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Throughput Analysis of In-Band Full-Duplex Transmission Networks With Wireless Energy Harvesting Enabled Sources

JIAMAN LI^{ID}, LE CHUNG TRAN^{ID}, (Senior Member, IEEE),
AND FARZAD SAFAEI^{ID}, (Senior Member, IEEE)

School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

Corresponding author: Jiaman Li (jl797@uowmail.edu.au)

ABSTRACT In this paper, we investigate a two-hop communication system in which the source utilizes radio frequency (RF) energy harvesting for the transmission of information. An intermediate relay works in a half-duplex (HD) mode in the energy harvesting (EH) phase to provide energy to the source. In the information transmission phase, the relay works in a full-duplex (FD) mode to receive information signals from the source and simultaneously transmit information signals to the destination in the same frequency band. The paper provides the analysis of outage probability and throughput of a FD relaying system and two HD relaying systems. The first HD system (HD₁) has the same EH duration as the FD system while the second HD one (HD₂) has the same transmitting power from the source as the FD one. The results show that the throughput with respect to the time split between the EH phase and the information transmission one is a concave function and the optimal time split can be calculated numerically. Besides, the polarization dissimilarity factor of the antennas used has an influence on the system throughput, which is maximized when polarization states are orthogonal. The FD system can double the system throughput while having the outage probability as low as that of the HD₁ system, at a cost of adopting the extra polarization-enabled digital cancellation (PDC) scheme. Meanwhile, the FD system can nearly double the system throughput while having the outage probability superior to that of the HD₂ system. Simulations are run to confirm the above analyses.

INDEX TERMS Full-duplex, self-interference cancellation, relaying, energy harvesting source, throughput.

I. INTRODUCTION

In wireless sensor networks, deployed devices generally have a finite battery life. Battery replacement is inconvenient, costly, or even impossible in some situations, such as underground and hazardous environments. Wireless energy harvesting (EH) provides a solution to prolong the lifetime of sensor networks [1]. Instead of the conventional EH technique harvesting energy from natural sources, such as solar, wind, and thermoelectric effects [2], [3], the radio frequency (RF) EH approach focuses on using man-made RF signals to achieve energy transfer. The RF signals are more controllable and less intermittent than natural sources. Besides, since the information signals are RF signals, adopting the RF EH to the

conventional wireless networks is easily compatible with the hardware, which makes the system cost-effective [4]–[6].

Cooperative communication using relays has been proposed to expand the transmission coverage [7], [8]. Combining cooperative communication with EH has become an attractive research topic. Two commonly used EH cooperative networks include the relaying system with EH relay nodes [9]–[17] and the ones with EH source nodes [18]–[22]. The authors in [9], [11], [12], [18], [22] consider a single transmit antenna and a single receive antenna at the relay. The multiple-input multiple-output (MIMO) relaying system is researched in [10], [16], [17], [19]. The dual-hop relaying system where the energy-limited relay relies on the energy harvested from RF signals to transmit information to the destination usually has a short communication range. This is because of two main reasons. Firstly, the source-relay distance is limited due to the path loss from the source to the

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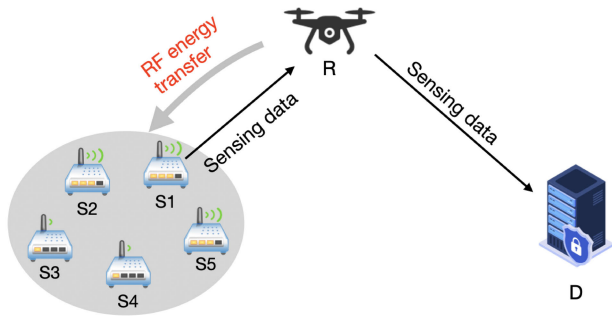


FIGURE 1. An unmanned aerial vehicle assisted sensor network with EH sources.

relay and the available transmitting power at the source. The RF energy emitted from the wireless energy transfer (WET) transmitter is always attenuated severely when it propagates toward the relay due to the high path loss [23]. Secondly, the relay-destination distance is constrained by the path loss from the relay to the destination and the harvested energy at the relay [24]. This means that the inadequate energy at the relay restricts further the transmission distance. Thus, the system throughput decreases significantly for a long-distance transmission. The relay-assisted system with an EH-capable source and a relay which has a fix and perpetual power supply is less relied on the distance [24]. Such system is preferred in many practical scenarios such as the ones shown in Figs. 1 and 2. In Fig. 1, an unmanned aerial vehicle works as a relay which transfers RF energy to nearby sensors $S_1 - S_5$ and then relays the sensing data, e.g., position, temperature, or timing, from the sources to the destination. Fig. 2 shows the scenario that an energy-limited source is placed within a tunnel. The unsafe environment in the tunnel leads to the difficulty of replacing its battery. An EH source system can ensure its proper operations, and with the assistance of the relay, the source node can consume a small amount of energy to transmit information to a distant destination.

Some of the recent researches in multi-hop wireless EH networks consider WET from the source to the relay [9], [10], [12], [13]. The works in [9], [10] research HD transmission while [12], [13] research in-band FD transmission. In contrast, the HD transmission and out-of-band FD transmission with WET from the relay to the source are considered in [18]–[21] and [22] respectively. In [16], [25], [26], multiple-antenna technologies and FD transmission are studied. The self-interference (SI) cancellation scheme in [16] requires the instantaneous channel state information (CSI) of the SI channel. In [25], [26], it is possible to use the information of direction of arrival (DOA) and direction of departure (DOD) of the SI channel for interference mitigation. Clearly, the estimations of DOA/DOD or the instantaneous CSI of the SI channels are usually required, thus the computational complexity and overhead are significant. This motivates the system model and analyses presented in this paper. The polarization-enabled digital cancellation (PDC) scheme is adopted at the relay to cancel the SI. This technique

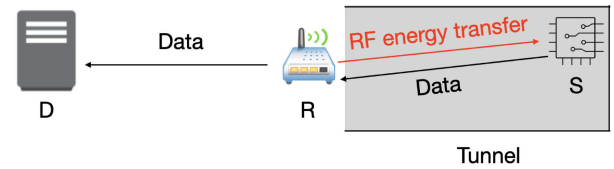


FIGURE 2. A relaying network that a EH source within a tunnel filled with toxic gas.

does not require the instantaneous CSI of the SI channels. In particular, we consider an in-band FD system as shown in Fig. 3 where the harvested energy at the source in the first phase is used to transmit data to the relay in the second phase. Besides, the relay works in the FD mode, receiving data from the source and simultaneously transmitting data to the destination. The purpose of this paper is to analyze the throughput of the two-hop in-band FD relaying system with the EH-capable sources using the PDC scheme for SI cancellation. To the best of our knowledge, there is no existing work that has the similar system model, which constitutes one of the novelties of this paper. Therefore, two HD transmission systems both of which have the WET capability from the relay to the source are examined as benchmarks. The reason is that the performance of the HD systems can be considered as the boundary of the FD system. The numbers of nodes and antennas of the HD systems are the same as those in the FD system. The first HD system, denoted as HD_1 , has the same EH duration as the FD system, and the second HD system, HD_2 , has the same transmitting power at the source with the FD system. The detailed descriptions of HD systems will be illustrated in Section III.C. Unlike our previous work in [13] which considers the polarization state of the transmitter at the source to be orthogonal with that at the relay, this paper not only considers orthogonal polarization states as a special case but also considers the effect of non-orthogonal polarization states on the FD EH-relaying system. It is worth noting that [13] considers a relaying system with an EH-capable relay while this paper examines a relaying system with an EH-enabled source. Besides, the two-hop FD system with an EH relay in [13] shows that its outage probability is worse than that of the HD EH system. In contrast, the outage probability of the FD relaying system comprising an EH source can be as small as the outage probability of the HD_1 EH system and superior to that of the HD_2 EH one.

The main contributions of the paper are summarized as follows.

- The analytical expressions of the system outage probability and throughput are presented and validated by simulations for both FD EH and HD EH relaying systems.
- The optimal time splits for FD and HD relaying systems are obtained numerically.
- In FD relaying systems, we find that the dissimilarity ρ between the polarization states of the relay antennas influences the PDC cancellation effect in terms of noise power. When $\rho > 0.5$, the output noise power of the PDC scheme is suppressed. When $\rho < 0.5$, its output

noise power is amplified. The system throughput is more sensitive to ρ when the background noise power is higher.

- When the dissimilarity factor is $\rho = 1$ (i.e., their polarization states are orthogonal), the PDC scheme can suppress best the interference and noise. Thus, the polarization states should be selected as close to orthogonal as possible to maximize the FD system throughput.
- The PDC scheme is adopted for the SI cancellation at the relay because this technique does not require the knowledge of the instantaneous CSI of the SI channels. Thereby, the complexity and overhead of the FD system are reduced.
- Comparisons of the FD and HD relaying architectures show that, at the cost of dual-polarized antennas and self-interference cancellation module, the outage probability of the FD system with the optimal ρ can be as small as that of the HD₁ system and superior to that of the HD₂ system. Besides, with the optimal time split and a proper transmit power of the relay node, the FD system can double the system throughput of the HD₁ counterpart and nearly double that of the HD₂ counterpart.

II. RELATED WORKS

Comparisons of some recent works in the literature are shown in Table 1. The authors in [9]–[13], [16], [17] consider dual-hop scenarios with EH relay nodes, of which [9], [10] deploy the half-duplex (HD) mechanism while [11]–[13], [16], [17] deploy the full-duplex (FD) mechanism. In [9], a HD “harvest-then-transmit” time switching-based relaying protocol is proposed. The throughput is determined by deriving the outage probability and the ergodic capacity for delay-limited and delay-tolerant transmission modes, respectively. In [10], a multiple-antenna relay system with a “harvest-then-transmit” strategy is considered. In the first phase, the relay receives signals from the source where some antennas are used to process information while the remaining antennas are used to harvest energy based on the power splitting protocol. In the second phase, the relay uses the harvested energy to forward signals to the destination. The presented joint power splitting and antenna selection technique outperforms the conventional relay-assisted transmission. However, the deployed HD mode in [9], [10] cannot achieve bi-directional transmission simultaneously in the same frequency band, thus having a low spectral efficiency. With the advances in signal processing technology, FD transmission has attracted the interest of researchers, which can transmit and receive information concurrently in the same frequency band. This FD mode is a solution to improve spectral efficiency and decrease transmission delay in the networks. In [11], a two-phase protocol is used to conduct FD transmission in the multi-relay system where the total transmission block time is divided into two subslots equally. In the first subslot, the source node transmits information to relays. Then a suitable relay is selected based on the best instantaneous signal-to-noise ratio (SNR) received from the

source. In the second subslot, the chosen relay receives the energy signal from the source and at the same time forwards information signals to the destination. The authors in [12], [13] adopt the protocol where a fraction of time is used for harvesting energy and the remaining time is used for FD information transmission. The authors in [12] consider a single-carrier system while the authors in [13] consider a multi-carrier system and adopt the polarization-enabled digital cancellation scheme with orthogonal polarization states to cancel SI signals. However, the works in [9]–[13] consider that the source has its own internal energy source and does not need external charging. In contrast, we consider the system that the source is energy-constrained and relies on the WET from the relay to achieve EH.

The two-hop relay-assisted networks with WET from the relay to the source are studied in [18]–[22]. The authors in [18] consider a decode-and-forward (DF) HD system where the two proposed schemes, namely, jointly optimal power and time fraction allocation and optimal power allocation with a fixed time fraction, are superior to a fixed power and a fixed time fraction allocation. A two-way relaying system with two EH sources and K relays is researched in [19]. The transmission nodes work in a HD time-division mode. A joint beamforming and relay selection method is investigated to improve system performance. The works in [20], [21] consider HD transmissions as well as simultaneously energy transfer and information transmission by utilizing the characteristics of RF signals. In the first time slot, the source transmits data to the relay. In the second phase, the relay forwards signals to both source and destination. The source harvests energy from the RF signal from the relay while the destination receives the desired information from the relay-transmitted signal. A communication system consists of an EH source and an out-of-band full-duplex relay node is investigated in [22]. The channel capacity is derived in two scenarios that the EH source can store energy using a battery and the EH source does not have a storage capacity. The above works consider HD and out-of-band FD transmission. Conversely, the system proposed in this paper assumes EH-enabled source and in-band FD transmission with the PDC scheme.

The combination of FD and MIMO relaying in simultaneous wireless information and power transfer systems are promising as spectral efficiency is improved. However, the associated interference control is challenging [17]. The work in [16] assumes an imperfect analog/digital interference cancellation scheme is applied at the relay. The residual loop-back interference channels are without a line-of-sight component between transmit antennas and receive antennas [16]. The spatial cancellation technique is deployed to suppress residual interference. However, the instantaneous CSI of the SI channel is required in such SI cancellation method. A new framework of interference mitigation is considered in [25], [26]. The residual SI is suppressed by using the DOA and DOD information of the SI channel instead of instantaneous CSI. The long-term estimation of DOA/DOD is feasible as the DOA/DOD changes slowly than instantaneous CSI.

TABLE 1. Literature comparison of cooperative communication with EH.

No. of EH nodes	[9]	[10]	[11]	[12]	[13]	[16]	[18]	[19]	[20]	[21]	[22]	[25]	[26]	This paper
EH relay	1	1	Multiple	1	1	1	1	2	1	1	1	Multiple	Multiple	1
EH source	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EH method	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals	RF signals
Antenna	Single-antenna at S and D; two-antenna at R	Single-antenna at S and D; multiple-antennas at R	Single-antenna at S and D; two-antennas at R _s	Single-antenna at S and D; two-antennas at R	Single dual-polarized antenna at S and D; two dual-polarized antennas at R (orthogonal polarization states)	Single-antenna at S and D; multiple-antennas at R	Single-antenna at S and D; two-antennas at R	Single-antenna at S and D; multiple-antennas at R	N/A	Single-antenna	Single-antenna at S and D; two-antennas at R	Single-antenna at S and D; multiple-antennas at R	Single-antenna at S and D; multiple-antennas at R	Single dual-polarized antenna at S and D; two dual-polarized antennas at R
	HD	HD	In-band FD (transmitting information and receiving energy)	In-band FD (transmitting information and receiving information)	In-band FD (transmitting information and receiving information)	HD	HD	HD	HD	HD	Out-of-band FD (transmitting information and receiving energy)	In-band FD (transmitting information and receiving information)	In-band FD (transmitting information and receiving information)	In-band FD (transmitting information and receiving information)
Transmission mode	Rayleigh fading channels	Rayleigh fading channels	Rayleigh fading channels	Rayleigh fading channels	Rayleigh fading channels	Rayleigh fading channels	Rayleigh fading channels	Rayleigh fading channels	Constant channel power gains	Rician fading of S-R link; Rayleigh fading of R-D link	Real-valued AWGN channel	Small-scale fading channels	Small-scale fading channels	Rayleigh fading channels
	No	No	Yes	No	No	No	No	No	With and without	No	No	Yes	Yes	No
Relaying protocol	AF	AF	AF and DF	AF and DF	AF	DF	DF	AF	DF	N/A	DF	N/A	N/A	AF
OFDM	×	×	×	×	✓	×	×	×	×	×	×	×	×	×
SI Channel estimation	×	×	×	×	×	✓	×	×	×	×	×	✓	✓	×
SIC	×	×	×	×	✓	✓	×	×	×	×	×	✓	✓	✓
Antenna selection	×	✓	×	×	×	×	×	×	×	✓	×	×	×	×
Relay selection	×	×	✓	×	×	×	×	✓	×	×	×	×	×	×
Analytical results	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

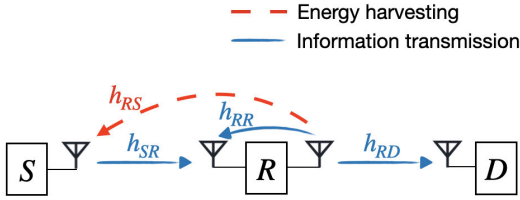


FIGURE 3. System model comprised of an EH source (S), a relay (R) and a destination (D).

However, since the DOA/DOD is required, the system complexity and overhead are still significant. In this paper, the channel estimation of the SI channel is not required in the PDC scheme and it is possible for the polarization states to be unchanged among different blocks. This means that the relay only needs to synchronize its polarization state with the source and destination once. Besides, the optimal time split is numerically calculated.

A. FD SYSTEM DESCRIPTION

We consider an amplify-and-forward (AF) relaying system which is comprised of an EH source (S), a relay (R), and a destination (D) as shown in Fig. 3. S and D are equipped with one dual-polarized antenna each while R is equipped with two sets of dual-polarized antennas, i.e., one for transmission and the other for reception. The direct link between S and D is not available because of the long-distance or heavy shadowing effects (i.e., obstructions, such as skyscrapers). h_{RS} , h_{SR} , h_{RR} and h_{RD} denote the channel coefficients of the Rayleigh block fading channels between R and S, S and R, the transmit and receive antennas at R, and R and D, respectively. We assume their expectation values satisfy $E\{|h_{RS}|^2\} = E\{|h_{SR}|^2\} = E\{|h_{RR}|^2\} = E\{|h_{RD}|^2\} = 1$. A “harvest-then-transmit” FD time switching-based relaying (TSR) protocol is considered in this paper as shown in Fig. 4. The overall block time is T seconds in which energy is harvested at the source and then information is transmitted from S to D through R. The time split factor for EH is α , where $0 < \alpha < 1$. Phase I is the EH phase with the duration of αT . In this phase, the antenna in S works in the receiving mode and S harvests energy from the RF signal transmitted from R. Phase II is the information transmission phase, which occupies the remaining time $(1 - \alpha)T$. It is assumed that D can estimate the S–R and R–D channels at the start of this phase in each block by using the pilots signal sent from S. It is worth noting that, the channel estimation of the SI channels at the relay is not needed because the PDC scheme does not require the knowledge of the instantaneous CSI of the SI channels. We assume the overhead for pilot transmission is negligible, which is in line with the works in [15], [27]. The antenna in S works in the transmitting mode and R works in the in-band FD mode. R receives information from S and at the same time forwards information to D in the same frequency band. The PDC scheme proposed in [28], including polarization and

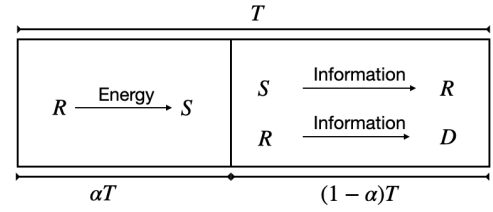


FIGURE 4. The FD TSR protocol for energy transfer and information transmission.

digital signal processing technology, is adopted in this paper to enable FD transmission. Detailed explanations of the working concepts of the PDC scheme can be found in our previous journal [13]. This digital self-interference cancellation (SIC) module is placed at the relay and is powered by the fixed power supply of the relay node. It is assumed that the power consumed by the SIC module is negligible compared to the signal power. In the information transmission process during Phase II, the polarization state used in the transmitter of S and the transmitter of R are denoted as **S** and **I** respectively. The selection of polarization states and the theory of SI signal cancellation will be detailed below.

III. SYSTEM MODEL

A. SIGNAL MODELING OF FD EH SYSTEM

1) ENERGY HARVESTING

In Phase I of the FD TSR protocol, the RF signal x_e is sent from the relay to the EH receiver at the source node. During this EH phase, the received energy signal at the source can be expressed as

$$y_s[i] = \sqrt{\frac{P_r}{d_1^m}} h_{RS} x_e[i] + n_s[i], \quad (1)$$

where h_{RS} is the channel coefficient of the R – S channel and d_1 is the distance between the source and relay. P_r is the constant transmitted power of the relay node, x_e is the energy symbol transmitted from the relay at the time instant i with the expectation value $E\{|x_e[i]|^2\} = 1$ and $n_s[i]$ is the additive white Gaussian noise (AWGN). Hence, if noise power is significantly smaller than $\frac{P_r}{d_1^m}$, the harvested energy at the source during the time αT is

$$E_s = \alpha T \left(\frac{\eta P_r |h_{RS}|^2}{d_1^m} \right), \quad (2)$$

where $0 < \eta < 1$ is the energy conversion efficiency. We assume all the harvested energy E_s at the source is used in Phase II for transmitting information signals. The transmission power of the source is

$$P_s = \frac{E_s}{(1 - \alpha)T} = \frac{\alpha \eta P_r |h_{RS}|^2}{d_1^m (1 - \alpha)}. \quad (3)$$

2) INFORMATION TRANSMISSION

In Phase II of the FD TSR protocol, the duration $(1 - \alpha)T$ is used for transmitting information from the source to the relay and, at the same time, transmitting information from the

relay to the destination. The polarization state of the desired information signal is $\mathbf{S}$ and the polarization state of the SI signal is $\mathbf{I}$, which are

$$\begin{aligned}\mathbf{S} &= [\cos(\varepsilon_s) \quad \sin(\varepsilon_s) \exp(j\delta_s)]^T \\ \mathbf{I} &= [\cos(\varepsilon_i) \quad \sin(\varepsilon_i) \exp(j\delta_i)]^T,\end{aligned}\quad (4)$$

where $\varepsilon_i, \varepsilon_s \in [0, \pi/2]$ are polarized angles of the dual-polarized antennas, $\delta_i, \delta_s \in [0, 2\pi]$ are phase differences between the vertical and horizontal polarized components of the dual-polarized antennas and $(\cdot)^T$ represents transpose of a vector. $\mathbf{S}$ and $\mathbf{I}$ are unit vectors, i.e., $\mathbf{S}^H \mathbf{S} = \mathbf{I}^H \mathbf{I} = 1$ and $\mathbf{S} \neq \mathbf{I}$. We introduce ρ as the polarization dissimilarity factor of $\mathbf{S}$ and $\mathbf{I}$. The expression of ρ can be defined as

$$\begin{aligned}\rho &= 1 - \|\mathbf{I}^H \mathbf{S}\|^2 = 1 - \mathbf{S}^H \mathbf{I} \mathbf{I}^H \mathbf{S} \\ &= \mathbf{S}^H \mathbf{P}_\perp^\perp \mathbf{S},\end{aligned}\quad (5)$$

where $\|\cdot\|$ denotes the Euclidean norm and $(\cdot)^H$ denotes the Hermitian transposition. It is well known that if $\mathbf{U}_o$ is a complex-valued unit vector on a line, then the orthogonal projection is $\mathbf{P}_{\mathbf{U}_o} = \mathbf{U}_o \mathbf{U}_o^H$. This operator leaves $\mathbf{U}_o$ invariant while annihilating all vectors orthogonal to $\mathbf{U}_o$. Thus, $\mathbf{P}_\perp^\perp = \mathbf{E} - \mathbf{P}_\perp = (\mathbf{E} - \mathbf{I} \mathbf{I}^H)$ is the orthogonal projection with the range $\langle \mathbf{I} \rangle^\perp$ and $\mathbf{P}_\perp^\perp \mathbf{I} = \mathbf{0}$, where $\mathbf{E} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$. From (5), when the vectors $\mathbf{S}$ and $\mathbf{I}$ are orthogonal, i.e., $\mathbf{I}^H \mathbf{S} = 0$, ρ gets the maximum value 1. The value $\rho = 0$ occurs when $\mathbf{I}^H \mathbf{S} = 1$. However, $\mathbf{S} \neq \mathbf{I}$ leads to $\rho \neq 0$. Thus, the range of ρ is $\rho \in (0, 1]$.

The received signal at the relay can be expressed as

$$y_r[i] = \sqrt{\frac{P_s}{d_1^m}} h_{SR} \mathbf{S} x_s[i] + \sqrt{P_i} h_{RR} \mathbf{I} x_r[i] + \mathbf{N}_r[i], \quad (6)$$

where $x_s[i]$ is the information signal transmitted by the source and $x_r[i]$ is the loopback interference due to the full-duplex transmission at the relay with $E\{|x_s[i]|^2\} = 1$ and $E\{|x_r[i]|^2\} = 1$. h_{SR} is the channel coefficient of the S-R channel and h_{RR} is the loopback interference channel gain. P_i is the power of the loopback interference signal, which is assumed to be less than the transmitting power of the relay P_r , due to some passive SIC technologies used at the relay, such as absorptive shielding [29], and the difference in polarization of the transmit and receive antennas at the relay. In the later simulation, for illustration and without loss of generality, we assume P_i is 25 dB smaller than P_r . $\mathbf{N}_r[i]$ is the AWGN at the relay node, which can be represented as

$$\mathbf{N}_r[i] = \begin{bmatrix} n_H[i] \\ n_V[i] \end{bmatrix}, \quad (7)$$

where $n_H[i]$ represents the horizontal polarized component and $n_V[i]$ represents the vertical polarized component. $n_H[i]$ and $n_V[i]$ obey the Gaussian distribution with a zero mean and a variance of $\frac{N_0}{2}$. From (6), the relay not only receives the information signal $x_s[i]$ from the source but also receives the SI signal from its own transmitter. A cancellation scheme, i.e., an oblique projection [13, Section II.B],

is needed to maintain the desired signal with the polarization state $\mathbf{S}$ while canceling the SI signal with the polarization state $\mathbf{I}$. We introduce $\mathbf{Q}_{SI}$ as the oblique projection.

$$\begin{aligned}\mathbf{Q}_{SI} &= [\mathbf{S} \ \mathbf{0}] \begin{bmatrix} \mathbf{S}^H \mathbf{S} & \mathbf{S}^H \mathbf{I} \\ \mathbf{I}^H \mathbf{S} & \mathbf{I}^H \mathbf{I} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{S}^H \\ \mathbf{I}^H \end{bmatrix} \\ &= \mathbf{S} [\mathbf{S}^H \mathbf{P}_\perp^\perp \mathbf{S}]^{-1} \mathbf{S}^H \mathbf{P}_\perp^\perp.\end{aligned}\quad (8)$$

The operator $\mathbf{Q}_{SI}$ is used at the relay as a digital signal processing module to cancel SI.

It can be easily shown that

$$\begin{aligned}\mathbf{Q}_{SI} \mathbf{S} &= \mathbf{S} [\mathbf{S}^H \mathbf{P}_\perp^\perp \mathbf{S}]^{-1} \mathbf{S}^H \mathbf{P}_\perp^\perp \mathbf{S} \\ &= \mathbf{S},\end{aligned}\quad (9)$$

$$\begin{aligned}\mathbf{Q}_{SI} \mathbf{I} &= \mathbf{S} [\mathbf{S}^H \mathbf{P}_\perp^\perp \mathbf{S}]^{-1} \mathbf{S}^H \mathbf{P}_\perp^\perp \mathbf{I} \\ &= \mathbf{0}.\end{aligned}\quad (10)$$

In (10), we use the fact that $\mathbf{P}_\perp^\perp \mathbf{I} = \mathbf{0}$ as mentioned before. Equations (9) and (10) indicate the oblique projection $\mathbf{Q}_{SI}$ has the range $\langle \mathbf{S} \rangle$ and null space $\langle \mathbf{I} \rangle$. From (5), if $\rho = \mathbf{S}^H \mathbf{P}_\perp^\perp \mathbf{S} = 1$, the oblique projection $\mathbf{Q}_{SI}$ is simplified to the orthogonal projection whose range and null space are orthogonal. These equations are the key of the PDC scheme to protect the information and cancel the SI in the FD transmission. After the PDC scheme, the post cancellation signal at the relay is

$$\begin{aligned}y_{out}[i] &= \mathbf{S}^H \mathbf{Q}_{SI} y_r[i] \\ &= \sqrt{\frac{P_s}{d_1^m}} h_{SR} x_s[i] + \mathbf{S}^H \mathbf{Q}_{SI} \mathbf{N}_r[i],\end{aligned}\quad (11)$$

where $\mathbf{S}^H \mathbf{Q}_{SI} \mathbf{N}_r$ is the residual noise because of the imperfect cancellation of the PDC scheme. If the input noise power of the PDC scheme is denoted as P_{ni} and its output noise power as P_{no} , we have [28]

$$\frac{P_{no}}{P_{ni}} = \frac{E[\|\mathbf{S}^H \mathbf{Q}_{SI} \mathbf{N}_r\|^2]}{N_0} = \frac{1}{2\rho}.$$

Since $P_{ni} = N_0$, the power of the residual noise is $\frac{N_0}{2\rho}$. From (11), the relay amplifies the input signal by a factor β in the AF protocol, which is given by

$$\beta^2 = \frac{P_r}{\frac{|h_{SR}|^2 P_s}{d_1^m} + \frac{N_0}{2\rho}}. \quad (13)$$

Hence, the transmitted signal from the relay can be expressed as

$$x_r[i] = \beta y_{out}[i - \tau], \quad (14)$$

where τ is the time delay caused by the relay processing. The received signal at the destination is

$$\begin{aligned}y_d[i] &= \frac{h_{RD}}{\sqrt{d_2^m}} x_r[i] + n_d[i] \\ &= \underbrace{\frac{h_{SR} h_{RD} \beta \sqrt{P_s}}{\sqrt{d_1^m d_2^m}} x_s[i - \tau]}_{\text{signal part}} + n_d[i]\end{aligned}$$

$$+ \underbrace{\frac{h_{RD}\beta}{\sqrt{d_2^m}} \mathbf{S}^H \mathbf{Q}_{SI} \mathbf{N}_r[i - \tau] + n_d[i]}_{\text{noise part}}, \quad (15)$$

where h_{RD} and d_2 are the channel coefficient of the R–D channel and the distance between the relay and destination, respectively. $n_d[i]$ is the AWGN at the destination. It can be seen from (11) and (15) that the cancellation scheme can eliminate the effect of SI channel h_{RR} and maintains the information signal with the same power. However, the oblique projection also causes the residual noise at the relay $\mathbf{S}^H \mathbf{Q}_{SI} \mathbf{N}_r$ with the variance $\frac{N_0}{2\rho}$ (cf. (12)). This output noise power is regarded as the side-effect of the PDC scheme. From (13) and (15), the instantaneous end-to-end signal-to-noise ratio (SNR) can be expressed as

$$\gamma = \frac{\frac{P_s \beta^2 |h_{SR}|^2 |h_{RD}|^2}{d_1^m d_2^m} + N_0}{\frac{|h_{RD}|^2 \beta^2 N_0}{2d_2^m \rho} + N_0} = \frac{\frac{P_r P_s |h_{SR}|^2 |h_{RD}|^2}{d_1^m d_2^m \left(\frac{N_0}{2\rho} + \frac{P_s |h_{SR}|^2}{d_1^m} \right)}}{\frac{N_0 P_r |h_{RD}|^2}{2d_2^m \rho \left(\frac{N_0}{2\rho} + \frac{P_s |h_{SR}|^2}{d_1^m} \right)} + N_0}. \quad (16)$$

B. HD SYSTEM DESCRIPTION

For comparison, we consider two HD EH relaying systems, denoted as HD₁ and HD₂, as benchmarks. It is because that the performance of the HD systems can be considered as the boundary of the FD system. More specifically, in theory, the throughput in FD systems can be twice the HD systems. Similar to the FD system, these two HD systems are consisted of an EH source (S), a relay (R), and a destination (D). S and D are equipped with one dual-polarized antenna each while R is equipped with two sets of dual-polarized antennas, i.e., one for transmission and the other for reception. The number of RF chains of HD₁, HD₂ and FD systems is the same. The direct link between S and D is not available. h_{RS} , h_{SR} and h_{RD} denote the channel coefficients of the Rayleigh block fading channels between R and S, S and R, and R and D, respectively. We assume their expectation values satisfy $E\{|h_{RS}|^2\} = E\{|h_{SR}|^2\} = E\{|h_{RD}|^2\} = 1$. We also assume the CSI of S–R and R–D channels is available at the destination and the overhead of the channel estimation is negligible. Besides, the PDC scheme does not require the knowledge of the instantaneous CSI of the SI channel at the relay, thus the overhead complexity is the same as that in the HD systems. So, from the overhead complexity perspective, this allows a fair comparison between our system and the HD counterparts. In addition, the FD system and HD systems are equipped with the same number of antennas at the source and destination nodes for a fair comparison in terms of the system diversity. Both throughput and outage probability comparisons between our FD system and the HD counterparts have been included.

For the HD₁ TSR protocol shown in Fig. 5, the RF signal $\hat{x}_e$ is sent from the relay to the EH-enabled receiver at the source node in Phase I during the time αT . The remaining time $(1 - \alpha)T$ is divided into two time slots where Phase II with duration $\frac{(1-\alpha)T}{2}$ is used for transmitting information

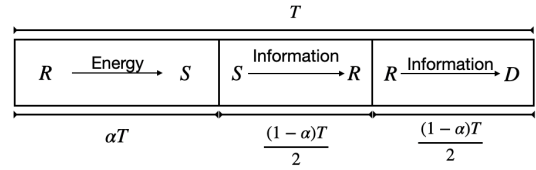


FIGURE 5. The HD₁ TSR protocol for energy transfer and information transmission.

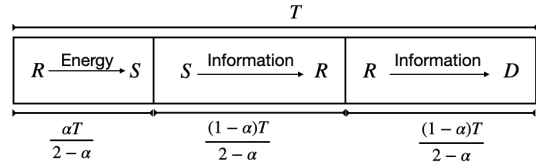


FIGURE 6. The HD₂ TSR protocol for energy transfer and information transmission.

from the source to the relay and Phase III with the remaining duration $\frac{(1-\alpha)T}{2}$ is used for transmitting information from the relay to the destination. This HD₁ system has the same total frame duration and EH duration as the FD system considered in Section III.B. For the HD₂ TSR protocol shown in Fig. 6, the EH duration in Phase I is reduced to $\alpha'T$ to ensure the transmitting power per symbol in the HD₂ system to be the same as that of the FD system. Then, Phase II and Phase III have the duration of $\frac{(1-\alpha')T}{2}$ each for information transmission. From (3), the time split factor α' is calculated as

$$\frac{\alpha \eta P_r |h_{RS}|^2}{d_1^m (1 - \alpha)} = \frac{2\alpha' \eta P_r |h_{RS}|^2}{d_1^m (1 - \alpha')}. \quad (17)$$

Hence,

$$\alpha' = \frac{\alpha}{2 - \alpha}. \quad (18)$$

As a result, the duration $\frac{(1-\alpha')T}{2} = \frac{(1-\alpha)T}{2-\alpha}$.

C. SIGNAL MODELING OF HD EH SYSTEM

1) ENERGY HARVESTING

In the EH phase of the HD₁ system, the RF energy harvested during the duration αT at the source is the same as that in the FD system with $E_s = \alpha T \left(\frac{\eta P_r |h_{RS}|^2}{d_1^m} \right)$, which is used by the source to transmit information to the relay (cf. Eq. (2)). The transmitting power of the source node is given by

$$\hat{P}_s = \frac{E_s}{\frac{(1-\alpha)T}{2}} = \frac{2\alpha \eta P_r |h_{RS}|^2}{d_1^m (1 - \alpha)}. \quad (19)$$

From (3) and (19), it can be seen that the transmitting power of the source in HD₁ is doubled, compared to that in FD because the source in HD₁ only transmits half the amount of information in the FD counterpart.

In the HD₂ system, the EH phase is reduced from αT to $\alpha'T$. The transmitting power of the source node is

$$P'_s = \frac{E_s}{\frac{(1-\alpha')T}{2}} = \frac{\alpha' T \left(\frac{\eta P_r |h_{RS}|^2}{d_1^m} \right)}{\frac{(1-\alpha')T}{2}} = \frac{\alpha \eta P_r |h_{RS}|^2}{d_1^m (1 - \alpha)}. \quad (20)$$

From (3) and (20), it can be seen that the transmitting power per symbol in the FD and HD₂ is the same.

2) INFORMATION TRANSMISSION

In the HD₁ system, the first time slot $\frac{(1-\alpha)T}{2}$ is used for the information transmission from the source to the relay. The received signal at the relay node is given by

$$\hat{y}_r[i] = \sqrt{\frac{\hat{P}_s}{d_1^m}} h_{SR} \hat{x}_s[i] + \hat{n}_r[i], \quad (21)$$

where $\hat{x}_s[i]$ is the information signal transmitted by the source and $\hat{n}_r[i]$ is the AWGN. In the AF protocol, the relay amplifies the received signal and forwards the signal to the destination. The second time slot $\frac{(1-\alpha)T}{2}$ is used for the information transmission from the relay to the destination. The transmitted signal $\hat{x}_r[i]$ at the relay is

$$\hat{x}_r[i] = \frac{\sqrt{P_r} \hat{y}_r[i - \tau]}{\sqrt{\frac{|h_{SR}|^2 \hat{P}_s}{d_1^m} + N_0}}. \quad (22)$$

The received signal at the destination can be expressed as

$$\hat{y}_d[i] = \frac{h_{RD}}{\sqrt{d_2^m}} \hat{x}_r[i] + \hat{n}_d[i], \quad (23)$$

where $\hat{n}_d[i]$ is the AWGN. Substituting (21) and (22) into (23), $\hat{y}_d[i]$ is given by

$$\begin{aligned} \hat{y}_d[i] = & \underbrace{\frac{\sqrt{P_r} \sqrt{\hat{P}_s} h_{SR} h_{RD} x_s[i - \tau]}{\sqrt{d_1^m} \sqrt{d_2^m} \left(\sqrt{\frac{|h_{SR}|^2 \hat{P}_s}{d_1^m} + N_0} \right)}}_{\text{signal part}} \\ & + \underbrace{\frac{\sqrt{P_r} h_{RD} \hat{n}_r[i - \tau]}{\sqrt{d_2^m} \left(\sqrt{\frac{|h_{SR}|^2 \hat{P}_s}{d_1^m} + N_0} \right)}}_{\text{noise part}} + \hat{n}_d[i]. \end{aligned} \quad (24)$$

The SNR at the destination in the HD₁ system is

$$\hat{\gamma} = \frac{\frac{P_r \hat{P}_s |h_{SR}|^2 |h_{RD}|^2}{d_1^m d_2^m \left(\frac{|h_{SR}|^2 \hat{P}_s}{d_1^m} + N_0 \right)}}{\frac{P_r |h_{RD}|^2 N_0}{d_2^m \left(\frac{|h_{SR}|^2 \hat{P}_s}{d_1^m} + N_0 \right)} + N_0}. \quad (25)$$

Similarly, the SNR at the destination in the HD₂ system is

$$\gamma' = \frac{\frac{P_r P'_s |h_{SR}|^2 |h_{RD}|^2}{d_1^m d_2^m \left(\frac{|h_{SR}|^2 P'_s}{d_1^m} + N_0 \right)}}{\frac{P_r |h_{RD}|^2 N_0}{d_2^m \left(\frac{|h_{SR}|^2 P'_s}{d_1^m} + N_0 \right)} + N_0}. \quad (26)$$

In the following, the outage probability and throughput at the destination node of the FD system, the HD₁ system, and the HD₂ system are determined based on the received SNR, namely γ , $\hat{\gamma}$, and γ' respectively.

IV. THROUGHPUT ANALYSIS

A. FD EH RELAYING

Assuming that all channel coefficients h_{SR} , h_{RS} , h_{RR} and h_{RD} are independently and identically distributed (i.i.d.) random variables (RVs). Assuming further that $|h_{SR}|^2$ and $|h_{RS}|^2$ are i.i.d. exponential RVs with the mean λ_s while $|h_{RD}|^2$ is an i.i.d. exponential RV with the mean λ_d .

The system outage probability p_{out} is defined as the probability that the received power value falls below the threshold. In the FD system, the outage probability is given by

$$p_{out} \triangleq p\{\gamma < \gamma_{th}\}, \quad (27)$$

where $\gamma_{th} = 2^{R_c} - 1$ is the required threshold SNR and R_c is the fixed transmission rate at the source. Invoking the received SNR at the destination in (16), we have

$$p_{out} = p \left\{ \frac{\frac{P_r P_s |h_{SR}|^2 |h_{RD}|^2}{d_1^m d_2^m \left(\frac{N_0}{2\rho} + \frac{P_s |h_{SR}|^2}{d_1^m} \right)}}{\frac{N_0 P_r |h_{RD}|^2}{2d_2^m \rho \left(\frac{N_0}{2\rho} + \frac{P_s |h_{SR}|^2}{d_1^m} \right)} + N_0} < \gamma_{th} \right\}. \quad (28)$$

The result (29), as shown at the bottom of the page, can be obtained after some simple algebraic manipulations. Denote $a = 2\eta\alpha\rho P_r^2$, $b = 2\gamma_{th}\rho\eta\alpha P_r d_2^m N_0$, $c = \gamma_{th} N_0 P_r (d_1^m)^2 (1 - \alpha)$, and $d = \gamma_{th} N_0^2 (d_1^m)^2 d_2^m (1 - \alpha)$. The outage probability p_{out} can be rewritten as

$$\begin{aligned} p_{out} &= p \left(\frac{a |h_{SR}|^2 |h_{RS}|^2 |h_{RD}|^2}{b |h_{SR}|^2 |h_{RS}|^2 + c |h_{RD}|^2 + d} < 1 \right) \\ &= p \left((a |h_{RD}|^2 - b) |h_{SR}|^2 |h_{RS}|^2 < c |h_{RD}|^2 + d \right) \\ &= \begin{cases} p \left(X < \frac{cY + d}{aY - b} \right), & Y > b/a \\ 1, & Y \leq b/a, \end{cases} \end{aligned} \quad (30)$$

where $X \triangleq |h_{SR}|^2 |h_{RS}|^2$, $Y \triangleq |h_{RD}|^2$. Following (30), p_{out} is given by

$$p_{out} = \int_0^{b/a} f_Y(z) dz + \int_{b/a}^{\infty} f_Y(z) p \left(X < \frac{cz + d}{az - b} \right) dz, \quad (31)$$

where

$$f_Y(z) = \frac{1}{\lambda_d} e^{-z/\lambda_d} \quad (32)$$

$$p \left(X < \frac{cz + d}{az - b} \right) = F_X \left(\frac{cz + d}{az - b} \right)$$

$$p_{out} = p \left(\frac{2\eta\alpha\rho P_r^2 |h_{SR}|^2 |h_{RS}|^2 |h_{RD}|^2}{2\eta\alpha\rho P_r d_2^m N_0 |h_{SR}|^2 |h_{RS}|^2 + N_0 P_r (d_1^m)^2 (1 - \alpha) |h_{RD}|^2 + N_0^2 (d_1^m)^2 d_2^m (1 - \alpha)} < \gamma_{th} \right). \quad (29)$$

$$= 1 - 2\sqrt{\frac{cz+d}{\lambda_s^2(az-b)}} K_1\left(2\sqrt{\frac{cz+d}{\lambda_s^2(az-b)}}\right), \quad (33)$$

where z is the integration variable, $f_Y(z)$ in (32) is the probability density function (PDF) of the exponential random variable Y and λ_d is the mean value of Y , $F_X\left(\frac{cz+d}{az-b}\right)$ in (33) is the cumulative distribution function (CDF) of the exponential RV X and λ_s is the mean value of the exponential RVs $|h_{SR}|^2$ and $|h_{RS}|^2$ [12], and $K_1(\cdot)$ is the first-order modified Bessel function of the second kind [30]. Substituting $f_Y(z)$ and $F_X(z)$ into (31), we have

$$\begin{aligned} p_{out} &= \int_0^{b/a} \frac{1}{\lambda_d} e^{-z/\lambda_d} dz \\ &+ \int_{b/a}^{\infty} \frac{1}{\lambda_d} e^{-z/\lambda_d} (1 - uK_1(u)) dz \\ &= 1 - \int_{b/a}^{\infty} uK_1(u) \frac{1}{\lambda_d} e^{-\frac{z}{\lambda_d}} dz, \end{aligned} \quad (34)$$

where $u \triangleq 2\sqrt{\frac{cz+d}{(az-b)\lambda_s^2}}$.

The system throughput can be computed as

$$\begin{aligned} R(\alpha) &= (1 - p_{out})R_c(1 - \alpha) \\ &= R_c(1 - \alpha) \int_{b/a}^{\infty} uK_1(u) \frac{1}{\lambda_d} e^{-\frac{z}{\lambda_d}} dz, \end{aligned} \quad (35)$$

The throughput $R(\alpha)$ is a function of system parameters and its optimization in terms of ρ and α will be illustrated below.

From (12) and (29), it is clear that the polarization dissimilarity factor ρ of $\mathbf{S}$ and $\mathbf{I}$ affects the output noise power of the PDC scheme and the system outage probability. When $\mathbf{S}$ and $\mathbf{I}$ are orthogonal, the corresponding ρ is 1, which minimizes the residual noise power output of the PDC scheme as well as the system outage probability. Thus, the throughput in (35) is maximized when ρ is 1.

It can also be seen from (29) and (35) that the time split factor, α , of the TSR protocol affects the system throughput. The optimal α can be obtained by solving the following optimization problem

$$\begin{aligned} \alpha^* &= \arg \max_{\alpha} R(\alpha) \\ \text{subject to } &0 < \alpha < 1. \end{aligned} \quad (36)$$

$R(\alpha)$ is a concave function of α . The optimal value α^* is obtained by solving the equation $\frac{dR(\alpha)}{d\alpha} = 0$. Due to the involvement of Bessel function in the expression of $R(\alpha)$, finding the closed-form solution of α^* is difficult. Thus, the value α^* is numerically calculated using the built-in function “solve” of Matlab.

B. HD EH RELAYING

In the HD₁ system, using the definition of the outage probability in (27) and invoking (25), the outage probability is

$$\begin{aligned} \hat{p}_{out} &\triangleq p\{\hat{\gamma} < \gamma_{th}\} \\ &= p\left\{\frac{\frac{P_r \hat{P}_s |h_{SR}|^2 |h_{RD}|^2}{d_1^m d_2^m \left(\frac{|h_{SR}|^2 \hat{P}_s}{d_1^m} + N_0\right)}}{\frac{P_r |h_{RD}|^2 N_0}{d_2^m \left(\frac{|h_{SR}|^2 \hat{P}_s}{d_1^m} + N_0\right)} + N_0} < \gamma_{th}\right\}. \end{aligned} \quad (37)$$

Equation (38), as shown at the bottom of the page, is derived by substituting $\hat{P}_s$ in (19) into (37). Set $\hat{a} = 2\eta\alpha Pr^2$, $\hat{b} = 2\gamma_{th}\eta\alpha Pr d_2^m N_0$, $\hat{c} = \gamma_{th} N_0 Pr(d_1^m)^2(1 - \alpha)$, and $\hat{d} = \gamma_{th} N_0^2(d_1^m)^2 d_2^m(1 - \alpha)$. The outage probability is given by

$$\hat{p}_{out} = \begin{cases} p(X < \frac{\hat{c}Y + \hat{d}}{\hat{a}Y - \hat{b}}), & Y > \hat{b}/\hat{a} \\ 1, & Y \leq \hat{b}/\hat{a}. \end{cases} \quad (39)$$

where $X \triangleq |h_{SR}|^2 |h_{RS}|^2$, $Y \triangleq |h_{RD}|^2$. After substituting the PDF and CDF of the exponential RVs into (39), we have

$$\begin{aligned} \hat{p}_{out} &= \int_0^{\hat{b}/\hat{a}} f_Y(z) dz + \int_{\hat{b}/\hat{a}}^{\infty} f_Y(z) F_X\left(\frac{\hat{c}z + \hat{d}}{\hat{a}z - \hat{b}}\right) dz \\ &= 1 - \int_{\hat{b}/\hat{a}}^{\infty} \hat{u}K_1(\hat{u}) \frac{1}{\lambda_d} e^{-\frac{z}{\lambda_d}} dz, \end{aligned} \quad (40)$$

where $\hat{u} \triangleq 2\sqrt{\frac{\hat{c}z + \hat{d}}{(\hat{a}z - \hat{b})\lambda_s^2}}$. Thus, the system throughput is

$$\begin{aligned} \hat{R}(\alpha) &= \frac{1 - \alpha}{2} R_c(1 - \hat{p}_{out}) \\ &= \frac{R_c(1 - \alpha)}{2} \int_{\hat{b}/\hat{a}}^{\infty} \hat{u}K_1(\hat{u}) \frac{1}{\lambda_d} e^{-\frac{z}{\lambda_d}} dz, \end{aligned} \quad (41)$$

The optimal α can be obtained by solving the following optimization problem

$$\begin{aligned} \hat{\alpha}^* &= \arg \max_{\alpha} \hat{R}(\alpha) \\ \text{subject to } &0 < \alpha < 1. \end{aligned} \quad (42)$$

The value $\hat{\alpha}^*$ depends on many parameters, such as efficiency η , distances d_1 and d_2 , powers P_r and $\hat{P}_s$, noise variance N_0 , threshold γ_{th} and transmission rate R_c . The computational complexity of $\hat{R}(\alpha)$ makes the closed-form expression of the optimal α difficult. Thus, the value $\hat{\alpha}^*$ is numerically calculated using the built-in function “solve” of Matlab.

Similarly, by the definition of the outage probability in (27) and invoking (26), the outage probability in the HD₂ system is

$$p'_{out} \triangleq p\{\gamma' < \gamma_{th}\}$$

$$\hat{p}_{out} = p\left(\frac{2\eta\alpha Pr^2 |h_{SR}|^2 |h_{RS}|^2 |h_{RD}|^2}{2\eta\alpha Pr d_2^m N_0 |h_{SR}|^2 |h_{RS}|^2 + N_0 Pr(d_1^m)^2(1 - \alpha) |h_{RD}|^2 + N_0^2(d_1^m)^2 d_2^m(1 - \alpha)} < \gamma_{th}\right). \quad (38)$$

$$= p \left\{ \frac{\frac{P_r P_s' |h_{SR}|^2 |h_{RD}|^2}{d_1^m d_2^m (\frac{|h_{SR}|^2 P_s'}{d_1^m} + N_0)}}{\frac{P_r |h_{RD}|^2 N_0}{d_2^m (\frac{|h_{SR}|^2 P_s'}{d_1^m} + N_0)} + N_0} < \gamma_{th} \right\}. \quad (43)$$

Equation (44), as shown at the bottom of the page, is derived by substituting P_s' in (20) into (43). Set $' = \eta \alpha P_r^2$, $b' = \gamma_{th} \eta \alpha P_r d_2^m N_0$, $c' = \gamma_{th} N_0 P_r (d_1^m)^2 (1 - \alpha)$, and $d' = \gamma_{th} N_0^2 (d_1^m)^2 d_2^m (1 - \alpha)$. Hence, the outage probability is given by

$$\begin{aligned} p'_{out} &= \int_0^{b'/a'} f_Y(z) dz + \int_{b'/a'}^{\infty} f_Y(z) F_X\left(\frac{c'z + d'}{a'z - b'}\right) dz \\ &= 1 - \int_{b'/a'}^{\infty} u' K_1(u') \frac{1}{\lambda_d} e^{-\frac{z}{\lambda_d}} dz, \end{aligned} \quad (45)$$

where $u' \triangleq 2\sqrt{\frac{c'z + d'}{(a'z - b')\lambda_d^2}}$. Thus, the system throughput is

$$\begin{aligned} R'(\alpha) &= \frac{1 - \alpha}{2 - \alpha} R_c(1 - p'_{out}) \\ &= \frac{R_c(1 - \alpha)}{2 - \alpha} \int_{b'/a'}^{\infty} u' K_1(u') \frac{1}{\lambda_d} e^{-\frac{z}{\lambda_d}} dz, \end{aligned} \quad (46)$$

The optimal α can be obtained by solving the following optimization problem

$$\begin{aligned} \alpha'^* &= \arg \max_{\alpha} R'(\alpha) \\ &\text{subject to } 0 < \alpha < 1. \end{aligned} \quad (47)$$

The value α'^* is numerically calculated using the built-in function “solve” of Matlab.

V. NUMERICAL RESULTS

We assume the path loss exponent $m = 3$, $d_{SR} = 20$ m, $d_{RD} = 200$ m, the EH efficiency $\eta = 0.8$, and the carrier frequency is 2.4 GHz. The noise power N_0 is assumed to be either -90 dBm or -80 dBm, and the transmission power of the relay is assumed to be $P_r = 1$ Watt. The transmission rate of the source is 8 bits/sec/Hz. The throughputs derived in this paper are in bits/sec/Hz. The considered range of the time split factor α and polarization dissimilarity factor ρ are $0 < \alpha < 1$ and $0 < \rho \leq 1$, respectively. To calculate the throughput in bits per seconds, $R(\alpha)$, $\hat{R}(\alpha)$, and $R'(\alpha)$ need to be multiplied with the system bandwidth B .

Fig. 7 illustrates the FD analytical result based on (35) with respect to ρ ranging from 10^{-5} to 1 since $\rho \in (0, 1]$ as shown in Section II. The figure illustrates that the polarization dissimilarity factor ρ and the time split factor α affect the throughput performances. In this simulation, the relay transmission power is $P_r = 1$ Watt and AWGN is $N_0 = -80$ dBm. As shown in the figure, for all α values, the throughput increases with the increase of ρ and the throughput is maximized when ρ approaches to 1, i.e., the polarization states

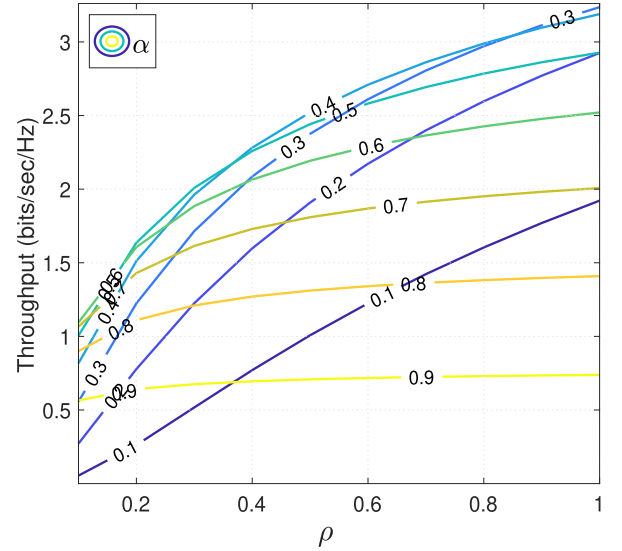


FIGURE 7. Throughput vs. the dissimilarity ρ of polarization states with different time splits α in the FD EH system. $P_r = 1$ Watt and $N_0 = -80$ dBm.

of the transmitters at the source and the relay are orthogonal. The throughput is sensitive to the dissimilarity, especially for the α close to its optimal value, as the throughput decrease significantly if ρ decreases. This means that the polarization states of the transmitters of the source and the relay are required to be orthogonal with each other to achieve the maximum system throughput for any particular value of α . Besides, it is also shown that the throughput is reduced in both the lower and higher range of the α values. For the increment of α in the figure being 0.1, the maximum throughput can be found at $\alpha = 0.3$ for $\rho = 1$.

Fig. 8 illustrates the influence of dissimilarity on the throughput R by plotting both analytical results (cf. (5) and (35)) and simulation results. The FD analytical results are denoted by the letter A and the FD simulation results are denoted by the letter S. In this simulation, the time split factor is 0.3 and transmission power of the relay is 1 Watt. The five specific polarization states randomly chosen for this simulation and the corresponding values of ρ and R are presented in Table 2. Fig. 8 shows that the maximum throughput is about 3.2 bits/sec/Hz when $N_0 = -80$ dBm while that is about 5.1 bits/sec/Hz when $N_0 = -90$ dBm. Fig. 8 also indicates that the throughput is more sensitive to ρ in more noisy environments. The throughput increases 1.10 bits/sec/Hz when $N_0 = -90$ dBm while it increases 2.13 bits/sec/Hz when $N_0 = -80$ dBm for the researched ρ range. Besides, it can be seen that the analytical and simulation results match for both scenarios, which verifies the accuracy of the expression in (35).

$$p'_{out} = p \left(\frac{\eta \alpha P_r^2 |h_{SR}|^2 |h_{RS}|^2 |h_{RD}|^2}{\eta \alpha P_r d_2^m N_0 |h_{SR}|^2 |h_{RS}|^2 + N_0 P_r (d_1^m)^2 (1 - \alpha) |h_{RD}|^2 + N_0^2 (d_1^m)^2 d_2^m (1 - \alpha)} < \gamma_{th} \right). \quad (44)$$

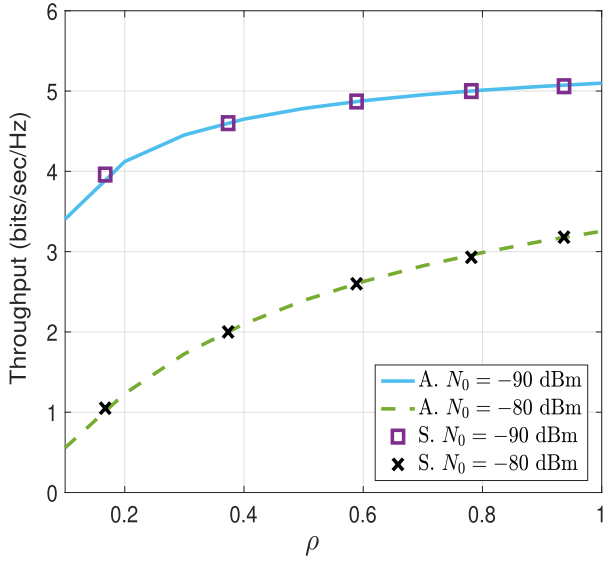


FIGURE 8. Analytical and simulation results for $N_0 = -80$ and -90 dBm in the FD EH system. $\alpha = 0.3$ and $P_r = 1$ Watt.

TABLE 2. Data collected from the simulation result where R is the FD throughput. $\alpha = 0.3$ and $P_r = 1$ Watt.

ρ	S	I	R
0.1672	$\begin{bmatrix} 0.7174 + 0.0000i \\ -0.6850 - 0.1268i \end{bmatrix}$	$\begin{bmatrix} 0.8279 + 0.0000i \\ -0.4613 + 0.3189i \end{bmatrix}$	$\begin{bmatrix} 3.96(-90 \text{ dBm}) \\ 1.05(-80 \text{ dBm}) \end{bmatrix}$
0.3734	$\begin{bmatrix} 0.9703 + 0.0000i \\ -0.0197 - 0.2410i \end{bmatrix}$	$\begin{bmatrix} 0.8907 + 0.0000i \\ -0.2990 + 0.3425i \end{bmatrix}$	$\begin{bmatrix} 4.60(-90 \text{ dBm}) \\ 2.00(-80 \text{ dBm}) \end{bmatrix}$
0.5888	$\begin{bmatrix} 0.9287 + 0.0000i \\ -0.0750 - 0.3632i \end{bmatrix}$	$\begin{bmatrix} 0.4166 + 0.0000i \\ 0.6291 - 0.6563i \end{bmatrix}$	$\begin{bmatrix} 4.87(-90 \text{ dBm}) \\ 2.60(-80 \text{ dBm}) \end{bmatrix}$
0.7813	$\begin{bmatrix} 0.3050 + 0.0000i \\ 0.5023 - 0.8091i \end{bmatrix}$	$\begin{bmatrix} 0.9832 + 0.0000i \\ 0.0406 - 0.1778i \end{bmatrix}$	$\begin{bmatrix} 5.00(-90 \text{ dBm}) \\ 2.93(-80 \text{ dBm}) \end{bmatrix}$
0.9368	$\begin{bmatrix} 0.8436 + 0.0000i \\ 0.5252 + 0.1115i \end{bmatrix}$	$\begin{bmatrix} 0.6649 + 0.0000i \\ -0.7316 + 0.1503i \end{bmatrix}$	$\begin{bmatrix} 5.06(-90 \text{ dBm}) \\ 3.18(-80 \text{ dBm}) \end{bmatrix}$

Fig. 9 plots the analytical results of the outage probabilities of the HD EH relaying systems, i.e., HD₁ and HD₂, and the FD EH relaying system with respect to $0 < \alpha < 1$. The noise and transmitting power of the relay are set to be -90 dBm and 1 Watt, respectively. The HD₁ and HD₂ systems are considered as two benchmarks. In the FD case, the effects of different polarization dissimilarity factors on the outage probability are researched. It is clear that for all cases the outage probabilities decline with the increase of α , i.e., with the increase of the EH time. In comparison, the FD system has the same EH duration as the HD₁ system. The source of the FD EH system uses the same total energy as the HD₁ EH system to transmit the double amount of information. Thus, the transmitting power per symbol $\hat{P}_s$ in the HD₁ case is twice as much as the P_s in the FD case. At the cost of antenna polarization and the digital cancellation scheme, the FD EH system can achieve the same outage probability as the HD₁ EH system when $\rho = 1$ as shown in Fig. 9. Unlike the HD₁ system, the EH duration in the HD₂ system is reduced compared to the HD₁ and FD systems to keep the transmitting power per symbol P'_s in the HD₂ system is the same as P_s in the FD system. The results show that the outage probability of “A. FD $\rho = 1$ ” is lower than that

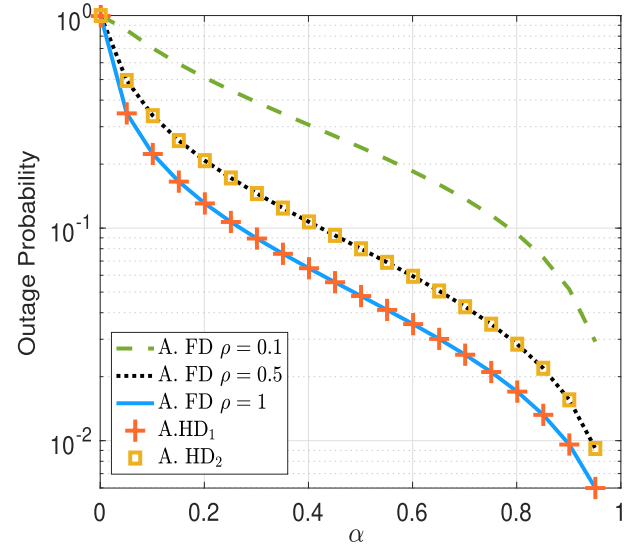


FIGURE 9. Outage probability vs. time split factor α for the HD EH and FD EH systems. $N_0 = -90$ dBm and $P_r = 1$ Watt.

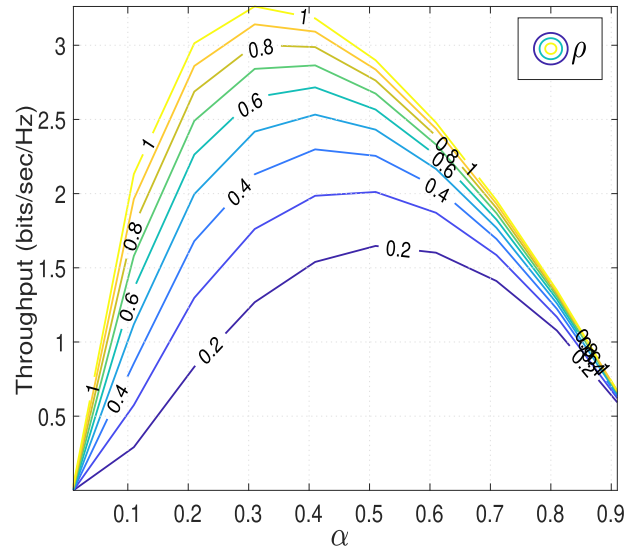


FIGURE 10. Throughput vs. time split factor α for different values of $\log(\rho)$ in the FD EH system. $P_r = 1$ Watt and $N_0 = -80$ dBm.

of “A. HD₂”. It is because the PDC scheme can suppress the noise power at the relay by the factor 2ρ as shown in (12). Moreover, “A. FD $\rho = 0.5$ ” matches “A. HD₂” as the outage probabilities of the FD system and the HD₂ system are the same when the polarization dissimilarity factor $\rho = 0.5$ as illustrated in (29) and (44). In addition, consistent with Figs. 7 and 8, the decrease of the dissimilarity increases the outage probability as the performance for the case $\rho = 0.1$ is inferior to that for $\rho = 1$.

Fig. 10 plots the change of throughput performance along with the time split factor α in the FD EH system when $P_r = 1$ Watt and $N_0 = -80$ dBm. The results are obtained from the analytical expression of throughput in (35). The curves with different colors represent different values of ρ , where the lighter colors stand for the larger values of ρ .

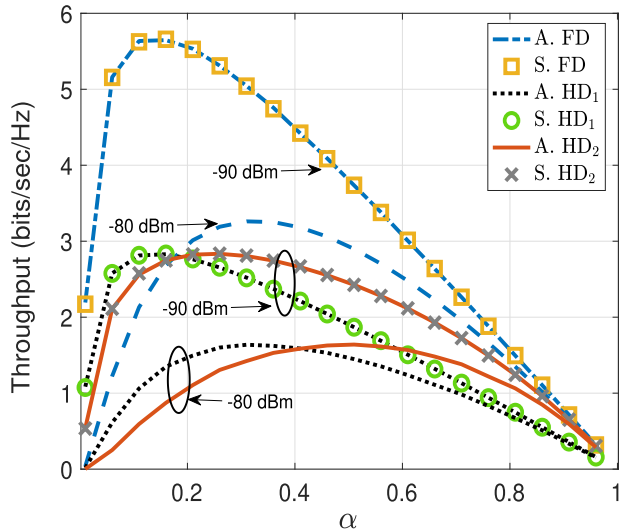


FIGURE 11. Throughput vs. time split factor α for different noise variance N_0 , $\rho = 1$ and $P_r = 1$ Watt.

Fig. 10 clearly shows that $R(\alpha)$ in (35) is a concave function and the optimal α exists and is unique for each specific ρ value. It is observed that the optimal α value increases along with the decrease of the maximum throughput and the decrease of ρ . For example, the throughput is maximized at 3.2 bits/sec/Hz with the corresponding $\alpha = 0.3$ and $\rho = 1$. Whereas, the throughput is maximized at 1.6 bits/sec/Hz when $\alpha = 0.5$ and $\rho = 0.2$.

Fig. 11 plots the analytical and simulation results of the system throughput with respect to α in the FD EH relaying system, HD₁ EH system, and HD₂ EH system with different noise variances. We can see that the noise variance has a significant influence on the maximum system throughput. For example, in the FD system, the peak value of the throughput is 5.6 bits/sec/Hz with $N_0 = -90$ dBm while that is 3.2 bits/sec/Hz with $N_0 = -80$ dBm. Similarly to Fig. 10, the optimal α increases along with the decrease of the maximum throughput even though the reduction of the maximum throughput in Fig. 11 is caused by the increase of the noise variance, rather than by the decrease of ρ . Also, in all cases, the maximum throughput of the FD system is almost twice of the HD counterpart. The HD₁ system and HD₂ system have almost the same maximum throughput but different optimal α values. In Fig. 11, the optimal α numerically evaluated with $N_0 = -90$ dBm in the FD system by (36) is 0.16, in the HD₁ system by (42) is also 0.16, and in the HD₂ system by (47) is 0.26. The simulation results match the analytical results, which verifies the correctness of the theoretical analyses. This means that the optimal time split values for the FD EH relaying system and the HD EH relaying systems can be obtained accurately by solving numerically the optimization problem in (36), (42) and (47).

Fig. 12 plots the contours of the analytical throughput in the FD EH system with the x-coordinates representing the dissimilarity and the y-coordinates representing the time split factor. The line with a lighter color, i.e., yellow color,

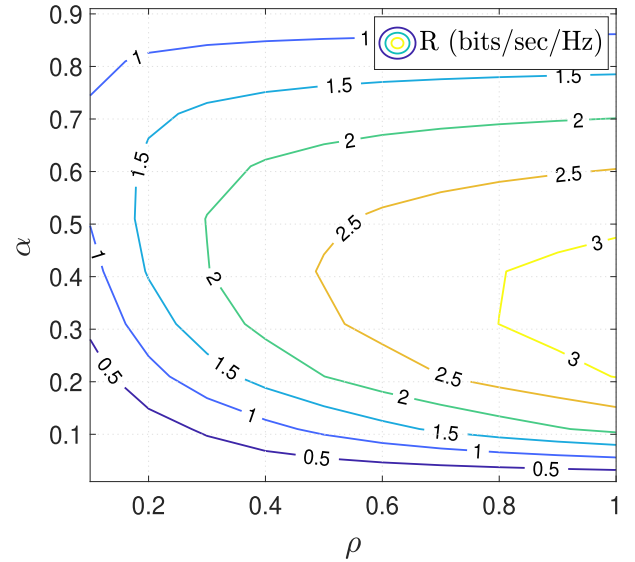


FIGURE 12. A contour plot of the FD throughput performance R . $P_r = 1$ Watt and $N_0 = -80$ dBm.

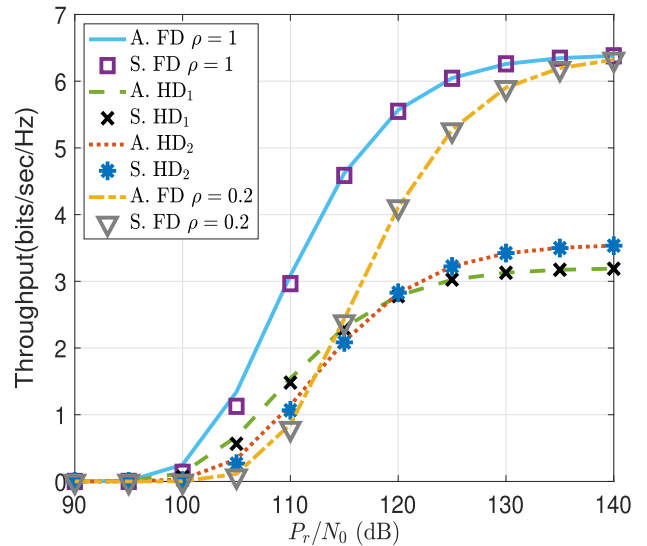


FIGURE 13. Throughput vs. P_r/N_0 in dB for the HD EH and FD EH systems. $\alpha = 0.2$.

represents a greater throughput. From this figure, the pairs of values α and ρ to achieve a specific throughput value can be found. For example, when $\alpha = 0.3$ and $\rho = 0.8$ or $\alpha = 0.2$ and $\rho = 1$, the throughput is 3 bits/sec/Hz. Recall that these analytical values ($\alpha = 0.2$, $\rho = 1$, $R = 3$ bits/sec/Hz) are consistent with those values numerically evaluated in Fig. 11.

Fig. 13 illustrates the analytical and simulation results of throughput with respect to P_r/N_0 in dB for the HD EH and FD EH systems. It is worth noting that P_r/N_0 is the transmit SNR at the source, thus its value is in a high dB range. We assume the time split is 0.2 and the polarization dissimilarity factor is 1. The throughputs of HD and FD systems have a small gap when P_r/N_0 is less than 100 dB. Then, for both systems, throughput increases significantly within the range $100 \text{ dB} < P_r/N_0 < 130 \text{ dB}$ and tends to

maintain the same value after 130 dB. For different polarization dissimilarity factors of the FD system, the throughput of $\rho = 1$ is higher than that of $\rho = 0.2$ within certain P_r/N_0 ranges and they gradually approach to the same maximum value. As for the HD₁ and HD₂ systems, the throughput of HD₂ is saturated at 3.5 bits/sec/Hz while HD₁ is saturated at 3.2 bits/sec/Hz, which illustrates that the former is 1.1 times than the latter. It is clear that, the FD system is saturated at 6.3 bits/sec/Hz. Thus, when the transmission power P_r at the relay is sufficiently large than the noise variance, the throughput in the FD system nearly double that of the HD systems. This observation also implies that the PDC scheme in the FD system can cancel the SI signal effectively, resulting in the received SNR at the destination being well above the threshold value γ_{th} . Besides, the simulation results of HD and FD systems match the analytical results, which verifies the theoretical analyses shown in (35) and (41), respectively.

From Figs. 9 and 13, it is clear that, with the cost of the polarized antennas and the digital SIC module, the FD EH system can double the system throughput while achieving the system outage probability as low as that in the HD EH counterpart.

VI. CONCLUSION

This paper considers a two-hop FD relaying system with the WET from the relay to the source. We assume the direct link from the source to the destination is not available and the information transmission between these two nodes relies on the assistance of the intermediate relay. The EH-capable source is utilized to achieve the self-sustainability of the wireless network. The relay is used to facilitate a long-distance transmission even when the transmitting power at the source node is low. A FD TSR protocol is used in the system to facilitate the cooperation of EH and HD information transmission at the source as well as enable the FD transmission at the relay. The PDC scheme, consisting of antenna polarization and digital signal processing, is adopted at the relay to cancel the SI signal generated by its own transmitter. The results show that the system throughput is a concave function with respect to the time split factor and the optimal time split can be numerically calculated. Moreover, the results reveal that the polarization dissimilarity factor has an influence on the interference and output noise power of the PDC scheme. When polarization states are orthogonal, the output noise of the PDC scheme is suppressed significantly, which leads to its best cancellation effect. Besides, at the cost of the polarized antennas and the additional digital signal processing module, the FD EH system can achieve the same outage probability as the HD₁ EH system, while doubling the system throughput. With the PDC scheme, the outage probability of the FD EH system can be superior to that of the HD₂ EH system. Besides, the throughput of the former nearly doubles that of the latter. Our future work includes the consideration of other promising SIC schemes [31], non-linear EH circuitry [32], [33], and the extension of the system model mentioned in

this paper to multiple antennas, multiple sources or multiple relays [34], [35].

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JIAMAN LI received the B.E. degree (Hons.) from the University of Wollongong, Australia, and Zhengzhou University, China, in 2016. She is currently pursuing the Ph.D. degree with the University of Wollongong. Her current research interest includes full-duplex communications in energy harvesting relaying networks.



LE CHUNG TRAN (Senior Member, IEEE) received the B.E. degree (Hons.) from the University of Transport and Communication (UTC), in 1997, the M.E. degree (Hons.) from the University of Science and Technology, Vietnam, in 2000, and the Ph.D. degree from the University of Wollongong (UOW), Australia, in 2006, all in telecommunications engineering. From 1997 to 2012, he was a Lecturer with UTC. From 2005 to 2006, he was an Associate Research Fellow with the Wireless Technologies Laboratory, UOW. From 2006 to 2008, he was a Postdoctoral Research Fellow with the University of Luebeck, Germany, under the Alexander von Humboldt (AvH) Fellowship. Since 2009, he has been with UOW, where he is currently a Senior Lecturer. He is the coauthor of over 90 publications, including the book *Complex Orthogonal Space-Time Processing in Wireless Communications* (Springer), which is available in 337 worldwide libraries. His research interests include 5G, MIMO, WBANs, positioning, navigation, and digital signal processing for communications. He has achieved the World University Services (WUS) Award (twice), the Vietnamese Government's Doctoral Scholarship, the International Postgraduate Research Scholarship (IPRS), the prestigious Humboldt Fellowship (twice), and the University Outstanding Contribution to Teaching and Learning (2019-OCTAL) Award. He has served as an Advisory Board Member for Cambridge Scholars Publishing, an Editorial Board Member for the *Electrical Engineering: An International Journal (EEIJ)*, a Keynote Speaker for the IEEE ICSPCS2019 Conference, an organizing committee member (the track chair, the session chair, and the publicity co-chair), and a technical program committee (TPC) member for over 30 IEEE conferences.



FARZAD SAFAEI (Senior Member, IEEE) received the Bachelor of Engineering degree in electronics from The University of Western Australia and the Ph.D. degree in telecommunications engineering from Monash University, in 1998. He was the Managing Director of the ICT Research Institute, from 2008 to 2013, and the Program Director of the Smart Services Cooperative Research Centre, Australia, from 2007 to 2014. He is currently the Chair of telecommunications engineering with the University of Wollongong. Before joining the University of Wollongong, he was the Manager of Internetworking Architecture and Services Section in Telstra Research Laboratories. His main research interests include multimedia signal processing and communications technology. He is the Winner of a number of awards, including the Top Australian and Asia Pacific Awards for ICT R&D, in 2012.

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