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Full-Duplex Wireless-Powered Relay in Two Way Cooperative Networks

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ABSTRACT This paper investigates a full duplex wireless-powered two way communication networks, where two hybrid access points (HAPs) and a number of amplify and forward relays both operate in full duplex scenario. We use time switching (TS) and static power splitting (SPS) schemes with two way full duplex wireless-powered networks as a benchmark. Then, the new time division duplexing static power splitting (TDD SPS) and the full duplex static power splitting (FDSPS) schemes as well as a simple relay selection strategy are proposed to improve the system performance. For TS, SPS, and FDSPS, the best relay harvests energy using the received RF signal from HAPs and uses harvested energy to transmit signal to each HAP at the same frequency and time, therefore only partial self-interference (SI) cancellation needs to be considered in the FDSPS case. For the proposed TDD SPS, the best relay harvests the energy from the HAP and its self-interference. Then, we derive closed-form expressions for the throughput and outage probability for delay limited transmissions over Rayleigh fading channels. Simulation results are presented to evaluate the effectiveness of the proposed scheme with different system key parameters, such as time allocation, power splitting ratio, and residual SI.

INDEX TERMS Energy harvesting, full duplex antenna, cooperative communications, throughput, relay selection.

I. INTRODUCTION

Recently, energy harvesting from the surrounding environment has become a prominent way to prolong the lifetime of energy-constrained wireless networks, such as sensor networks. Compared with conventional energy supplies such as batteries that have fixed operation time, energy harvested from the environment potentially provides an unlimited energy supply for wireless networks, because renewable energy sources such as solar and wind, background radio-frequency (RF) signals radiated by ambient transmitters can be utilized for wireless power transfer. RF signals have been widely used for wireless information transmission and it can also be used for power transmission at the same time which potentially offers great convenience to mobile users.

The fundamental performance limits of wireless systems with simultaneous information and power transfer has been analyzed by [1] and [2], where the receiver is ideally assumed to be able to decode the information and harvest the energy independently from the same received signal. However, this assumption implies that the received signal used for harvesting energy can be reused for decoding information without any loss, which is not realizable due to practical circuit limitations [3]. To address this problem, [3] conducted the study of rate-energy tradeoff in wireless information and power transmission networks. Unlike [1]–[3], which studied point-to-point single-antenna transmission, [4], [5] investigated multiple-input multiple-output (MIMO) systems. In particular, [4] studied the performance limits of a three-node MIMO broadcasting system, where one receiver harvests energy and another receiver decodes information from the signals sent by a common transmitter. [6] extended the work in [4] by considering imperfect channel state information (CSI) at the transmitter. The majority of the recent research in wireless energy harvesting and information processing has only considered point-to-point communication systems. In wireless cooperative sensor networks, the relay or sensor nodes may have limited battery reserves, thus need to rely on some external charging mechanism to remain active in the network [7] and [8]. Therefore, energy harvesting in such networks is particularly important in order to enable information relaying. [9] analyzed the throughput of a half duplex relaying protocol for wireless energy harvesting and information processing. The work in [9] was extended to consider the transmission from the source to the destination with relay selection in [10]. However, such a transmission incurs a 50% loss in spectral efficiency as two time slots are required to transmit one data packet, because of the half duplex relay [11]. Thanks to the development of the full duplex technique, the self-interference (SI) can be cancelled to noise level (e.g. [12], [13]). The one way and two way full-duplex relay selection, therefore, have been considered to maximize the channel capacity in [14] and [15], respectively. Recently, [16] and [17] have studied point-to-point multi-user systems with the full duplex hybrid access point (HAP). However, the user only has a half duplex antenna, HAP only can recharge users's battery at the down-link and at the same time receive independent information from the users by using time-division-multiple-access (TDMA), which is not a real full duplex system. The system in [16] and [17] was extend to consider the used of full duplex for both HAP and user with antenna selection scheme in [18]. With the advancement of wireless communications, more and more multi-hop networks will be deployed. [19] and [20] proposed a full-duplex relay to assist the source to transmit wireless information and power to the destination. Then [21] extended a full-duplex relay to multiple antenna full-duplex Relay by using beamforming scheme to maximize throughput. These works, however, have not considered the source and destination in full duplex model which also compromises the system's spectrum efficiency compared with our proposed two way full-duplex wireless-powered relay scheme.

In this paper, we investigate the throughput and outage performance of two way cooperative wireless energy harvesting and information transmission networks with full duplex antennas, which is the first time that a real practical full duplex wireless powered relay system is considered. We investigate the scenario in which the selected energy constrained relay harvests energy from the RF signal broadcasted by two HAPs and uses the energy to transmit signal to HAPs. We consider time switching (TS) and static power splitting (SPS) [4], and propose TDD and full duplex SPS receiver architecture. With the TS protocol, relay first performs energy harvesting and uses the remaining time for two way full duplex information transmission. With the SPS protocol, relay employs a portion of the received signal for energy harvesting and the rest for information detection, and at the same time relay uses the power to transmit signal to HAPs. In both cases, all nodes transmit and receive information signal at the same time and frequency, avoiding the transmission rate loss. However, the self-interference (SI) has to be cancelled. Compared with TS and SPS, in TDD SPS, relay takes a half block time to utilize a portion of the received signal for energy harvesting and the rest for information detection, and take the other half block time to transmit signal to HAPs by using the energy harvested from the HAP and itself. In TDD SPS systems, the SI is utilized for energy harvesting. In order to avoid the rate loss for TDD SPS schemes, we proposed a full duplex SPS protocol which allows the HAP and relay (R) to operate at the same time and frequency with partial SI cancellation. The contributions of the paper are summarized as follows:

- We propose new two way full duplex wireless-power transmission networks with relay selection which can improve the average throughput compared to half duplex networks.
- We propose new TDD and full duplex SPS protocols which can not only avoid the complex SI cancellation, but can also utilize the SI to recharge its battery [22].[1]
- Considering the delay limited transmissions, we obtain closed-form expressions of the outage probability and throughput for the TS, SPS, TDD and full duplex SPS protocols over the Rayleigh fading channels.

The remainder of the paper is organized as follows: Section II describes the system model. Section III and IV provide the individual and joint performance for the TS, SPS, TDD and full duplex SPS protocols without and with relay selection, respectively. Section V presents numerical results to assess the performance of the proposed scheme and validate the theoretical analysis. Finally, conclusions are drawn in Section VI.

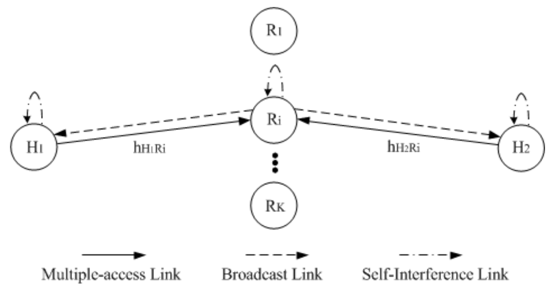

FIGURE 1. The full duplex cooperative energy harvesting system model.

II. SYSTEM MODEL

As shown in Fig. 1, we study the two way cooperative wireless-powered communication networks with AF relay selection, where two HAPs (H_1 and H_2) and a set K relays (R) are equipped with a full duplex antenna.[2] For simplicity, we assume that there is no direct link between two users as high path loss or shadowing renders it unusable [23]. The HAPs are assumed to have a constant energy supply, and they not only recharge the relay's battery, but also transmit

[1]The proposed TDD SPS does not need to cancel SI. For proposed full duplex SPS protocol only partial SI needs to be cancelled.

[2]In our paper, we consider separate transmit and receive antenna for full duplex transmissions, which also has been used in many literatures about full-duplex antenna communications, i.e. [16], [17]

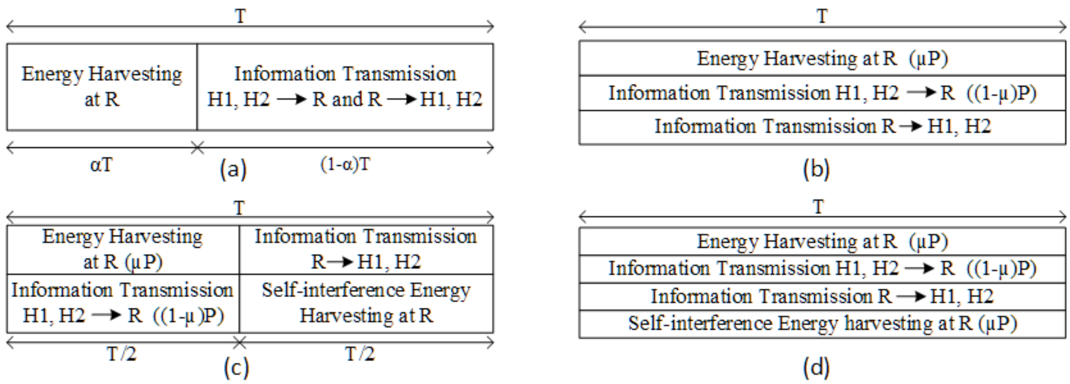

FIGURE 2. **The four protocols for energy harvesting and information transmission at the H_1 or H_2, where (a) the TS protocol, (b) the SPS protocol (c) the TDD SPS protocol and (d) the FDSPS protocol.**

signal to the each other via a selected AF relay. All relays are energy constrained nodes, which need to receive energy from the HAP and use the harvested energy to transmit signal to HAP. Assume that the channels are reciprocal, the channel coefficients for $H_1 \rightarrow R$ or $R \rightarrow H_1$ and $H_2 \rightarrow R$ or $R \rightarrow H_2$ are denoted as h_{H_1R} and h_{H_2R}, respectively. We assume that all channels experience block Rayleigh fading and the channels remain constant over one block but vary independently from one block to another.[3] The corresponding channel gains, denoted as $\gamma_j = \frac{|h_j|^2}{d_j^\epsilon}$ $(j \in \{H_1R, H_2R\})$, where d is the distance between two nodes and ϵ is the pathloss exponent, are independently exponentially distributed with mean of λ_j.[4] The noise at H_1, H_2 and R are denoted as $n_{H_1}(t)$, $n_{H_2}(t)$ and $n_R(t)$ with zero mean and variances of σ_j^2 $(j \in \{H_1, H_2, R\})$ respectively. We assume that perfect channel state information (CSI) is available at the H_1 and H_2.[5]

III. INDIVIDUAL PERFORMANCE ANALYSIS WITH A SINGLE RELAY

In this section, we provide the performance benchmark for different proposed protocols with a single relay system which are shown in Fig. 2, where T is the block time in which a certain block of information is transmitted from H_1 to H_2 and H_2 to H_1, P is the power of the received signal. The individual outage and throughput analysis for transmission between H_2 to H_1 will be considered in the sequel. Since the outage and throughput analysis procedure of H_1 to H_2 and H_2 to H_1 is identical, we only focus on the transmission from H_2 to H_1 via a single AF relay.

[3]For convenience but without loss of generality, we assume the SI channel which is used to recharge its battery for TDD SPS protocols has strong line of sight component due to the small distance between its transmitter and receiver antenna.

[4]In this work, seem as in [20], we assume a normalized path loss model in order to show the path loss degradation effects on the system performance. In real-world scenarios, path loss significantly reduces the system performance and therefore potential scenarios are limited to near-field applications such as sensor [24] and wearable/body networks [25].

[5]The CSI is usually estimated through pilots and feedback (e.g. [26]), and the CSI estimation without feedback may also be applied (e.g [27]).

A. TIME SWITCHING PROTOCOL

Fig. 2 (a) shows the main parameters in the TS protocol for energy harvesting and information processing, where α $(0 < \alpha < 1)$ is the fraction of the block time in which the relay (R) harvests energy from H_1 and H_2. The remaining block time, $(1-\alpha)T$ is used for information transmission from H_1 to H_2 and H_2 to H_1 at the same frequency in the full duplex scenario. To this end, the SI at R and H_1 and H_2 have to be cancelled by RF, analog and digital cancellation schemes[6] [12], [13]. According to [28], the harvested energy of R during energy harvesting time αT is given by

$$E_R = \beta P_H \left(\frac{|h_{H_1R}|^2}{d_{H_1R}^\epsilon} + \frac{|h_{H_2R}|^2}{d_{H_2R}^\epsilon} \right) \alpha T, \tag{1}$$

where $0 < \beta < 1$ is the energy conversion efficiency which depends on the rectification process and the energy harvesting circuitry [29], and P_H denotes the transmission power of H_1 and H_2. Furthermore, the transmission power of relay is

$$P_R = \frac{E_R}{(1-\alpha)T} = \frac{P_H \alpha \beta}{1-\alpha} \left(\frac{|h_{H_1R}|^2}{d_{H_1R}^\epsilon} + \frac{|h_{H_2R}|^2}{d_{H_2R}^\epsilon} \right). \tag{2}$$

Then H_1 and H_2 exchange information with each other via an AF relay. Due to the full duplex antenna capability, the multiple-access phase (MAP) and the broadcast phase (BCP) can work at the same time. Therefore, the received signal at the R at time slot t can be expressed as

$$y_R[t] = \frac{\sqrt{P_H} h_{H_1R}}{\sqrt{d_{H_1R}^\epsilon}} x_1[t] + \frac{\sqrt{P_H} h_{H_2R}}{\sqrt{d_{H_2R}^\epsilon}} x_2[t] + h_{RR} V[t] + n_R[t], \tag{3}$$

where $x_1[t]$ and $x_1[t]$ are the transmission signal from H_1 and H_2, respectively, h_{RR} denotes the residual self-interference channel at R and $n_R[t]$ denotes the additive white Gaussian noise (AWGN) at R, and

$$V[t] = \sqrt{P_R} \theta y_R[t-1], \tag{4}$$

[6]Self-interference cancellation algorithms design is beyond the scope of this paper.

where θ is the power constraint factor at R [9]

$$\theta = \frac{1}{\sqrt{\frac{P_H|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}} + \frac{P_H|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}} + P_R|h_{RR}|^2 + \sigma_R^2}}. \tag{5}$$

The received signal at the H_1 is formed as

$$\begin{aligned} y_{H_1}[t] &= \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}V[t] + \sqrt{P_H}h_{H_1H_1}x_1[t] + n_{H_1}[t] &\text{(6a)}\\ &= \theta\sqrt{P_RP_H}\left(\frac{h_{H_1R}^2}{d_{H_1R}^{\epsilon}}x_1[t-1] + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\frac{h_{H_2R}}{\sqrt{d_{H_2R}^{\epsilon}}}x_2[t-1]\right) &\text{(6b)}\\ &+ \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\theta\sqrt{P_R}h_{RR}V[t-1] + \sqrt{P_H}h_{H_1H_1}x_1[t] &\text{(6c)}\\ &+ \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\theta\sqrt{P_R}n_R[t-1] + n_{H_1}[t], &\text{(6d)} \end{aligned}$$

where $h_{H_1H_1}$ denotes the self-interference channel at H_1. The first term of (6b) can be totally cancelled due to network coding [30]. The second term of (6b) is the desired signal from H_2. The first and second terms of (6c) denote the residual SI from R and H_1. The first and second terms of (6d) denote the noise at R and H_1. Substituting (2), (4) (5) into (6), with some mathematic manipulation, the instantaneous received SINR at H_1 can be obtained as

$$\begin{aligned} \gamma_{H_1} &= \frac{\phi\varphi^2\gamma_{H_1R}\gamma_{H_2R}(\gamma_{H_1R}+\gamma_{H_2R})}{(\gamma_{H_1R}+\gamma_{H_2R})\varphi\phi\gamma_{H_1R} + (\gamma_{H_1R}+\gamma_{H_2R})\varphi + 1}\\ &\simeq \frac{\phi\varphi\gamma_{H_1R}\gamma_{H_2R}}{\phi\gamma_{H_1R}+1}, \end{aligned} \tag{7}$$

where $\phi = \frac{\alpha\beta}{1-\alpha}$ and $\varphi = \frac{P_H}{\sigma_{RR}^2+1} = \frac{P_H}{\sigma_{H_1H_1}^2+1}$ and the approximation holds on the high SNR region. For convenience but without loss of generality, the residual SI at three nodes is modeled as AWGN with zero mean and variance of σ_{RR}^2, $\sigma_{H_1H_1}^2$ and $\sigma_{H_2H_2}^2$ [31], which are identical. In this work we consider the delay limited transmission mode, where the average throughput can be calculated by the outage probability (P_{out}) of the system at a fixed transmission rate R_T bps/Hz. In the full duplex TS scenario, the throughput can be calculated as

$$T_o = R_T(1-P_{out})(1-\alpha). \tag{8}$$

where the outage probability P_{out} is defined as

$$P_{out} = P(\gamma_{H_1} < \gamma_{th}) = P\left(\frac{\phi\varphi\gamma_{H_1R}\gamma_{H_2R}}{\phi\gamma_{H_1R}+1} < \gamma_{th}\right), \tag{9}$$

where $P(.)$ gives the probability of the enclosed, and γ_{th} is the target SNR, which is $\gamma_{th} = 2^{R_T} - 1$. Letting $X = \gamma_{H_1R}$ and $Y = \gamma_{H_2R}$, and according to (9), we have

$$P_{out} = P\left(Y < \frac{\gamma_{th}(\phi x + 1)}{\phi\varphi x}\right). \tag{10}$$

The PDF of X and Y are $f_X(x) = \frac{1}{\lambda_{H_1R}}e^{-\frac{x}{\lambda_{H_1R}}}$ and $f_Y(y) = \frac{1}{\lambda_{H_2R}}e^{-\frac{x}{\lambda_{H_2R}}}$, respectively. Therefore,

$$\begin{aligned} P_{out} &= \int_0^{\infty}\int_0^{\frac{\gamma_{th}(\phi x+1)}{\phi\varphi x}} f_X(x)f_Y(y)dydx\\ &= 1 - 2Ae^{-\frac{\gamma_{th}}{\varphi\lambda_{H_2R}}}K_v(1, 2A), \end{aligned} \tag{11}$$

where $K_v(1, x)$ is the modified Bessel functions of the second kinds [32], and $A = \sqrt{\frac{\gamma_{th}}{\lambda_{H_1R}\lambda_{H_2R}\phi\varphi}}$.

Finally, substituting (11) into (8), we can obtain the throughput of the TS scenario, which will be verified by the simulation results shown in Section V. In the next section the SPS will be analyzed.

B. STATIC POWER SPLITTING PROTOCOL

Fig. 2 (b) shows the main parameters in the SPS protocol for energy harvesting and information processing. For the SPS protocol, during the whole block time T, HAPs not only recharge the battery of R with power μP, but also transmit information to R with power $(1-\mu)P$, where μ $(0 < \mu < 1)$ is the power fraction, which can affect the system throughput.

According to [28], the harvested energy of R during energy harvesting time T is given by

$$E_R = \beta\mu P_H\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}} + \frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right)T. \tag{12}$$

The transmission power of relay is

$$P_R = E_R/T = \beta\mu P_H\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}} + \frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right). \tag{13}$$

Then the received signal at the R in time slot t can be expressed as

$$\begin{aligned} y_R[t] &= \frac{\sqrt{P_H(1-\mu)}h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}x_1[t] + \frac{\sqrt{P_H(1-\mu)}h_{H_2R}}{\sqrt{d_{H_2R}^{\epsilon}}}x_2[t]\\ &+ h_{RR}V[t] + n_R[t], \end{aligned} \tag{14}$$

where $V[t]$ is the same as in (4), and θ is the power constraint factor at R as

$$\theta = \frac{1}{\sqrt{P_H(1-\mu)\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}} + \frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right) + P_R|h_{RR}|^2 + \sigma_R^2}}.$$

At the same time, the received signal at H_1 is

$$y_{H_1}[t] = \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}V[t] + \sqrt{P_H}h_{H_1H_1}x_1[t] + n_{H_1}[t]$$

$$
\begin{aligned}
&= \frac{h_{H_1R}^2}{d_{H_1R}^{\epsilon}}\theta\sqrt{P_R P_H(1-\mu)}x_1[t-1] \\
&\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\frac{h_{H_2R}}{\sqrt{d_{H_2R}^{\epsilon}}}\theta\sqrt{P_R P_H(1-\mu)}x_2[t-1] \\
&\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\theta\sqrt{P_R}h_{RR}V[t-1] + \sqrt{P_H}h_{H_1H_1}x_1[t] \\
&\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\theta\sqrt{P_R}n_R[t-1] + n_{H_1}[t]. \qquad (15)
\end{aligned}
$$

After some mathematic manipulation, the instantaneous received SINR at H_1 can be derived as

$$
\begin{aligned}
\gamma_{H_1} &= \frac{(1-\mu)\mu\beta\varphi^2\gamma_{H_1R}\gamma_{H_2R}(\gamma_{H_1R}+\gamma_{H_2R})}{(\gamma_{H_1R}+\gamma_{H_2R})\varphi\mu\beta\gamma_{H_1R}+(\gamma_{H_1R}+\gamma_{H_2R})\varphi(1-\mu)+1} \\
&\simeq \frac{(1-\mu)\mu\beta\varphi\gamma_{H_1R}\gamma_{H_2R}}{\mu\beta\gamma_{H_1R}+1-\mu}, \qquad (16)
\end{aligned}
$$

Following the same procedure, the theoretical outage probability of SPS can be approximated as

$$
P_{out} = 1 - 2A_1 e^{-\frac{\gamma_{th}}{(1-\mu)\varphi\lambda_{H_2R}}} K_v(1, 2A_1), \qquad (17)
$$

where $A_1 = \sqrt{\frac{\gamma_{th}}{\lambda_{H_1R}\lambda_{H_2R}\mu\beta\varphi}}$. Given that the system transmits at rate R_T bps/Hz and $T = 1$ is the effective communication time from H_2 to H_1 in the block of time T seconds, as shown in Fig. 2 (b), the throughput at the H_1 in delay limited transmission mode is defined by

$$
T_o = R_T(1 - P_{out}). \qquad (18)
$$

Next the throughput analysis in the TDD SPS scenarios will be provided.

C. TDD STATIC POWER SPLITTING PROTOCOL

Compared with TS and SPS scenarios, in TDD SPS, the SI does not need to be cancelled, however, it is used to recharge its own battery as in [22], because the desired signal and SI signal have been received at the different time slots as shown in Fig. 2 (c).

For TDD SPS, the harvested energy at $S1$ and $S2$ during energy harvesting time T is given by

$$
\begin{aligned}
E_R^{TDD}[t] &= \beta\mu P_H\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}} + \frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right)T/2 \\
&\quad + \frac{E_R^{TDD}[t-1]}{T/2}|h_{RR}|^2\beta T/2. \qquad (19)
\end{aligned}
$$

Because H_1 and H_2 take $T/2$ to transmit signal to each other in the TDD mode, the transmission power of relay is obtained as:

$$
P_R = \beta\mu P_H\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}} + \frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right)(1+\beta|h_{RR}|^2). \qquad (20)
$$

Then the received signal at R during time slot t can be obtained as

$$
\begin{aligned}
y_R[t] &= \frac{\sqrt{P_H(1-\mu)}h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}x_1[t] + \frac{\sqrt{P_H(1-\mu)}h_{H_2R}}{\sqrt{d_{H_2R}^{\epsilon}}}x_2[t] \\
&\quad + n_R[t]. \qquad (21)
\end{aligned}
$$

Then the received signal at the H_1 is

$$
\begin{aligned}
y_{H_1}[t] &= \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}V[t] + n_{H_1}[t] \\
&= \frac{h_{H_1R}^2}{d_{H_1R}^{\epsilon}}\theta\sqrt{P_R P_H(1-\mu)}x_1[t-1] \\
&\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\frac{h_{H_2R}}{\sqrt{d_{H_2R}^{\epsilon}}}\theta\sqrt{P_R P_H(1-\mu)}x_2[t-1] \\
&\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\theta\sqrt{P_R}n_R[t-1] + n_{H_1}[t], \qquad (22)
\end{aligned}
$$

where $V[t]$ is defined in (4), θ is the power constraint factor at the HAP, i.e.,

$$
\theta = \frac{1}{\sqrt{P_H(1-\mu)\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}} + P_H(1-\mu)\frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}} + \sigma_R^2}}. \qquad (23)
$$

After some mathematic manipulations, the instantaneous received SINR at H_1 can be obtained as (15) shown at the top of the next page.

Finally, the theoretical approximate outage probability of TDD SPS is

$$
P_{out} = 1 - 2A_2 e^{-\frac{\gamma_{th}}{(1-\mu)P_H\lambda_{H_2R}}} K_v(1, 2A_2), \qquad (25)
$$

where $A_2 = \sqrt{\frac{\gamma_{th}}{\lambda_{H_1R}\lambda_{H_2R}\mu\beta(1+\beta\lambda_{RR})P_H}}$, and λ_{RR} denotes the SNR of the SI for charging its own battery. for the Given that the system transmits at rate R_T bps/Hz, in TDD SPS, $T/2$ is the effective communication time from H_2 to H_1 in the block time T seconds. For TDD SPS the throughput at the H_1 is defined by

$$
T_o = R_T(1 - P_{out})/2. \qquad (26)
$$

The above analysis will be verified by the simulation results in Section V.

$$
\gamma_{H_1} = \frac{(1-\mu)\mu\beta P_H^2\gamma_{H_1R}\gamma_{H_2R}(\gamma_{H_1R}+\gamma_{H_2R})(1+\beta|h_{RR}|^2)}{(\gamma_{H_1R}+\gamma_{H_2R})(1+\beta|h_{RR}|^2)P_H\mu\beta\gamma_{H_1R} + (\gamma_{H_1R}+\gamma_{H_2R})P_H(1-\mu)+1} \simeq \frac{(1-\mu)\mu\beta P_H\gamma_{H_1R}\gamma_{H_2R}(1+\beta|h_{RR}|^2)}{\mu\beta(1+\beta|h_{RR}|^2)\gamma_{H_1R}+1-\mu} \qquad (24)
$$

D. FULL DUPLEX STATIC POWER SPLITTING PROTOCOL

Fig. 2 (d) provides the key parameters in the full duplex SPS (FDSPS) protocol for energy harvesting and information processing. For the FDSPS protocol, during the whole block time T, HAPs not only recharge the battery of R with power μP, but also transmit information to R with power $(1-\mu)P$. Compared with the TDD case, in the FDSPS protocol, we only need to cancel part of SI power $(1-\mu)P$ and the remaining part of SI power μP can be used for charging its own battery.

According to [28], the harvested energy of R during energy harvesting time T is given by

$$E_R[t] = \beta\mu P_H\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}}+\frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right)T + \frac{E_R[t-1]}{T}|h_{RR}|^2\mu\beta T. \quad (27)$$

The transmission power of relay is

$$P_R = E_R[t]/T = \beta\mu P_H\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}}+\frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right)(1+\mu\beta|h_{RR}|^2). \quad (28)$$

The received signal at the R in time slot t can thus be obtained as

$$y_R[t] = \sqrt{P_H(1-\mu)}\frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}x_1[t] + \sqrt{P_H(1-\mu)}\frac{h_{H_2R}}{\sqrt{d_{H_2R}^{\epsilon}}}x_2[t] + \sqrt{1-\mu}h_{RR}V[t]+n_R[t], \quad (29)$$

where $V[t]$ is defined in (4), and θ is the power constraint factor at R as

$$\theta = \frac{1}{\sqrt{P_H(1-\mu)\left(\frac{|h_{H_1R}|^2}{d_{H_1R}^{\epsilon}}+\frac{|h_{H_2R}|^2}{d_{H_2R}^{\epsilon}}\right)+(1-\mu)P_R|h_{RR}|^2+\sigma_R^2}}. \quad (30)$$

At the same time, the received signal at H_1 is formed as

$$\begin{aligned} y_{H_1}[t] &= \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}V[t]+P_H h_{H_1H_1}x_1[t]+n_{H_1}[t] \\ &= \frac{h_{H_1R}^2}{d_{H_1R}^{\epsilon}}\theta\sqrt{P_RP_H(1-\mu)}x_1[t-1] \\ &\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\frac{h_{H_2R}}{\sqrt{d_{H_2R}^{\epsilon}}}\theta\sqrt{P_RP_H(1-\mu)}x_2[t-1] \\ &\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\theta\sqrt{(1-\mu)P_R}h_{RR}V[t-1] \\ &\quad + \sqrt{P_H}h_{H_1H_1}x_1[t] \\ &\quad + \frac{h_{H_1R}}{\sqrt{d_{H_1R}^{\epsilon}}}\theta\sqrt{P_R}n_R[t-1]+n_{H_1}[t]. \end{aligned} \quad (31)$$

After some mathematic manipulation, the instantaneous received SINR at H_1 can be derived as (27) shown at the top of the next page. Following the same procedure, the theoretical outage probability of SPS can be approximated as

$$P_{out} = 1-2A_3e^{-\frac{\gamma_{th}}{(1-\mu)\varphi\lambda_{H_2R}}}K_v(1,2A_3), \quad (33)$$

where $A_3 = \sqrt{\frac{\gamma_{th}}{\lambda_{H_1R}\lambda_{H_2R}\mu\beta\varphi(1+\mu\beta\lambda_{RR})}}$. Given that the system transmits at rate R_T bps/Hz and $T=1$ is the effective communication time from H_2 to H_1 in the block of time T seconds, the throughput at the H_1 in delay limited transmission mode is defined by

$$T_o = R_T(1-P_{out}). \quad (34)$$

In the next section joint system performance analysis with relay selection will be provided.

IV. JOINT PERFORMANCE ANALYSIS WITH RELAY SELECTION

The previous section has studied individual system performance with a single relay. However, for the relay selection scenario, if we only consider the best relay to service H_1 to H_2, the performance of H_2 to H_1 will be affected. In this section, we provide a joint performance analysis with the best relay selection for different protocols. Without loss of generality, we assume that only selected relay switches from dormant to active mode and harvest energy from two HAPs, other relays still remain dormant at that time. Therefore, the relay selection scheme only considers the instantaneous channel state information.[7]

A. TIME SWITCHING PROTOCOL

According to (7), the received SINR for R_i at H_1 and H_2 are

$$\gamma_{H_1} \simeq \frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_1R_i}+1} \text{ and } \gamma_{H_2} \simeq \frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_2R_i}+1}. \quad (35)$$

Next, we derive the joint outage probability for R_i. Based on the achievable rate pair (35), the probabilities for two outage events are

$$P_{out,1} = P(\gamma_{H_1}<\gamma_{th}) = P\left(\frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_1R_i}+1}<\gamma_{th}\right)$$

[7]In fact, this work can also be extended to a more complex scenario which considers both the energy of relay and channel state information.

$$\gamma_{H_1} = \frac{(1-\mu)\mu\beta\varphi^2\gamma_{H_1R}\gamma_{H_2R}(\gamma_{H_1R}+\gamma_{H_2R})(1+\mu\beta|h_{RR}|^2)}{(1+\mu\beta|h_{RR}|^2)(\gamma_{H_1R}+\gamma_{H_2R})\varphi\mu\beta\gamma_{H_1R}+(\gamma_{H_1R}+\gamma_{H_2R})\varphi(1-\mu)+1} \simeq \frac{(1-\mu)\mu\beta\varphi\gamma_{H_1R}\gamma_{H_2R}(1+\mu\beta|h_{RR}|^2)}{\mu\beta\gamma_{H_1R}(1+\mu\beta|h_{RR}|^2)+1-\mu} \quad (32)$$

$$P_{out,2} = P(\gamma_{H_2} < \gamma_{th}) = P\left(\frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_2R_i}+1} < \gamma_{th}\right). \quad (36)$$

Thus, the joint outage probability for R_i is defined as:

$$\begin{aligned} P_{out} &= P\left(\min(\gamma_{H_1}, \gamma_{H_2}) < \gamma_{th}\right) \\ &= P\left(\min\left(\frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_1R_i}+1}, \frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_2R_i}+1}\right) < \gamma_{th}\right). \end{aligned} \quad (37)$$

Therefore, the best joint outage performance is

$$\begin{aligned} P^b_{out} &= \min_{R_i} P\left(\min(\gamma_{H_1}, \gamma_{H_2}) < \gamma_{th}\right) \\ &= P\left(\max_{R_i} \min\left(\frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_1R_i}+1}, \frac{\phi\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\phi\gamma_{H_2R_i}+1}\right) < \gamma_{th}\right). \end{aligned} \quad (38)$$

The exact joint outage probability based on (38) is generally intractable, because there are terms which are dependent on R_i. However, we can derive the approximate outage probability as

$$P^b_{out} \simeq P\left(\max_{R_i} \min\left(\gamma_{H_2R_i}, \gamma_{H_1R_i}\right) < \gamma_{th}/\varphi\right), \quad (39)$$

where (39) holds when $\gamma_{H_1R_i} \gg 1$ and $\gamma_{H_2R_i} \gg 1$. Therefore, we can use a traditional max-min relay selection scheme to achieve the joint outage probability and the index of the best relay is

$$k = \arg\max_{R_i} \min\left(\gamma_{H_2R_i}, \gamma_{H_1R_i}\right). \quad (40)$$

Letting $X = \gamma_{H_1R_i}$ and $Y = \gamma_{H_2R_i}$ and $Z = \max_{R_i} \min\left(\gamma_{H_2R_i}, \gamma_{H_1R_i}\right)$, then we can obtain the best joint outage probability as

$$\begin{aligned} P^b_{out} &= F_Z(z) = 1 - (1 - F_X(x))(1 - F_Y(y)) \\ &= \left[1 - e^{-\frac{(\lambda_{H_1R}+\lambda_{H_2R})z}{\lambda_{H_1R}\lambda_{H_2R}}}\right]^K, \end{aligned} \quad (41)$$

where $z = \gamma_{th}/\varphi$.

B. STATIC POWER SPLITTING PROTOCOL

According (16), the received SINRs for R_i at H_1 and H_2 are given as:

$$\begin{aligned} \gamma_{H_1} &\simeq \frac{(1-\mu)\mu\beta\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\mu\beta\gamma_{H_1R_i} + 1 - \mu} \\ \gamma_{H_2} &\simeq \frac{(1-\mu)\mu\beta\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}}{\mu\beta\gamma_{H_2R_i} + 1 - \mu}, \end{aligned} \quad (42)$$

We can follow the same procedure from (37) to (40) to obtain the best joint outage probability as

$$P^b_{out} = \left[1 - e^{-\frac{(\lambda_{H_1R}+\lambda_{H_2R})z_1}{\lambda_{H_1R}\lambda_{H_2R}}}\right]^K, \quad (43)$$

where $z_1 = \frac{\gamma_{th}}{\varphi(1-\mu)}$.

C. TDD STATIC POWER SPLITTING PROTOCOL

According (16), the received SINRs for R_i at H_1 and H_2 are given by:

$$\begin{aligned} \gamma_{H_1} &\simeq \frac{(1-\mu)\mu\beta P_H\gamma_{H_1R_i}\gamma_{H_2R_i}(1+\beta|h_{RR}|^2)}{\mu\beta(1+\beta|h_{RR}|^2)\gamma_{H_1R_i} + 1 - \mu} \\ \gamma_{H_2} &\simeq \frac{(1-\mu)\mu\beta P_H\gamma_{H_1R_i}\gamma_{H_2R_i}(1+\beta|h_{RR}|^2)}{\mu\beta(1+\beta|h_{RR}|^2)\gamma_{H_2R_i} + 1 - \mu}. \end{aligned} \quad (44)$$

We can follow the same procedure shown from (37) to (40) to obtain the best joint outage probability as

$$P^b_{out} = \left[1 - e^{-\frac{(\lambda_{H_1R}+\lambda_{H_2R})z_2}{\lambda_{H_1R}\lambda_{H_2R}}}\right]^K, \quad (45)$$

where $z_2 = \frac{\gamma_{th}}{P_H(1-\mu)}$. In this work we consider the delay limited transmission mode, where the best average throughput can be calculated by P^b_{out} at a fixed transmission rate R_T bps/Hz.

D. FULL DUPLEX STATIC POWER SPLITTING PROTOCOL

According (27), the received SINRs for R_i at H_1 and H_2 are:

$$\begin{aligned} \gamma_{H_1} &\simeq \frac{(1-\mu)\mu\beta\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}(1+\mu\beta|h_{RR}|^2)}{\mu\beta\gamma_{H_1R_i}(1+\mu\beta|h_{RR}|^2) + 1 - \mu} \\ \gamma_{H_2} &\simeq \frac{(1-\mu)\mu\beta\varphi\gamma_{H_1R_i}\gamma_{H_2R_i}(1+\mu\beta|h_{RR}|^2)}{\mu\beta\gamma_{H_2R_i}(1+\mu\beta|h_{RR}|^2) + 1 - \mu}. \end{aligned} \quad (46)$$

We can follow the same procedure shown from (37) to (40) to obtain the best joint outage probability for FDSPS as

$$P^b_{out} = \left[1 - e^{-\frac{(\lambda_{H_1R}+\lambda_{H_2R})z_1}{\lambda_{H_1R}\lambda_{H_2R}}}\right]^K. \quad (47)$$

Therefore, for the TS, SPS, TDD SPS and FDSPS scenarios, the best joint throughput can be obtained as:

$$\begin{aligned} &T_o^{TS} = 2R_T(1-P^b_{out})(1-\alpha) \text{ and } T_o^{SPS} = 2R_T(1-P^b_{out}) \\ &T_o^{TDDSPS} = R_T(1-P^b_{out}) \text{ and } T_o^{FDSPS} = 2R_T(1-P^b_{out}), \end{aligned} \quad (48)$$

respectively. The above analyses will be validated by the simulation in the next section.

V. SIMULATION RESULTS

In this section, simulation results are presented to evaluate the performance of the proposed protocols and validate the analysis conducted in the previous section. In the simulations, we assume the noise variances $\sigma^2_{H_1}$, $\sigma^2_{H_2}$ and σ^2_R and the HAP transmission power P_H are all normalized to unity and the residual self-interference to noise ratio (SINR) at all the nodes are the same, i.e.,, $\sigma^2_{H_1H_1} = \sigma^2_{H_2H_2} = \sigma^2_{RR} = \sigma^2_{SI}$. The block time is also normalized to unity, i.e., $T = 1$. The simulation results are obtained by averaging over 1, 000, 000 independent Monte Carlo runs. We let $\lambda_{H_1R} = \lambda_{RH_1}$ and $\lambda_{H_2R} = \lambda_{RH_2}$ are the function of the distance between two nodes. For convenience but without loss of generality, we only focus on the channel SNR to provide the guideline for designing full

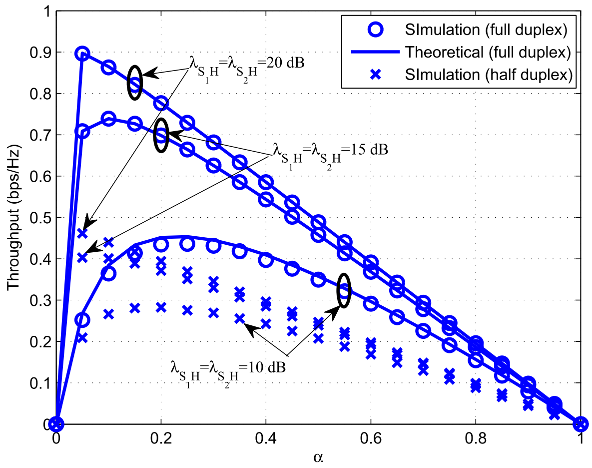

FIGURE 3. Theoretical *vs* numerical throughput for the TS scenario with respect to α, where transmission rate $R_T = 1$ bps/Hz, $\sigma_{SI}^2 = 0$ dB and the energy conversion efficiency $\beta = 0.5$.

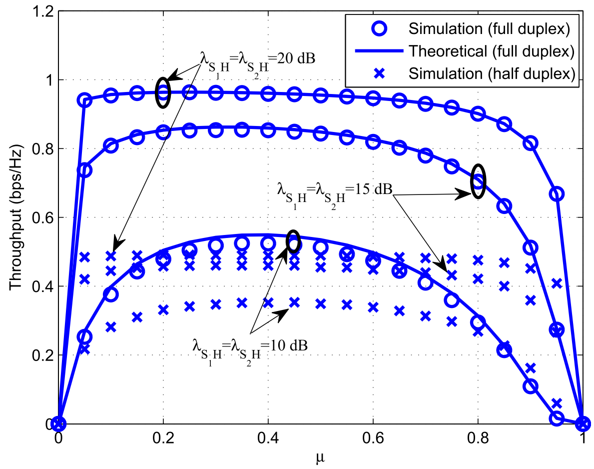

FIGURE 4. Theoretical *vs* numerical throughput for the SPS scenario with respect to μ, where transmission rate $R_T = 1$ bps/Hz, $\sigma_{SI}^2 = 0$ dB and the energy conversion efficiency $\beta = 0.5$.

duplex wireless-power networks. In order to investigate the impact of key system parameters on the throughput of the system, the distances between HAP and R are normalized to unit value. However, our analysis is generic and can be used to evaluated the throughput performance for different distances.

Fig. 3 verifies the throughput of the TS scenario introduced in Section III-A, where we let the transmission rate $R_T = 1$ bps/Hz, $\sigma_{SI}^2 = 0$ dB and the energy conversion efficiency $\beta = 0.5$. The theoretical outage probability is obtained by (8). It is clearly shown that, at high SNRs (namely, short distance or low pathloss), the theoretical and simulated outage probabilities match very well. At low SNRs, the relay need to take more time fraction to recharge its battery in order to achieve the maximum throughput, i.e. $\alpha = 0.2$ is the optimal value when $\lambda_{H_1R} = \lambda_{H_2R} = 10$ dB. On the contrary, at high SNRs, the throughput can reach the optimum value with a small fraction of time, since in this situation the received energy at relay is sufficient to transmit signal with a low outage probability. Furthermore, the throughput of proposed full duplex scheme is almost twice compare to half duplex scheme at different SNRs.

Fig. 4 shows the throughput of the SPS scenario introduced in Section III-B, where we let the transmission rate $R_T = 1$ bps/Hz, $\sigma_{SI}^2 = 0$ dB and the energy conversion efficiency $\beta = 0.5$. It is obvious that at high SNRs, the theoretical outage probabilities expressed by (18) and simulation results coincide with each other. Furthermore, the throughput increases as μ increases from 0 to the optimal value $\mu = 0.4$, at low SNRs, it starts decreasing as μ departs from its optimal value. This follows from the fact that for the values of μ smaller than the optimal μ, there is less power available for energy harvesting. Consequently, low transmission power is available from the relay node and low throughput is observed at H_1 due to large outage probability. On the other hand, for the values of μ greater than the optimal μ, low power is left for the information transmission, which increases outage probability and reduces the throughput. Finally, the throughput of proposed full duplex scheme is almost twice as that of half duplex scheme at different SNRs.

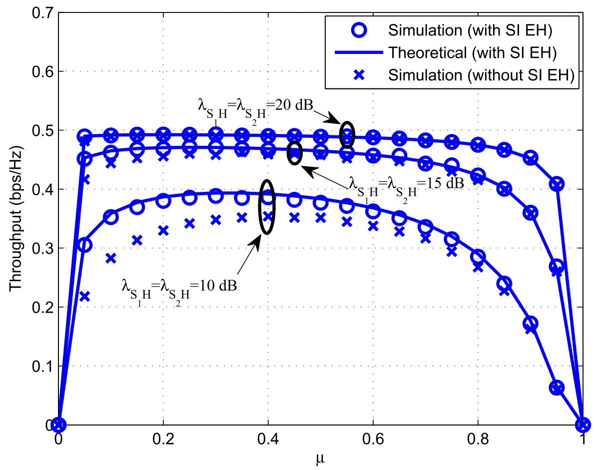

FIGURE 5. Comparison of the throughput of the TDD SPS scenario with SI energy harvesting (EH) and without SI EH with respect to μ, where transmission rate $R_T = 1$ bps/Hz, the energy conversion efficiency $\beta = 0.5$ and $\lambda_{RR} = 5$ dB.

Fig. 5 shows comparison of the throughput of the TDD SPS scenario introduced in Section III-C with SI energy harvesting (EH) and without SI EH, where the transmission rate $R_T = 1$ bps/Hz, the energy conversion efficiency $\beta = 0.5$ and $\lambda_{RR} = 5$ dB. It is obvious that at high SNRs, the theoretical outage probabilities shown in (26) and simulation results match very well. Furthermore, TDD SPS has a same trend as SPS, the optimal power fraction is almost 0.25 at low SNRs. Furthermore, the throughput of the TDD with SI EH significantly outperforms the case without SI EH at low SNRs, because the received energy from SI constitutes a large percentage of total received energy when relay is far away from the HAP. On the contrary, for the high channel SNR, the received energy from HAP plays a major role, therefore, the difference of throughput between the cases with and without SI EH is not significant.

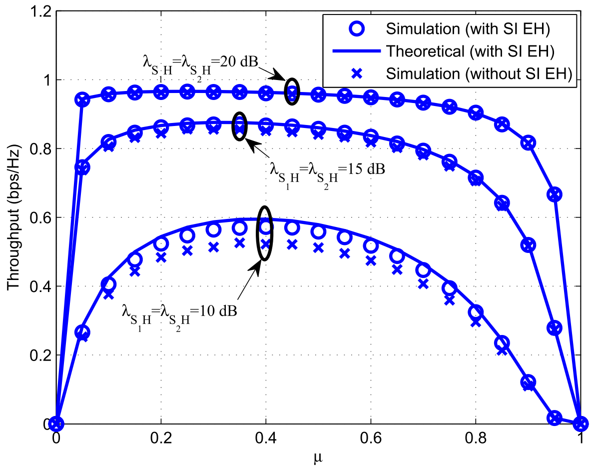

FIGURE 6. **Comparison of the throughput of the full duplex SPS scenario with SI energy harvesting (EH) and without SI EH with respect to μ, where transmission rate $R_T = 1$ bps/Hz, the energy conversion efficiency $\beta = 0.5$ and $\lambda_{RR} = 5$ dB.**

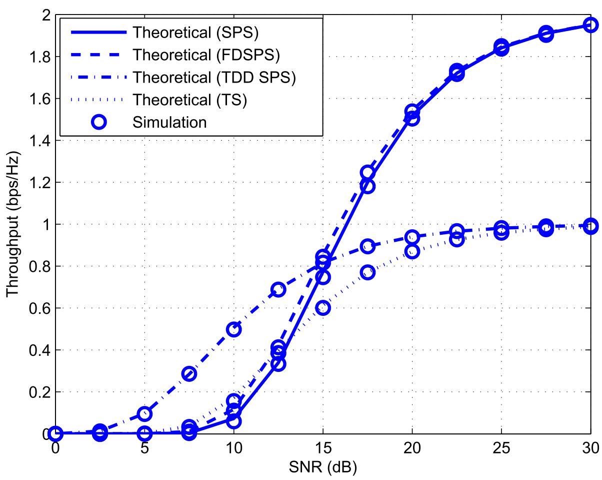

FIGURE 7. **The throughput comparison of different protocols, where transmission rate $R_T = 2$ bps/Hz, $\sigma_{SI}^2 = 5$ dB, $\lambda_{RR} = 10$ dB, the energy conversion efficiency $\beta = \alpha = \mu = 0.5$.**

Fig. 6 shows comparison of the throughput of the full duplex SPS scenario introduced in Section III-D with and without SI EH, where the transmission rate $R_T = 1$ bps/Hz, the energy conversion efficiency $\beta = 0.5$ and $\lambda_{RR} = 5$ dB. It can be seen that at high SNRs, the theoretical outage probabilities expressed by (34) and simulation results match very well. The optimal power fraction of FDSPS is approximately 0.25 at low SNRs. Furthermore, the throughput of the FDSPS with SI EH significantly outperforms the case without SI EH at low SNRs, because the received energy from SI constitutes a large percentage of total received energy when the relay is far away from the HAP. On the contrary, at high SNRs, the received energy from HAP plays a major role, therefore, the difference in throughput between the cases with and without SI EH is not significant.

Fig. 7 shows the throughput comparison of different protocols, where transmission rate $R_T = 2$ bps/Hz, $\sigma_{SI}^2 = 5$ dB, $\lambda_{RR} = 10$ dB, the energy conversion efficiency $\beta = 0.5$, $\alpha = 0.5$ and $\mu = 0.5$. It is shown that, as SNR increases, the throughput of SPS protocol increases and converges to the transmission rate 2 bps/Hz, the throughput of the TS protocol increases to the half transmission rate because of $\alpha = 0.5$ in (8), and the throughput of TDD SPS protocol increases to achieve the half transmission rate because two frequencies and two time slots are used in (26), respectively. Moreover, in the high SNR region, the throughput performance of the FDSPS is the best, but in the low SNR region, TDD SPS has the best throughput performance.

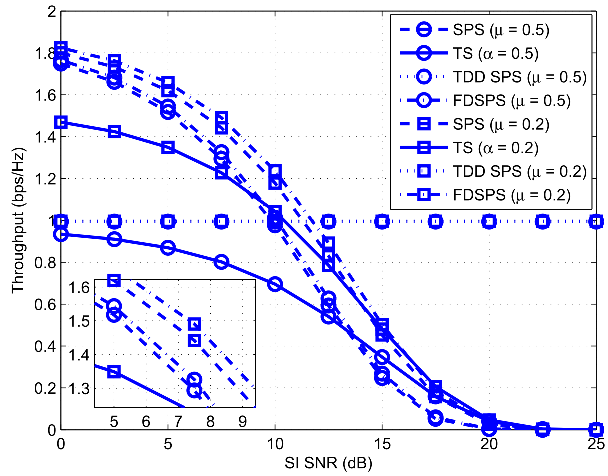

FIGURE 8. **Throughput *vs* residual self-interference σ_{SI}^2 for the TS, SPS, TDD and full duplex SPS protocols, where $R_T = 2$ bps/Hz, $\lambda_{H_1R} = \lambda_{H_2R} = 20$ dB, $\lambda_{RR} = 10$ dB and $\beta = 0.5$.**

Fig. 8 shows throughput *vs* self-interference σ_{SI}^2 for TS, SPS, TDD and full duplex SPS protocols, where $R_T = 2$ bps/Hz, $\lambda_{H_1R} = \lambda_{H_2R} = 20$ dB, $\lambda_{RR} = 10$ dB and $\beta = 0.5$. According to [33], any radio will always encounter a bandwidth constraint that bounds maximum SI cancellation, therefore, it is useful to consider the different residual SI levels which can affect the performance of TS and SPS protocols. It is clearly shown that, as the SI level increases, the throughput of TS, SPS and FDSPS decrease, but the throughput of TDD SPS remains constant. When $\alpha = 0.5$ and $\mu = 0.5$, the throughput of TS is always less that that of TDD SPS, because the TS protocol uses half of the time to recharge the users's battery according to (8), and the throughput of SPS and FDSPS is greater than that of TDD SPS, when σ_{SI}^2 is less that 10 and 10.5 dB, respectively. When $\alpha = 0.2$ and $\mu = 0.2$, the throughput of ST, SPS and FDSPS is greater than that of TDD SPS, when σ_{SI}^2 is less that 10.7, 11.5 and 12 dB, respectively.

Fig. 9 verifies the joint outage probability of the TS, SPS, TDD SPS and FDSPS scenarios analyzed in Section IV, where we let the transmission rate $R = 1$ bps/Hz, $\sigma_{SI}^2 = 10$ dB, $\lambda_{RR} = 10$ dB, $\alpha = 0.5$ and $\beta = 0.5$. One can see that, the theoretical and simulated outage probabilities match very well in all cases at the high SNR region. As expected, when the number of relay increases, the outage probability decreases. Moreover, the secrecy diversity order is K which can be confirmed by Fig. 9. Finally, because the SI has been used to charge, the outage probability of TDD SPS is

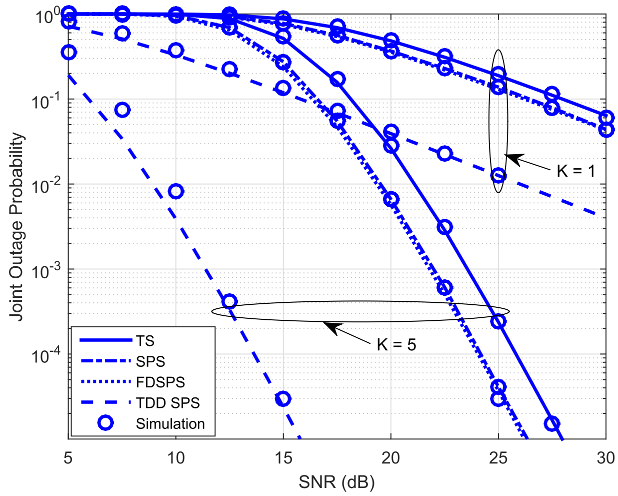

FIGURE 9. The comparison of the joint outage probability for different protocols, where target rate $R_T = 1$ bps/Hz, $\sigma_{SI}^2 = 10$ dB, the energy conversion efficiency $\beta = 0.5$ and $\alpha = 0.5$.

significantly lower than that of other cases. However, TDD SPS incurs 50% loss in spectral efficiency. Therefore, according to different RSI, α and μ, we can switch between TDD SPS and FDSPS modes to enhance the throughput performance of system.

There are some small gaps between simulation and theoretical results for the full-duplex case in Figs. 3, 4; as well as for the SI EH case in Figs. 5 and 6, because the theoretical analysis is based on the approximation of SINR at H1 which is more accurate at the high SNR region, i.e. (7), (16), (24) and (32). Therefore, the gaps will be decreased when the SNR increases as shown in Fig. 9. Moreover, the gaps between full-duplex and half-duplex in Figs. 3 and 4, and the gaps between SI EH and without SI EH cases in Fig. 5 and 6 demonstrate the performance gain of proposed scheme.

VI. CONCLUSION

In this paper, we investigated the throughput performance of a full duplex wireless-power communication networks with TS and SPS. The TDD and full duplex SPS protocols were proposed to further utilize the SI energy, leading to significantly prolonged battery life and improved the throughput performance and reduced system complexity. A simple relay selection scheme has been used to improve the joint outage probability. The closed-form outage probability and throughput for different protocols have been analyzed and derived under the delay limited transmission framework. The proposed TDD SPS schemes have been shown to yield better throughput performance than the TS and SPS schemes in the cases of high residual SI and low SNRs. For the low residual SI and high SNRs, the full duplex SPS achieves the highest throughput. The presented theoretical framework provides deep insights and useful guidance for the design and development of full-duplex wireless powered relay systems. Furthermore, we will consider multi-antenna scheme and the different types of channel fading, i.e., Rician and Nakagami-m fading, in our future work.

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