before Sect. 5 concludes the paper.

Notation: Bold lower and upper case letters are used to denote column vectors and matrices, respectively. The superscripts $\mathbf{H}^T$, $\mathbf{H}^H$, $\mathbf{H}^{-1}$ are standard transpose, (Hermitian) conjugate transpose and inverse of $\mathbf{H}$, respectively. rank($\mathbf{S}$) and Tr($\mathbf{S}$) denote the rank and trace of matrix $\mathbf{S}$, respectively. $\mathbf{S} \succeq \mathbf{0} (\succ \mathbf{0})$ means that matrix $\mathbf{S}$ is positive semidefinite (positive definite).

2 System Model and Problem Formulation

Considering a full-duplex system where one FD-BS, one uplink user (U_U), one downlink user (U_D) and one idle user (U_I) are included, as illustrated in Fig. 1. The FD-BS concurrently communicates with U_D in the downlink and U_U in the uplink . Meanwhile, the idle user scavenges the RF energy broadcasted during the communication. Assume that FD-BS has $N = N_T + N_R$ antennas, of which N_T are used for downlink transmission and N_R are used for uplink receiving. Other users in the system all have a single antenna due to the hardware limitation. Suppose that FD-BS knows all the channel state information (CSI). The idle user also feedbacks its CSI to FD-BS for the purpose of harvesting more energy.

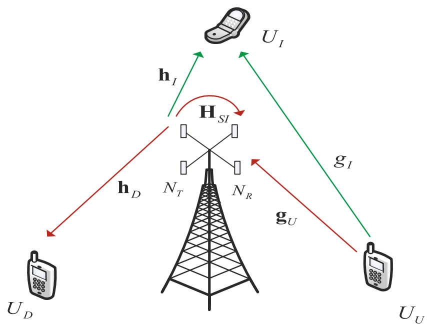

Fig. 1. System Model

In order to facilitate energy harvesting, the idle user is assumed to be deployed in more proximity to the FD-BS than the downlink and uplink user.

Thus, signals transmitted by FD-BS is a dominant part of the signals received at idle user. It becomes more easier for the vicious idle user to eavesdrop the information sent by FD-BS. Consequently, in this paper, we mainly prevent the eavesdropping in the downlink channel.

To prevent the eavesdropping, AN is adopted at FD-BS. The transmit message broadcasted by FD-BS is then given as

$$\mathbf{x}_D = \mathbf{s}_D + \mathbf{v}, \tag{1}$$

where $\mathbf{s}_D \in \mathbb{C}^{N_T \times 1}$ is the useful signal vector for U_D and $\mathbf{s}_D \sim \mathcal{CN}(\mathbf{0}, \mathbf{S})$ with the covariance matrix $\mathbf{S} \succeq \mathbf{0}$. $\mathbf{v} \in \mathbb{C}^{N_T \times 1}$ is the AN vector with $\mathbf{v} \sim \mathcal{CN}(\mathbf{0}, \mathbf{V})$ and $\mathbf{V} \succeq \mathbf{0}$. Note that AN also provides another energy source for the idle user.

The data symbol sent by U_U is $s_U \sim \mathcal{CN}(0, 1)$ and its transmission power is P_U. Hence, denote the message sent by U_U as

$$x_U = \sqrt{P_U} s_U. \tag{2}$$

The observations at U_D and U_I are respectively represented as

$$y_D = \mathbf{h}_D^H \mathbf{s}_D + \mathbf{h}_D^H \mathbf{v} + z_D \tag{3}$$

and

$$y_I = \mathbf{h}_I^H \mathbf{s}_D + \mathbf{h}_I^H \mathbf{v} + \underbrace{g_I x_U}_{UN} + z_I, \tag{4}$$

where $\mathbf{h}_D \in \mathbb{C}^{N_T \times 1}$ and $\mathbf{h}_I \in \mathbb{C}^{N_T \times 1}$ denote the channel vector from FD-BS to U_D and U_I, respectively. g_I represents the complex channel coefficient from U_U to U_I. $z_D \sim \mathcal{CN}(0, \sigma_Z^2)$ and $z_I \sim \mathcal{CN}(0, \sigma_Z^2)$ are the corresponding background noise at U_D and U_I, respectively. In this paper, we assume that the scheduled U_D and U_U are far from each other and thus ignore the co-channel interference (CCI) from U_U to U_D. Note that the third term in (4) also plays as noise to avoid malicious eavesdropping and thus we call it as uplink noise (UN).

The received signal to interference plus noise ratio (SINR) at U_D is given by

$$\gamma_D = \frac{\mathbf{h}_D^H \mathbf{S} \mathbf{h}_D}{\mathbf{h}_D^H \mathbf{V} \mathbf{h}_D + \sigma_Z^2}. \tag{5}$$

The SINR at vicious idle user U_I is given by

$$\gamma_I = \frac{\mathbf{h}_I^H \mathbf{S} \mathbf{h}_I}{\mathbf{h}_I^H \mathbf{V} \mathbf{h}_I + P_U |g_I|^2 + \sigma_Z^2}. \tag{6}$$

Thus, the achievable secrecy rate at downlink user U_D is represented as

$$\begin{aligned} R_D^{\text{sec}}(\mathbf{S}, \mathbf{V}) &= \log_2(1 + \gamma_D) - \log_2(1 + \gamma_I) \\ &= \log_2\left(1 + \frac{\mathbf{h}_D^H \mathbf{S} \mathbf{h}_D}{\mathbf{h}_D^H \mathbf{V} \mathbf{h}_D + \sigma_Z^2}\right) - \log_2\left(1 + \frac{\mathbf{h}_I^H \mathbf{S} \mathbf{h}_I}{\mathbf{h}_I^H \mathbf{V} \mathbf{h}_I + P_U |g_I|^2 + \sigma_Z^2}\right). \end{aligned} \tag{7}$$

Meanwhile, the amount of harvested energy at U_I is expressed as

$$E = \zeta \left(\mathbf{h}_I^H \mathbf{S} \mathbf{h}_I + \mathbf{h}_I^H \mathbf{V} \mathbf{h}_I + P_U |g_I|^2 \right), \tag{8}$$

where $0 < \zeta \leqslant 1$ is the RF energy conversion efficiency.

Next, for the uplink channel, we denote the received signal vector at FD-BS as

$$y_U = \mathbf{w}_R^H \mathbf{g}_U \sqrt{P_U} s_U + \underbrace{\mathbf{w}_R^H \mathbf{H}_{SI} (\mathbf{s}_D + \mathbf{v})}_{SI} + \mathbf{w}_R^H \mathbf{z}_U, \tag{9}$$

where $\mathbf{g}_U \in \mathbb{C}^{N_R \times 1}$ is the complex channel vector from the FD-BS to U_U and $z_U \sim \mathcal{CN}(\mathbf{0}, \sigma_Z^2 \mathbf{I}_{N_R})$ is the noise vector. $\mathbf{w}_R \in \mathbb{C}^{N_R \times 1}$ is the receive beamforming at FD-BS and the matrix $\mathbf{H}_{SI} \in \mathbb{C}^{N_R \times N_T}$ is the self-interference (SI) channel from the transmit antennas to the receive antennas at FD-BS.

Thus, the uplink channel information rate and SINR can be respectively given by

$$R_U(\mathbf{S}, \mathbf{V}, \mathbf{w}_R) = \log_2 (1 + \gamma_U) \tag{10}$$

and

$$\gamma_U = \frac{P_U \left| \mathbf{w}_R^H \mathbf{g}_U \right|^2}{\mathbf{w}_R^H \mathbf{H}_{SI} \mathbf{S} \mathbf{H}_{SI}^H \mathbf{w}_R + \mathbf{w}_R^H \mathbf{H}_{SI} \mathbf{V} \mathbf{H}_{SI}^H \mathbf{w}_R + \sigma_z^2 \left\| \mathbf{w}_R \right\|_2^2}. \tag{11}$$

From (3), (4) and (9), we observe that the secure downlink and uplink transmission are coupled by the SI and the UN. Since we assume that U_I is interested in the information of FD-BS, the downlink secrecy rate and the uplink rate are two main objectives we desire to optimize. In order to achieve a tradeoff between them, the weighted sum rate of the secure downlink and uplink transmission, which is a very common and useful method to address the multi-objective optimization problem, are maximized in this paper. In particular, the problem is expressed as

$$\mathcal{P}1: \max_{\mathbf{S}, \mathbf{V}, \|\mathbf{w}_R\|^2 = 1} \quad w_D R_D^{\text{sec}}(\mathbf{S}, \mathbf{V}) + w_U R_U(\mathbf{S}, \mathbf{V}, \mathbf{w}_R) \tag{12a}$$

$$\text{s. t.} \quad \text{Tr}(\mathbf{S}) + \text{Tr}(\mathbf{V}) \leqslant P_{BS}, \tag{12b}$$

$$\zeta \left(\mathbf{h}_I^H \mathbf{S} \mathbf{h}_I + \mathbf{h}_I^H \mathbf{V} \mathbf{h}_I + P_U |g_I|^2 \right) \geqslant e^2, \tag{12c}$$

where P_{BS} is the allowable transmission power at the FD-BS and e^2 is the minimal amount of energy harvested by idle user U_I. w_D and w_U are the positive downlink and uplink weighted factors, respectively. (12b) and (12c) are the power constraint at FD-BS and harvested energy constraint at U_I, respectively.

According to [2], the feasible condition of problem $\mathcal{P}1$ is $e^2 \leqslant \zeta \left(P_{BS} \left\| \mathbf{h}_I \right\|_2^2 + P_U |g_I|^2 \right)$. Throughout this paper, we consider the non-trivial case where the positive downlink secrecy rate is achievable.

3 Optimal Transmitter Design with ZF Receiver

Under the assumption of $N_R > N_T$, ZF receiver is designed to cancel the SI at the FD-BS perfectly, i.e., $\mathbf{w}_R^H \mathbf{H}_{SI} \mathbf{S} \mathbf{H}_{SI}^H \mathbf{w}_R + \mathbf{w}_R^H \mathbf{H}_{SI} \mathbf{V} \mathbf{H}_{SI}^H \mathbf{w}_R = 0$. It also means that $\mathbf{H}_{SI}^H \mathbf{w}_R = \mathbf{0}$. Via the singular value decomposition (SVD) method, $\mathbf{H}_{SI}^H$ can be expressed as

$$\mathbf{H}_{SI}^H = \mathbf{U} \boldsymbol{\Lambda} \mathbf{V'}^H = \mathbf{U} \boldsymbol{\Lambda} [\hat{\mathbf{V}} \ \tilde{\mathbf{V}}]^H, \tag{13}$$

where $\mathbf{U} \in \mathbb{C}^{N_T \times N_T}$ and $\mathbf{V}' \in \mathbb{C}^{N_R \times N_R}$ are unitary matrices, $\boldsymbol{\Lambda}$ is a $N_T \times N_R$ rectangular diagonal matrix. In addition, $\hat{\mathbf{V}} \in \mathbb{C}^{N_R \times N_T}$ and $\tilde{\mathbf{V}} \in \mathbb{C}^{N_R \times (N_R - N_T)}$ is made up of the first N_T and the last $N_R - N_T$ right singular vectors of $\mathbf{H}_{SI}^H$, respectively. Note that $\tilde{\mathbf{V}}$ with $\tilde{\mathbf{V}}^H \tilde{\mathbf{V}} = \mathbf{I}$ forms an orthogonal basis for the null space of $\mathbf{H}_{SI}^H$. Hence, to satisfy $\mathbf{H}_{SI}^H \mathbf{w}_R = \mathbf{0}$, $\mathbf{w}_R$ is expressed as:

$$\mathbf{w}_R = \tilde{\mathbf{V}} \tilde{\mathbf{w}}_R. \tag{14}$$

Notice that design of $\tilde{\mathbf{w}}_R$ is only related to uplink transmission after SI cancellation. It can be shown that to maximize the uplink rate, $\tilde{\mathbf{w}}_R$ should be aligned to the same direction as the equivalent channel $\tilde{\mathbf{V}}^H \mathbf{g}_U$, i.e., $\tilde{\mathbf{w}}_R^* = \frac{\tilde{\mathbf{V}}^H \mathbf{g}_U}{\|\tilde{\mathbf{V}}^H \mathbf{g}_U\|}$. Then the achievable uplink rate is expressed as

$$R_U^{ZF} = \log_2 \left(1 + \frac{P_U \left\| \tilde{\mathbf{V}}^H \mathbf{g}_U \right\|^2}{\sigma_z^2} \right). \tag{15}$$

It is observed that the uplink channel rate, R_U^{ZF}, is independent of transmitter design with the ZF receiver, which simplifies the problem $\mathcal{P}1$.

Next, we only focus on the maximization of secrecy downlink rate. According to [14], the original problem $\mathcal{P}1$ without uplink rate is equivalent to following $\mathcal{P}2$ with the optimal SINR constraint γ_i.

$$\mathcal{P}2: \quad \max_{\mathbf{S},\mathbf{V}} \quad \frac{\mathrm{Tr}(\mathbf{H}_D \mathbf{S})}{\mathrm{Tr}(\mathbf{H}_D \mathbf{V}) + \sigma_Z^2} \tag{16a}$$

$$\text{s. t.} \quad \mathrm{Tr}(\mathbf{H}_I \mathbf{S}) \leqslant \gamma_i \left[\mathrm{Tr}(\mathbf{H}_I \mathbf{V}) + P_U |g_I|^2 + \sigma_Z^2 \right], \tag{16b}$$

$$\mathrm{Tr}(\mathbf{S}) + \mathrm{Tr}(\mathbf{V}) \leqslant P_{BS}, \tag{16c}$$

$$\mathrm{Tr}(\mathbf{H}_I \mathbf{S}) + \mathrm{Tr}(\mathbf{H}_I \mathbf{V}) + P_U |g_I|^2 \geqslant e^2/\zeta, \tag{16d}$$

where $\mathbf{H}_D = \mathbf{h}_D \mathbf{h}_D^H$, $\mathbf{H}_I = \mathbf{h}_I \mathbf{h}_I^H$, and γ_i is an introducing positive variable. However, it is still a non-convex optimization problem due to the linear fractional objective function.

From Charnes-Cooper transformation [10], we define $\bar{\mathbf{S}} = \rho\mathbf{S}$, $\bar{\mathbf{V}} = \rho\mathbf{V}$ and rewrite the problem $\mathcal{P}2$ in terms of $\bar{\mathbf{S}}$ and $\bar{\mathbf{V}}$.

$$\begin{aligned}
\mathcal{P}2.1: \quad \max_{\bar{\mathbf{S}},\bar{\mathbf{V}},\rho} \quad & \mathrm{Tr}(\mathbf{H}_D\bar{\mathbf{S}}) && \text{(17a)}\\
\text{s. t.} \quad & \mathrm{Tr}(\mathbf{H}_D\bar{\mathbf{V}}) + \rho\sigma_Z^2 = 1, && \text{(17b)}\\
& \mathrm{Tr}(\mathbf{H}_I\bar{\mathbf{S}}) - \gamma_i \,\mathrm{Tr}(\mathbf{H}_I\bar{\mathbf{V}}) - \rho\gamma_i \left(P_U|g_I|^2 + \sigma_Z^2\right) \leqslant 0, && \text{(17c)}\\
& \mathrm{Tr}(\bar{\mathbf{S}}) + \mathrm{Tr}(\bar{\mathbf{V}}) - \rho P_{BS} \leqslant 0, && \text{(17d)}\\
& \mathrm{Tr}(\mathbf{H}_I\bar{\mathbf{S}}) + \mathrm{Tr}(\mathbf{H}_I\bar{\mathbf{V}}) + \rho P_U|g_I|^2 - \rho e^2/\zeta \geqslant 0, && \text{(17e)}\\
& \rho > 0. && \text{(17f)}
\end{aligned}$$

This is a convex SDP problem[1] and hence can be solved by CVX [11].

By denoting its objective value as $h(\gamma_i)$, the original problem $\mathcal{P}1$ without uplink rate becomes $\max_{\gamma_i \geqslant 0} w_D \log_2\left(\frac{1+h(\gamma_i)}{1+\gamma_i}\right)$. Clearly, it is the same as $\max_{\gamma_i \geqslant 0} f(\gamma_i) = \frac{1+h(\gamma_i)}{1+\gamma_i}$.

Proposition 1: $f(\gamma_i)$ is quasi-concave in γ_i and its maximum can be found through a one-dimensional search.

Proof: We first prove that $h(\gamma_i)$ is concave in γ_i. Let λ, μ, ν, θ denote the dual variables of the corresponding constraints in problem $\mathcal{P}2.1$, respectively. Then the Lagrangian function of problem $\mathcal{P}2.1$ is given by

$$L(\bar{\mathbf{S}}, \bar{\mathbf{V}}, \rho, \lambda, \mu, \nu, \theta, \gamma_i) = \mathrm{Tr}(\mathbf{A}\bar{\mathbf{S}}) + \mathrm{Tr}(\mathbf{B}\bar{\mathbf{V}}) + \eta\rho + \lambda \tag{18}$$

where

$$\mathbf{A} = \mathbf{H}_D - \mu\mathbf{H}_I + \nu\mathbf{I} + \theta\mathbf{H}_I, \tag{19}$$

$$\mathbf{B} = -\lambda\mathbf{H}_D + \mu\gamma_i\mathbf{H}_I - \nu\mathbf{I} + \theta\mathbf{H}_I \tag{20}$$

and

$$\eta = -\lambda\sigma_Z^2 + \mu\gamma_i\left(P_U|g_I|^2 + \sigma_Z^2\right) + \nu P_{BS} + \theta\left(P_U|g_I|^2 - e^2/\zeta\right). \tag{21}$$

The Lagrangian dual function is given by

$$g(\lambda, \mu, \nu, \theta, \gamma_i) = \max_{\bar{\mathbf{S}}\succ\mathbf{0},\bar{\mathbf{V}}\succ\mathbf{0},\rho>0} L(\bar{\mathbf{S}}, \bar{\mathbf{V}}, \rho, \lambda, \mu, \nu, \theta, \gamma_i). \tag{22}$$

Since $\mathcal{P}2.1$ is a convex problem and satisfies the slater's condition, the strong duality holds. Thus, $h(\gamma_i) = \min_{\lambda,\mu,\nu,\theta} g(\lambda, \mu, \nu, \theta, \gamma_i)$. It is easily verified that $h(\gamma_i)$ is a point-wise minimum of a family of affine function and hence concave for $\gamma_i > 0$ [12].

[1] It has been proved in [5] that, there exist $\bar{\mathbf{S}}^*$ and $\bar{\mathbf{V}}^*$ which satisfy $\mathrm{rank}(\bar{\mathbf{S}}^*) = 1$ and $\mathrm{rank}(\bar{\mathbf{V}}^*) = 1$.

Then, we use the definition of quasi-concave to prove that $f(\gamma_i)$ is quasi-concave. The superlevel set of function $f(\gamma_i)$ is $\{\gamma_i|1+h(\gamma_i) \geqslant \alpha(1+\gamma_i)\}$ which is a convex set due to the concavity of $h(\gamma_i)$. So $f(\gamma_i)$ is a quasi-concave function in γ_i and its maximum can be found through a one-dimensional search. This completes the proposition. □

In order to find the optimal γ_i, we take the gradient of $f(\gamma_i)$, i.e.,

$$\frac{df(\gamma_i)}{d\gamma_i} = \frac{(1+\gamma_i)h'(\gamma_i) - (1+h(\gamma_i))}{(1+\gamma_i)^2}. \tag{23}$$

As analyzed before, we have $h(\gamma_i) = L(\bar{\mathbf{S}}^*, \bar{\mathbf{V}}^*, \rho^*, \lambda^*, \mu^*, \nu^*, \theta^*, \gamma_i)$, where $\bar{\mathbf{S}}^*, \bar{\mathbf{V}}^*, \rho^*$ are the optimal primary variables and $\lambda^*, \mu^*, \nu^*, \theta^*$ are the optimal dual variables for a given γ_i, respectively. With (18), the gradient of $h(\gamma_i)$ can be expressed as

$$\frac{dh(\gamma_i)}{d\gamma_i} = \mathrm{Tr}(\mu^* \mathbf{H}_I \bar{\mathbf{V}}^*) + \mu^*(P_U|g_I|^2 + \sigma_Z^2)\rho^*. \tag{24}$$

Above all, problem $\mathcal{P}2$ can be solved in two steps: (i) Given any $\gamma_i > 0$, we first solve the Problem $\mathcal{P}2.1$ to obtain $h(\gamma_i)$ and $f(\gamma_i)$; (ii) Then, we use the bisection method to find optimal γ_i by using the gradient of $f(\gamma_i)$. Repeat these two procedures until problem converges. Detailed steps of proposed algorithm are outlined in Algorithm 1. Different from Algorithm 1, the global optimization solution to the problem $\mathcal{P}2$ can be achieved by Algorithm 1.

Algorithm 1. SDP based bisection method for problem $\mathcal{P}2$

```
Initialize γ_i^min, γ_i^max and tolerance ε;
while γ_i^max − γ_i^min > ε do
    γ_i := (γ_i^min + γ_i^max)/2;
    solve problem P2.1 by CVX to obtain S̄*, V̄*, ρ*, λ*, μ*, ν* and θ*;
    Calculate df(γ_i)/dγ_i according to (23) and (24);
    if df(γ_i)/dγ_i ⩾ 0 then
        γ_i^min := γ_i;
    else
        γ_i^max := γ_i;
    end if
end while
return S* = S̄*/ρ*, V* = V̄*/ρ*.
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4 Simulation Results

In this section, computer simulation results are presented. Throughout the simulations, the transmission power of FD-BS is set as $P_{BS} = 10\,\mathrm{W}$. The number of antennas at FD-BS is $N = 6$. We set $N_T = 2$, $N_R = 4$. The uplink user transmission power is set as 1 W. The energy harvesting efficiency is set as 50% and the weighted factors of downlink and uplink transmission are equal to 1 for simplicity. We assume that the noise power is the same and equals to -80 dB. The channel attenuation from FD-BS to downlink user and uplink user is both 70 dB, and the channel attenuation from FD-BS to idle user is 50 dB. These channel entries are independently generated from i.i.d Rayleigh fading with the respective average power values. Moreover, the elements of $\mathbf{H}_{SI}$ is assumed to be $\mathcal{CN}(0, \sigma_{SI}^2)$, where σ_{SI}^2 is decided by the capability of the SIC techniques and is also equivalent to the negative value of self-interference channel attenuation.

In addition to the proposed full duplex scheme, the perfect full duplex scheme and the half duplex scheme are also introduced for comparison. The perfect full duplex scheme means that the SI is perfectly canceled by SIC techniques. In the half duplex scheme, all $N = 6$ antennas are used for data transmission/reception in 1/2 time slot. All results in this section are obtained by averaging over 100 independent channel realizations. Note that whenever a channel realization or a parameter setting makes the problem infeasible, the achievable sum rate is set to zero.

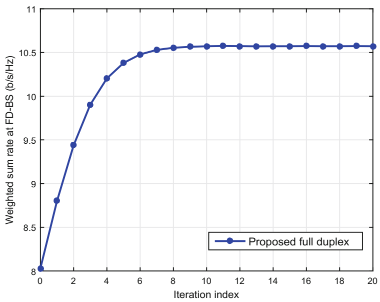

Fig. 2. Convergence rate with $N_T = 2$, $N_R = 4$ and $\sigma_{SI}^2 = -90$ dB, $e^2 = -20$ dBm

At first, we illustrate the convergence of proposed Algorithm 1 in Fig. 2 with $\sigma_{SI}^2 = -90$ dB, $e^2 = -20$ dBm. Each point on the curves of Fig. 2 records the optimal sum rate achieved at each iteration. It is shown that the Algorithm 1 converges to the optimal value within several iterations.

The impact of the minimum energy requirement on the weighted sum rate for different schemes are shown in Fig. 3 with $\sigma_{SI}^2 = -90$ dB . Note that the achieved weighted sum rate of FD-BS decreases with the increasing of the energy demand. What is more, both the proposed full duplex scheme and the perfect full duplex scheme greatly outperform half duplex scheme when $e^2 < -13$ dBm. However, their performances are slightly worse than that of half duplex when $e^2 > -12$ dBm. The reason is that it is easier for the half duplex scheme with $N = 6$ downlink antennas in 1/2 time slot than the full duplex schemes with

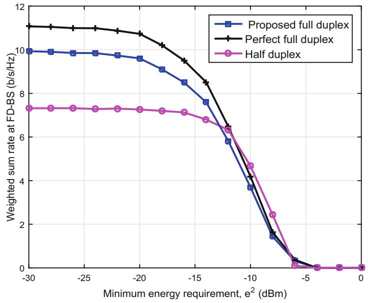

Fig. 3. The impact of the minimum energy requirement on the weighted sum rate for different schemes with $N_T = 4$, $N_R = 2$ and $\sigma_{SI}^2 = -90\,\text{dB}$

$N_T = 2$ downlink antennas in one time slot to satisfy the minimum energy requirement.

5 Conclusion

In this paper, we have designed a transceiver scheme for full duplex SWIPT with physical layer security. In the system, FD-BS is able to receive date from one uplink user and concurrently transmit data to one downlink user, and one idle user scavenges the RF signals energy. Since the idle user has great potential to intercept the downlink information, we have assumed that FD-BS exploits the artificial noise (AN), which is another energy source to idle user, to prevent it. The weighted sum rate of the secure downlink and uplink transmission has been maximized given the maximal allowable transmission power and the minimal harvested energy requirement. Extensive numerical experiments have been carried out to evaluate the sum rate performance of our proposed schemes.

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