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An overview of RF energy harvesting and information transmission in cooperative communication networks

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Abstract

Wireless energy harvesting and information transfer (WEHIT) is a new paradigm in cooperative communication networks. WEHIT enables energy constrained cooperative communication nodes to harvest the energy needed for information transmission from electromagnetic radiation sources. Energy harvesting via radio frequency (RF) signals reduces the reliance on the supply of power grid, which makes it suitable for deployment in cooperative networks given that RF signals can concurrently carry wireless energy and information. This paper presents a review on RF energy harvesting in cooperative communication networks and the various techniques to simultaneously achieve wireless information and power transfer (SWIPT). Moreover, application advantages and disadvantages are specified. The major challenges of the SWIPT approach are enumerated. Solutions to these challenges are highlighted for future research.

Keywords Cooperative network · RF energy harvesting · Full-duplex relaying · Half-duplex relaying · SWIPT · WEHIT

1 Introduction

Energy-constrained communication networks have a limited viable lifetime. Consequently, energy-constrained cooperative relay nodes, which also have a limited viable lifetime, cannot sustain steady network connectivity, thereby making reliable communication difficult. Furthermore, recharging or replacing the batteries in nodes of a wireless network entails high cost, inconvenience, risk, or highly negative effects, particularly in sensors placed inside the human body and in building structures [1–3]. Taking into consideration the aforementioned cases, collecting energy from renewable energy sources in the surroundings is a safe and convenient choice.

Energy harvesting (EH) appears to be a quick fix for perpetuating the lifetime of the energy-constrained wireless communication networks. EH has recently gained appreciable attention among researchers. [1, 4–7]. Advances made in EH technology have made self-sustaining wireless nodes possible, thereby creating a promising and suitable technique to charge batteries in 5G wireless cooperative communication networks in the future [2, 8, 9].

As a result of the advances made in EH technologies, a new developing solution to switch energy constrained nodes on by using radio frequency (RF) signals has been proposed recently, the rationale of which is that RF signals can concurrently transfer wireless energy and information [1, 10]. Thus, nodes with limited energy in wireless cooperative networks can harvest energy via RF signals broadcast from the energetic nodes, which will be used in the simultaneous processing and transmission of information [1, 2, 10].

In addition, radio signals emitted by neighboring transmitters can be a close alternative source for wireless EH. As reported in [11, 12], using a power-cast RF energy harvester operating at 915 MHz, the wireless energy of 3.5 mJ and 1 uJ can be scavenged from RF signals at the equivalent ranges of 0.6 and 11 m, respectively. Recent advances in the design of energy-saving rectifying antennas can pave the way for an efficient wireless EH via RF signals in the near future [13].

Wireless energy harvesting and information transfer (WEHIT) in wireless communication networks have attracted many researchers both in the academe and indus-

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Table 1 Summary of existing review on WEHIT

Review	Scope	Contributions
[14]	Wireless cooperative networks with energy harvesting via RF signals	Overview of Receiver architectures for EH, Performance comparison of EH receivers, Challenges for future research
[18]	Wireless networks with EH via RF signals	Overview of RF-EH system architecture, RF-EH techniques and existing applications, Various design issues in the development of RF-EH networks
[15]	Wireless communication networks with EH	Overview of Information-theoretic physical layer performance constraints to scheduling policies and medium access control protocols, Emerging paradigm of cooperative SWIPT networks, Energy consumption models for EH communication networks
[16]	Wireless powered communication networks (WPCN)	Overview of Basics and backgrounds of WPCN networks, Recent developments in WPCN, Open research issues for WPCN
[17]	Wireless powered communication networks (WPCN)	Overview of The fundamentals of separated and integrated receiver architectures in SWIPT, Implementation perspectives and tools for WPCN, Open research problems for WPCN
[19]	Wireless cooperative networks with energy harvesting via RF signals	Overview of Relaying protocols for RF-powered cooperative communication networks, Cooperative spectrum sharing techniques for cognitive RF-powered networks, Cooperative jamming strategies with regard to the security of RF-powered communication systems, Open research problems for cooperative WPCN

try. Pioneering work on WEHIT [10] assumed the extraction of power and information from one and self-same signal. This finding has paved the way for the emergence of simultaneous wireless information and power transfer (SWIPT) techniques.

In cooperative communication networks, cooperative relaying techniques can be employed to mitigate fading and attenuation problems by positioning relay nodes between a transmitter and a receiver. Therefore, network performance such as efficiency, throughput, and reliability can be improved. However, an energy-constrained relay node cannot guarantee good quality of service (QoS).

With the advent of WEHIT, EH from ambient RF signals enables energy-constrained nodes in wireless cooperative communication networks to renew their energy and consequently prolong their lifetime, thereby making SWIPT a promising supportive technology for wireless cooperative communication networks [2, 4, 10]. Nevertheless, the cost of the ever-increasing demand, resource allocation control, mobility of the communication nodes, and multi-objective potential for the development of SWIPT-enabled cooperative networks still constitute major challenges for the network designers. A list of reviews has been presented in relation to this area [14–19], and summarized in Table 1. For instance, an overview of various cooperative strategies for RF-powered communication was presented in [19]. The main focus in this review was on different relaying protocols for RF-powered cooperative communication networks, cooperative spectrum sharing techniques for cognitive RF-powered networks, and cooperative jamming strategies with regard to the security of RF-powered communication systems. It can be noticed from this review paper, none of the reviewed literature has drawn the attention of the research community to the classification of the existing SWIPT-enabled cooperative networks into relay operation mode with their objectives target orientation. Therefore, in this paper, we intend to present the review of the cutting-edge research activities.

1.1 Motivation

In this survey, we critically investigated the existing various techniques to achieve SWIPT based on the performance of existing SWIPT-enabled cooperative networks. In our quest, we observed that most reviews, as summarized in Table 1, have not provided information on the SWIPT-enabled cooperative networks based on the classification to be discussed in Sect. 4.

Having carefully investigated the existing SWIPT-enabled cooperative networks, we discovered that there is a need to classify them into relay operation mode with their targeted objectives to derive a true concept of an efficient and robust SWIPT technique.

1.2 Contributions

The contributions of this review are highlighted as follows:

- This study investigates the existing various techniques to achieve SWIPT in relation to their application advantages and disadvantages. Then, we classified the existing SWIPT-enabled cooperative networks into relay operation modes, namely, half-duplex and full-duplex transmission modes with their objectives target orientation.
- Our study shows that most of the existing SWIPT techniques and solutions are designed for a specific purpose which prevents their adaptation to fluctuating network characteristics and incapable to achieve certain target objectives apart from their sole objectives. Therefore, designing a multi-objective target SWIPT technique is a great achievement.
- This study highlights open areas of research on SWIPT in cooperative networks.

The remaining part of this paper is arranged as follows. Section 2 presents the background of WEHIT. The various techniques to achieve SWIPT is presented in Sect. 3. Section 4 presents an overview of RF-EH and information transfer in cooperative networks, which focuses on related works and open research issues on SWIPT in cooperative networks. Section 5 concludes the paper.

2 Background of WEHIT

Researchers have examined traditional renewable energy resources (e.g., solar, mechanical vibration, and wind) and studied a number of resource allocation schemes for various objective orientations and network topologies [20]. However, the unpredictable and periodic character of these energy sources cannot guarantee good QoS, thereby promoting the use of EH via RF. This drawback can be overcome in a wireless network with the use of RF signals by using SWIPT. The energy-constrained nodes renew their energy from RF signals that come from more energetic nodes [18, 20].

For WEHIT, energy can be scavenged strategically from the signal in the environs or from a well-managed and dedicated source, such as a grid-powered base station (BS), or BS which uses conventional forms of renewable energy. By the signal in the environs, we refer to the transmitters (e.g., television towers) that are not dedicated or designed for RF–EH. This type of RF energy is absolutely for free. By contrast, the dedicated RF sources are not for free (i.e., they have been commercialized). Therefore, these sources are employed to deliver power to network nodes when reliable power supply is required. Thus, a high price is needed in order for the network to be deployed [18]. Various dedicated RF energy transfer strategies for mobile power transmitter to renew energy in wireless sensor networks were also explored [21–23].

The effective utilization of RF signals emitted by both ambient and dedicated transmitters is recognized by SWIPT and thus, provides significant benefit to users [24]. In particular, the demand for RF–EH can be predictable, thereby making it suitable for QoS-based application support [25]. Moreover, notable advantages in terms of energy consumption, time delay, spectral efficiency, and management of interference by superimposing information and power transfer are possible [20]. Moreover, RF signals can simultaneously deliver controllable and efficient wireless information and energy when required, thereby providing an economical possibility for the maintainable operations of wireless systems without any alteration to the hardware at the transmitter end [18]. Nevertheless, contemporary research on SWIPT has identified that optimizing wireless information and energy transmission simultaneously introduces a trade-off to the design of a wireless communication system [10]. In this case, the amount of information and energy transferred cannot be maximized simultaneously. This issue remains an open question in the implementation of SWIPT, especially in cooperative networks. A SWIPT-enabled cooperative network in which an energy-constrained relay node is ready to assist information transmission between a source node and a destination node that are connected to power grid is shown in Fig. 1. The relay node has no implanted power supply; hence, it needs to harvest energy from the RF signals broadcast by the source node, which can be stored in a rechargeable battery and then utilized for the information transmission to the destination node [1, 26]. In practice, the source node or the relay node or both can be EH-enabled, but not the destination node since it does not perform any information transmission [19].

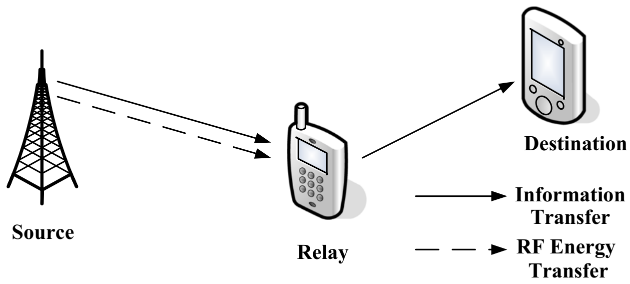

Fig. 1 A SWIPT-enabled cooperative network

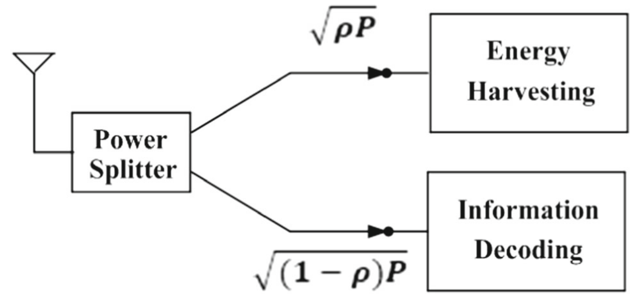

Fig. 2 Block diagram of PS technique

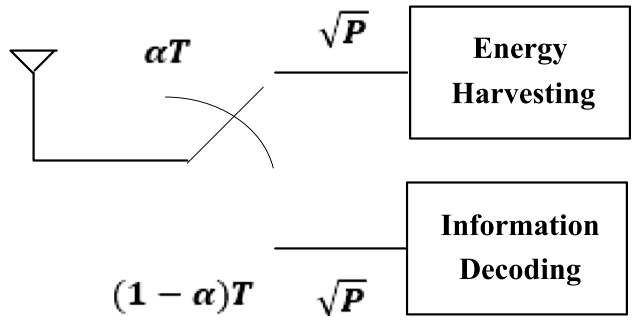

Fig. 3 Block diagram of TS technique

Some application areas of SWIPT include wireless sensors and transceivers, the Internet of things (IoT), and cellular systems. Dedicated power transmitters are used to implement wireless energy transfer in passive radio frequency identification networks [27]. The terms "energy" and "power" are used interchangeably in this paper.

3 Various techniques to achieve SWIPT

In the past, researchers provided information on SWIPT technology in their theoretical studies with the assumption that one signal can carry both power and information in the absence of any loss, thereby acknowledging a basic compromise between information and power transfer [10, 20, 28]. Nonetheless, this assumption of simultaneous transfer turns out to be false in real life [24] given that the practical circuits to scavenge energy from RF signals in the environs lack the capacity to instantly detect the carried information. Furthermore, the EH operation carried out in the RF region can destroy the content of the information [20]. Therefore, to virtually realize SWIPT, a receiver designed to separate the received signal into two segments, namely, for EH and information decoding, is needed. This method has been widely adopted [1, 2, 24, 29, 30]. The various techniques on signal separation in discrete domains proposed in the literature are discussed in the subsequent section.

3.1 Power splitting (PS) technique

In the PS technique, the signal power P at the receiver is split into two fractions, ρ: $(1-\rho)$ with $0 \leq \rho \leq 1$. The fractional ρ represents the EH receiver that scavenges energy for the transmission of the signal processed by the information receiver.

The remaining fraction $(1-\rho)$ is for the information decoding at the information receiver [1, 2, 31], as shown in Fig. 2.

The PS technique requires optimization of the PS factor (ρ), hence, achieving higher receiver complexity. However, this technique attains spontaneous SWIPT, because the signal received in a time slot of one-time block is used simultaneously for power transfer and information decoding. Therefore, PS technique is suitable for applications with delay constraints [13].

3.2 Time switching (TS) technique

In TS technique, the receiver is specifically designed to dynamically shift in time for EH and information decoding and achieve SWIPT using time fraction (α) [2]. In this scenario, the shifting of a signal is implemented based on the time factor. Hence, the signal received during a one-time slot is utilized either for power transfer or information decoding. The entire signal power received is used for EH at the EH receiver as the information receiver is off. As the information receiver is turned on, information decoding uses all the signal power received [24]. Thus, hardware implementation at the receiver in TS technique is not as complex as in PS technique, but requires proper time synchronization and information/energy scheduling [20]. Figure 3 depicts the block diagram of SWIPT transmission using TS technique.

3.3 Antenna switching (AS) technique

In AS technique, the receiving antennae are divided into two sets. In Fig. 4, one set of receiving antennae is employed for information decoding and another set for EH [2]. Consequently, this arrangement allows independent and simultaneous EH and information decoding. However, this technique

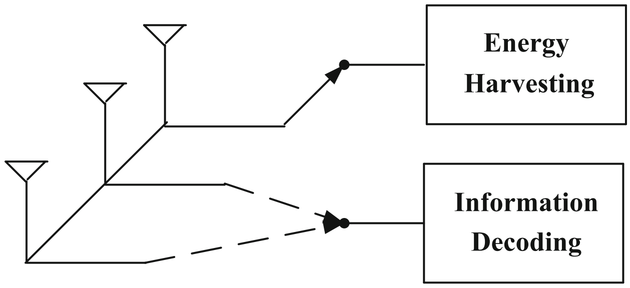

Fig. 4 Block diagram of AS technique

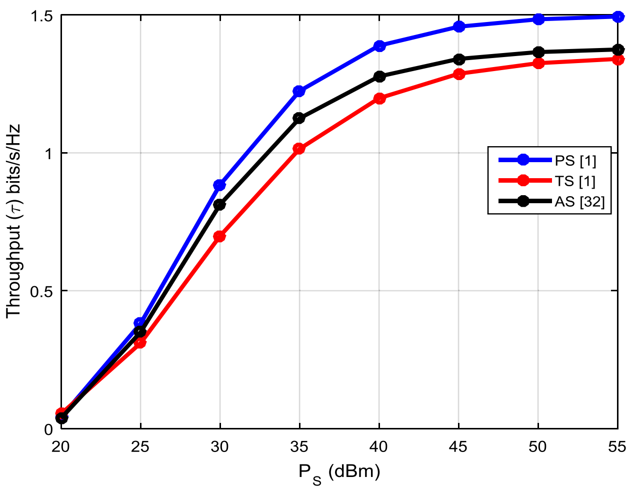

Fig. 5 Throughput performance of different SWIPT techniques against transmitted power from the source P_S

results in an optimization problem, which requires a solution in each communication frame for deciding the optimal allocation of the antenna sets for EH and information decoding. Furthermore, the AS technique is highly complex. Therefore, in the literature, a low-complexity AS scheme was developed by combining the principles of generalized selection [32, 33] to facilitate SWIPT.

3.4 Performance results of the SWIPT techniques

The throughput performances of the PS, TS, and AS techniques against various source transmitted power P_S is demonstrated in Fig. 5. We set the values of the simulation parameters similar as in [1, 32]. For the AS technique, the number of antenna at the EH-enabled relay is set to 3. It can be observed that the PS technique outperformed both the AS and TS techniques in terms of throughput. Therefore, the PS technique offers a tradeoff between the throughput and the transmitted power cost. From this figure, the performance of the TS technique is the lowest since the protocol requires time splitting activity [20].

In Table 2, we present the advantages and disadvantages of various techniques to achieve SWIPT.

4 Overview of RF-EH and information transfer in cooperative networks

The key issues for WEHIT include the decrease in energy transfer efficiency and signal fading over a long transmis-

Table 2 Advantages and disadvantages of various SWIPT techniques

SWIPT technique	Advantages	Disadvantages
1. Power splitting (PS)	It attains spontaneous SWIPT It is adequate for applications with delay constraints It achieves better tradeoffs between information rate and the amount of RF energy transfer as compared to other techniques [20, 33]	It requires optimization of the power factor Higher receiver complexity
2. Time switching (TS)	The receiver simply switches in time between EH and information decoding Hardware implementation of the receiver is simple	It requires proper time synchronization and information or energy scheduling [20, 33]
3. Antenna switching (AS)	It can acquire different tradeoffs between maximal information rate and RF energy transfer [2] The antennas can observe different channels, thereby perform EH and information decoding independently and simultaneously	The optimization problem is complex It suffers from high receiver complexity In case of hardware impairment, the system performance can be degraded

sion range. The effects of these issues can be mitigated by using the cooperative relaying technique with SWIPT. An intermediate relay node(s) with EH capability can be employed in transmitting a sourced information to a destination node, thereby resulting in reliable communication. Operation policy, selection scheme, power allocation strategy, and pre-coder optimization problem in the network should be considered in relay nodes. Basically, most researchers studied on how to enhance performance gain on the power allocation strategies, relay operation policy as well as relay selection schemes by applying amplify-and-forward (AF) and decode-and-forward (DF) relaying techniques [18, 34, 35]. Some related works are reviewed in the subsequent section.

4.1 Related works on SWIPT in cooperative networks

Recent studies have considered SWIPT with other techniques in cooperative communication networks [5, 6]. Now, we will review and classify the recent advances into two categories, namely, SWIPT in half-duplex (HD) and SWIPT in full-duplex (FD) wireless relaying networks.

4.1.1 SWIPT in HD wireless relaying network

The SWIPT in HD wireless cooperative communication networks has been investigated in the literature [1, 36–40]. An optimal resource allocation between EH and data transmission using TS and PS relaying protocols in an AF wireless cooperative network was investigated [1]. The objective function was to maximize the system throughput. An energy-constrained relay node collects power from the RF signal broadcast by a powerful source node. The relay makes use of the collected power to deliver the source signal to a destination in two transmission modes, namely, the delay-constrained and the delay-tolerant transmission modes. The achievable throughput of the network was determined at the destination by analyzing the ergodic capacity and the outage probability for the delay-tolerant transmission mode and the delay-constrained transmission mode, respectively. The assumptions of the authors were hinged on the fact that the channel statistics of the channel state information (CSI) may be obtained from the destination only. Moreover, no direct communication link exists between the source and destination nodes. Thus, the transmission is solely relay-assisted, and if an outage occurs at the energy-constrained relay node, no information will be received at the destination. A three-node communication network with DF relaying was studied [36], and the throughput maximization problem of the considered network was explored. In this present study, the transmission power of both the source and relay nodes are received from dedicated EH sources. A periodic model for EH was assumed, such that the duration of the arrival of energy and the amount of harvested energy is determined before transmission. However, in practice, many EH sources should be modeled as random processes, such as the block Markov model [41].

Two operation protocols, namely, PS with DF relaying protocol and TS with DF relaying protocol were proposed [37]. The system performances of the two protocols were characterized and determined based on their outage probabilities, and then compared with the outage performance of non-cooperative link transmission protocol. The analytical results were confirmed with Monte Carlo simulations. When the number of EH relays increased, the system performances of the proposed PS with DF relaying protocol and TS with DF relaying protocol improved and eventually outperformed the non-cooperative link transmission protocol. However, considering the limited energy at the relays, the destination cannot pick up all the CSIs from all relays. In view of this situation, the selected channel power gain from the source to the best relay may not be the maximum channel power gain, but this channel power gain is the maximum value acknowledged by the destination at that time. Hence, the relay selection scheme is still a challenge to practically realize SWIPT.

Based on the PS relaying protocol, a three-node cooperative network comprising one source, a battery-enabled relay with AF technique, and one destination node was investigated [38]. Unlike the previous work, direct link transmission and cooperative link transmission were considered. To exploit the diversity gain, a maximum ratio combining (MRC) technique was employed at the destination node. Considering a delay-constrained transmission mode, they derived a closed form expression for the outage probability of the considered network. This work was extended to the multi-relay scenario with two relay selection techniques. The results showed that the MRC technique gives a better outage performance than both direct link and relay transmission [38]. However, the capacity level of the battery used was not considered.

Two different power allocation techniques, namely, the centralized power allocation technique and auction-based power allocation technique with PS, were proposed for multi-pair communication via a single RF–EH relay [39]. The main focus was on the methods by which the RF–EH relay shares the harvested power among the multiple source-destination pair communication and their effect on the system performance. As can be observed from simulation results, the auction-based power allocation technique accomplishes a more desirable tradeoff between the system performance and complexity. Although, it necessitates CSI at the transmitter, thereby adding a significant system overhead as the number of source-destination pair increases [39].

An RF–EH-enabled cooperative communication network with TS–AF relaying protocol was studied [40]. The source and relay in this network have no other source of power aside from the RF signals transmitted by a hybrid-access point during the downlink phase and cooperatively transmitted information during the uplink phase. A number of past studies [1, 12, 22] were extended in a relatively more recent work [40] by assuming a delay-constrained transmission mode, and the analytical expression for the average throughput of the considered network was derived over Rayleigh fading channels. The selection-combining technique was applied at the destination node. The harvest-then-cooperate (HTC) protocol [40] was proposed and extended to the multi-relay scheme with two different relay selection techniques, and the results showed that the proposed HTC protocol performed better than the harvest-then-transmit protocol proposed in a previous work [12].

The problem of throughput efficiency maximization in a dual-hop EH relaying system [42] was studied with an adaptive TS for AF and DF relaying schemes. The optimal TS coefficient was adaptively modified following the dual-hop CSI, harvested power, and targeted signal-to-noise ratio (SNR), to obtain the maximum throughput efficiency per communication block. Then, the low-complexity TS coefficient model was proposed to minimize the CSI overhead at the EH-enabled relay. This model only required a single-hop CSI to evaluate the TS coefficient.

The problem of power allocation and power-splitting factor optimization for SWIPT over doubly-selective vehicular channels was explored [43]. Contrary to the conventional PS problem with constant time channels [24], the problem was designed as a joint optimization of power allocation, across frequency and time, and SWIPT PS coefficients across time slots. The goal was to maximize the transmission rate for information decoding within a number of time frames and a certain number of sub-bands. Subsequently, on the basis of previous findings [43], a dual-step technique called joint power allocation and splitting (JoPAS) was proposed. The exact outage probability performance of a relay selection strategy that considered battery capacity with the addition of CSI to construct the selection criterion in a wireless-powered cooperative network with AF relaying protocol was also explored [44], which is different from the previous literature that considered only CSI for the selection criterion. This relay selection strategy promised high accuracy but required a complex station.

The throughput performance of an EH-based cooperative AF relaying network was examined in [45]. The cooperative network comprises a source, two HD relays, and a destination. The two HD relays operate with EH and alternately assist in data transmission between the source and the destination. When one HD relay assists in data transmission, the other HD relay will harvest energy by listening to the transmissions from both the source and the transmitting HD relay. The authors in [45] derived the analytical expressions of the system throughput on the basis of the AF-PS and the AF-TS relaying protocols. Simulation results showed that the two HD relays system outperformed the single HD relay system in terms of throughput. The work in [45] was extended to an adaptive cooperative transmission with DF-PS relaying protocol in [46]. The two HD relays alternately forward source data to the destination by using a two-path successive relaying protocol. When one HD relay transmits the previous data together with the source transmitting current data using PS technique, the other HD relay harvests energy and decodes the current data from the received signals. Also, if the two-path successive relaying cannot be executed as a result of the failure of data decoding at either HD relay, the DF protocol will be executed by selecting a better HD relay. Simulation results revealed that the adaptive cooperative relaying scheme outperformed both the single HD relay DF scheme and the two-path successive relaying-only scheme in terms of throughput.

4.1.2 SWIPT in FD wireless relaying network

A new approach to achieve an efficient SWIPT in cooperative networks that is recently drawing considerable attention is SWIPT in FD wireless cooperative communication networks [47]. HD transmissions are hard to meet the high spectrum efficiency requirement of the future 5G wireless cooperative communication [48]. The FD transmission utilizes the channel bandwidth effectively because it needs only a single channel for the point-to-point transmission. However, the transmission is affected by residual loop interference as a result of the signal emitted between the relay receiving antenna and transmitting antenna [49, 50]. Moreover, FD transmission was regarded before as impractical because of strong self-interference [51, 52], but has regained significant attention from the academe and industry. With the advent of WEHIT, reports showed that the FD transmission improves spectral efficiency and achieves better SWIPT than the HD transmission [47, 53–56]. Particularly, it can be employed in developing future wireless local area networks [57], WiFi networks [58], 5G networks [59], and FD radio for local access projects [60]. These networks are a result of current development in antenna technology and signal processing.

The virtual harvest-use model and harvest-use-store model for PS–SWIPT in a DF FD relaying network were proposed [52]. For the former, the outage probability was designed and proposed in an exact integral form and the optimal PS factor that maximizes the end-to-end signal-to-interference-plus-noise ratio (e-SINR) was characterized in a closed form. The tradeoff between the e-SINR and recycled self-energy was also quantified [52]. For the latter, a greedy switching policy is applied with energy build-up throughout the transmission blocks. Similarly, the optimal PS factor of the greedy switching policy was determined and the equivalent outage probability was obtained by designing the relay's energy status as a Markov chain with a dual-stage state transition. The simulation results show that an increase in residual self-interference in the RF-domain is highly beneficial to the system by utilizing it as a recycled self-energy. Thus, the e-SINR and outage performance can be enhanced when minimizing the residual self-interference detected in the digital domain. The results showed better performance of SWIPT in FD than the SWIPT in HD in terms of outage probability [52].

The problem of optimal power allocation for an FD cooperative relaying network that utilizes EH and energy recycling was considered [61]. The cooperative relaying network was investigated by splitting each time slot into an EH stage and an information transmission stage. To evaluate the optimal source power levels for both EH stage and information transmission stage, a rate or correspondingly an SNR maximization problem was formulated and solved. The performance of the designed optimal power allocation technique with FD relaying was confirmed by Monte Carlo simulations, and findings showed that the setup was better than that wherein the source transmitted the same power level in both stages of the transmission. By considering the TS-based AF and DF relaying protocols, the performance of a cooperative network with an EH-enabled FD relay was investigated in [62]. The systems performance was characterized and determined based on the outage probability and throughput. Simulation results showed that the TS-based AF relaying protocol outperformed the TS-based DF relaying protocol in terms of outage probability and throughput under certain factors.

A wireless-powered symmetric FD AF relaying system for an efficient SWIPT was considered for constant information transmission and self-energy recycling by the relay [55]. Following the multiple-input single-output channel system, the beam-forming and power allocation models at the relay were developed to maximize system throughput. However, the role of SINR was not fully considered. For instance, the source-relay and relay-destination connections can rarely be identical in wireless-powered symmetric relay transmission system because the transmission power at the relay may be lower compared with that at the source, taking into account some factors, such as channel attenuation and low EH efficiency. Hence, the symmetric transmission system with uniform time slots naturally reduces the resource utilization efficiency, and the system throughput is always bound by the relay-destination connection. To overcome these issues, an asymmetric FD DF wireless-powered relay system was proposed in [63].

All the above-reviewed literature on SWIPT in FD wireless relay networks focused on the one-way relay which is not as efficient as the FD two-way relay [64–67]. The wireless-powered two-way AF TS-based relaying protocol with SWIPT in FD mode [67], in which an energy-limited relay node cooperates in the information transmission between a hybrid access point and a destination node, was examined. The relay node harvests energy from both the hybrid access point and its own loop-back signal (self-energy recycling) and then utilizes the harvested energy for transmission. Specifically, the sum-throughput optimization problem was formulated based on the energy constraint at the relay and then the TS parameter was optimized. The numerical results show that the two-way AF TS-based relaying protocol outperforms the existing one-way AF TS-based relaying protocol.

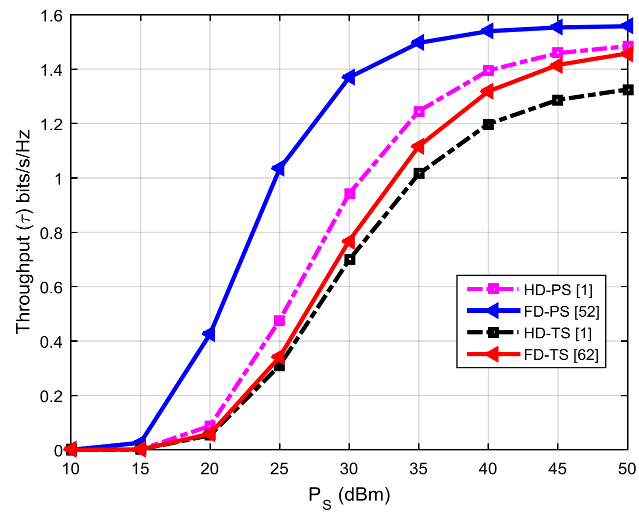

Fig. 6 Throughput performance of SWIPT techniques in HD and FD relaying

SWIPT was also investigated by considering the cooperative multiple-input-multiple-output (MIMO) two-way relay systems, where the FD AF relay is equipped with multiple antennas [68]. The optimal joint design of the receiver PS factor and the beamforming vector at the relay node were investigated by assuming that the CSI is perfect. The optimization was aimed at maximizing the achievable sum-rate of the SWIPT system. However, the optimization of the transmission power at the source nodes was not considered. Subsequently, to maximize the achievable sum-rate of a SWIPT system with an FD MIMO AF relaying, the joint optimization problem of two-way relay beamforming, receiver PS factor, and power transmitted at the source was formulated [69].

4.1.3 Performance of SWIPT techniques in HD and FD wireless relaying network

Figure 6 shows the throughput performances comparison between the PS technique and the TS technique. We set the same values of simulation parameters as presented in [1, 52, 62]. It can be observed that as the transmitted power

Table 3 Summary of some of the related works on WEHIT reported in the literature

Literature	Objective	Relay transmission mode	Transmission protocols	Number of relays	Channel model	CSI requirement	Remarks
[1]	Throughput maximization	HD	TS-based and PS-based with AF relaying	Single	Quasi-static block fading channel	CSI at the destination node	The PSR protocol gives a better performance over the TSR protocol at relatively high SNRs
[37]	Minimization of outage probability	HD	TS-based and PS-based with DF relaying	Single/Multiple	Rayleigh fading channel	CSI at the receivers	The performance of the system depends on the target SNR, the system parameters and the number of relays
[38]	Minimization of outage probability	HD	PS with AF relaying and MRC at destination	Single/multiple	Rayleigh fading channel	CSI at the destination node	A diversity order of 2 is obtained with the use of MRC at the destination
[39]	Minimization of outage probability	HD	PS with DF relaying	Single	Quasi-static Rayleigh fading channel	CSI at the transmitter	There is a remarkable system overhead as the number of source-destination pair increases
[40]	Throughput maximization	HD	TS-based HTC protocol with AF relaying and Selection combiner at destination	Single/multiple	Rayleigh fading channel	CSI at the destination node	The performance gain of the proposed HTC protocol is improved by increasing the number of assisted relays in the network
[42]	Throughput efficiency maximization	HD	TS with AF and DF relaying	Single	Slow fading channels	CSI at the receivers	It suffers Implementation complexity
[43]	Maximizing achievable data rate	HD	PS with DF relaying	Single	Doubly selective channels	CSI at the transmitter	The proposed technique, JOPAS improves flexibility and more efficient usage of the channels
[52]	Minimization of outage probability	FD	PS with DF relaying	Single	Nakagami-m fading	CSI at the receivers	The proposed scheme with FD relaying outperforms the existing HD PS-based SWIPT
[61]	Rate/SNR maximization	FD	AF relaying	Single	Rayleigh fading channel	CSI at the transmitter	The optimal power allocation technique achieves better performance than the existing technique but with computational complexity

Table 3 continued

Literature	Objective	Relay transmission mode	Transmission protocols	Number of relays	Channel model	CSI requirement	Remarks
[62]	Minimization of outage probability/ Throughput maximization	FD	TS-based AF and DF relaying	Single	Quasi-static block fading channel	CSI at the destination node	The DF relaying outperforms the AF relaying when the EH-enabled relay is deployed near the source. Otherwise, the AF relaying outperforms the DF relaying
[55]	Throughput maximization	FD	Symmetric FD and TS with AF relaying	Single	Rayleigh fading channel	CSI at the transmitter	The Symmetric FD transmission achieves a significant throughput gain over the existing TS-based
[63]	Spectral efficiency maximization	FD	Asymmetric FD and TS with DF relaying	Single	Rayleigh fading channel	CSI at the transmitter	The asymmetric FD transmission achieves a higher degree of freedom than the symmetric transmission in [55]

P_S increases, the throughput performances of the PS and TS techniques increased. Simulation results showed that the FD relaying outperforms the HD relaying in terms of throughput for both the PS and TS techniques. These show that the FD relaying can achieve better SWIPT than the HD relaying. It can also be observed that the PS technique is superior than the TS technique when using the same relaying scheme.

Table 3 presents the summary of the related works that dwelt with the WEHIT methods as reported in the literature.

4.2 Open research issues on SWIPT in cooperative networks

In the previous sections, we have provided an up-to-date overview on WEHIT by exploiting SWIPT techniques in cooperative networks and the applicable protocols proposed by early researchers. Now, we present the open research issues on SWIPT that demand the attention of both the academics and the industrialists in order to design more efficient and reliable EH-enabled cooperative communication networks.

4.2.1 Nodes mobility

In a cooperative communication network, one or two nodes can be mobile, which makes the harvested energy to be random [70]. Therefore, the mobility of the network nodes (e.g., RF sources and EH receivers) is of great concern in the WEHIT system because EH and information transfer performances become distance-dependent and time-varying. The power allocation strategy has to be dynamically employed. In future research, the tradeoffs between the transmitted power and information transfer with a reasonable transmission rate over a distance have to be explored by designing a hybridized power-time splitting technique that considers the channel statistics of the CSI variation.

4.2.2 Multi-user scheduling

With its dual purpose, an electromagnetic signal has the capability to concurrently convey energy and information to the receiving nodes. Thus, the dynamic range of the lowest power level for EH (-10 dBm) and information detection (-60 dBm) [20, 24] remains a bottleneck for the realization of SWIPT. Therefore, the introduction of user scheduling and joint power allocation plays a crucial role in the practical realization of SWIPT. For example, in a multi-user scenario, an idle user experiencing high channel gains can be scheduled for energy transfer to energy constrained node. Energy and information scheduling can also be used for a fair tradeoff within the communication system.

4.2.3 Multiple energy harvesting relay nodes

Even though some studies have been carried out in this area, designing an efficient relay selection technique is still a challenge in SWIPT when aiming to optimize the performance of a whole system consisting of multiple EH relay nodes. The key issue is that the selected relay for information transfer may not be the relay with the best channel for EH. Therefore, designing a relay selection technique that can address the tradeoff between the efficiency of information and power transfer is needed.

4.2.4 Resource allocation and interference management

One of the vital determinants that disturbs the system performance in conventional communication networks is co-channel interference [20]. This factor has to be overcome through resource allocation. By contrast, EH-enabled receivers in cooperative communication networks can use this energetic interference as a main source of energy. In this case, SWIPT in FD can be of great benefit for overall system efficiency by adding artificial interference to the communication system for energy-constrained node usage. The major challenge is how this can be managed adequately to prevent the communication system from suffering through self-interference.

4.2.5 Multi-objective SWIPT technique

Most of the existing SWIPT techniques are designed and deployed mainly in a single objective-oriented SWIPT-enabled cooperative communication net-works, which prevents adaptation to erratic network characteristics that are incapable of achieving certain target objectives aside from sole objectives. Therefore, designing a multi-objective target SWIPT technique is a great challenge to overcome.

4.2.6 Modeling of the relay energy status

The energy status of the SWIPT-enabled relay in most of the existing literature was not considered. The SWIPT-enabled relay may not use the harvested energy immediately after harvesting it. The relay may harvest energy from the more powerful node(s) opportunistically and store the energy into its rechargeable battery. Then the harvested energy maybe used only when it requires to forward the source's data to the intended destination. The major challenge is how to model the energy accumulation process at the relay. Therefore, modeling the accumulation process is a great challenge to overcome in the SWIPT-enabled communication system.

5 Conclusion

In this paper, we presented a review on RF–EH and information transfer in cooperative communication networks. We compared the benefits and shortcomings of each SWIPT technique, and we highlighted existing research issues and corresponding contemporary solutions related to RF–EH and information transfer in cooperative communication networks. Future research may address the critical issues we have identified in WEHIT.

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References

1. Ali, A. N., Zhou, X., Durrani, S., & Kennedy, R. A. (2013). Relaying protocols for wireless energy harvesting and information processing. *IEEE Transactions on Wireless Communications, 12*(7), 3622–3636.
2. Zhang, R., & Ho, C. K. (2013). MIMO broadcasting for simultaneous wireless information and power transfer. *IEEE Transactions on Wireless Communication, 12*(5), 1989–2001.
3. Zhai, C., & Liu, J. (2015). Cooperative wireless energy harvesting and information transfer in stochastic networks. *Eurasip Journal on Wireless Communications and Networking, 2015*(44), 1–22. https://doi.org/10.1186/s13638-015-0288-3.
4. Xu, J., & Zhang, R. (2014). Throughput optimal policies for energy harvesting wireless transmitters with non-ideal circuit power. *IEEE Journal on Selected Areas in Communications, 32*(2), 322–332.
5. Chalise, B. K., Zhang, Y. D., & Amin, M. G. (2012). Energy harvesting in an OSTBC based amplify-and-forward MIMO relay system. In *Proceedings of the 2012 IEEE international conference on acoustics, speech, and signal processing, ICASSP 2012* (pp. 3201–3204).
6. Fouladgar, A. M., & Simeone, O. (2012). On the transfer of information and energy in multi-user systems. *IEEE Communications Letters, 16*(11), 1733–1736.
7. Luo, S., Zhang, R., & Lim, T. J. (2013). Optimal save-then-transmit protocol for energy harvesting wireless transmitters. *IEEE Transactions on Wireless Communications, 12*(3), 1196–1207.
8. Liu, L., Zhang, R., & Chua, K. C. (2013). Wireless information and power transfer: A dynamic power splitting approach. *IEEE Transactions on Communications, 61*(9), 3990–4001.
9. Hoang-Sy, N., Dinh-Thuan, D., Thanh-Sang, N., & Miroslav, V. (2017). Exploiting hybrid time switching-based and power splitting-based relaying protocol in wireless powered communication networks with outdated channel state information. *AUTOMATIKA, 58*(1), 111–118.
10. Varshney, L. R. (2008). Transporting information and energy simultaneously. In *Proceedings of the 2008 IEEE international symposium on information theory* (pp. 1612–1616).
11. Zungeru, A. M., Ang, L. M., Prabaharan, S., & Seng, K. P. (2012). Radio frequency energy harvesting and management for wireless sensor networks. *Green Mobile Devices Network: Energy Opt. Scav. Tech.,* Boca Raton: CRC Press (pp. 341–368).
12. Ju, H., & Zhang, R. (2014). Throughput maximization in wireless powered communication networks. *IEEE Transactions on Wireless Communications, 13*(1), 418–428.
13. Vullers, R. J. M., Schaijk, R. V., Doms, I., Hoof, C. V., & Mertens, R. (2009). Micropower energy harvesting. *Elsevier Solid-State Circuits, 53*(7), 684–693.

14. Liu, K.-H., & Lin, P. (2015). Toward self-sustainable cooperative relays: State of the art and the future. *IEEE Communications Magazine, 53*(6), 56–62.
15. Ulukus, S., Yener, A., Erkip, E., Simeone, O., Zorzi, M., Grover, P., et al. (2015). Energy harvesting wireless communications: A review of recent advances. *IEEE Journal on Selected Areas in Communications, 33*(3), 360–381.
16. Niyato, D., Kim, D. I., Maso, M., & Han, Z. (2017). Wireless powered communication networks: Research directions and technological approaches. *IEEE Wireless Communications, 24*(6), 88–97.
17. Jameel, F., Faisal, Haider, M. A. A., & Butt, A. A. (2017). A technical review of simultaneous wireless information and power transfer (SWIPT). In *International symposium on recent advances in electrical engineering (RAEE) 2017* (pp. 1–6).
18. Xiao, L., Ping, W., Dusit, N., Dong, I. K., & Zhu, H. (2015). Wireless networks with RF energy harvesting: A contemporary survey. *IEEE Communications Survey & Tutorial, 17*(2), 1–34.
19. Chen, H., Zhai, C., Li, Y., & Vucetic, B. (2018). Cooperative strategies for wireless-powered communications: An overview. *IEEE Wireless Communications*. https://doi.org/10.1109/MWC.2017.1700245.
20. Ioannis, K., Stelios, T., Symeon, N., Gan, Z., Derrick, W. K. N., & Robert, S. (2014). Simultaneous wireless information and power transfer in modern communication systems. *IEEE Communications Magazine, 52*(11), 104–110.
21. Erol-Kantarci, M., & Mouftah, H. T. (2012). Sure sense: Sustainable wireless rechargeable sensor networks for the smart grid. *IEEE Wireless Communications, 19*(3), 30–36.
22. Erol-Kantarci, M., & Mouftah, H. T. (2012). Mission-aware placement of RF-based power transmitters in wireless sensor networks. In *Proceedings of the IEEE symposium on computers and communications, ISCC 2012* (pp. 12–17).
23. Erol-Kantarci, M., & Mouftah, H. T. (2012). DRIFT: Differentiated RF power transmission for wireless sensor network deployment in the smart grid. In *Proceedings of the 2012 IEEE globecom workshops*, Anaheim (pp. 1491–1495).
24. Xun, Z., Rui, Z., & Chin, K. H. (2013). Wireless information and power transfer: Architecture design and rate-energy tradeoff. *IEEE Transactions on Communications, 61*(11), 4754–4767.
25. Deepak, M., Swades, D., Soumya, J., Stefano, B., Kaushik, C., & Wendi, H. (2015). Smart RF energy harvesting communications: Challenges and opportunities. *IEEE Communications Magazine, 53*(4), 70–78.
26. Ojo, F. K., & Salleh, M. F. M. (2018). Throughput analysis of a hybridized power- time splitting based relaying protocol for wireless information and power transfer in cooperative networks. *IEEE Access*. https://doi.org/10.1109/ACCESS.2018.2828121.
27. Smith, J. R. (2013). *Wirelessly powered sensor networks and computational RFID*. New York, NY: Springer.
28. Grover, P., & Sahai, A. (2010). Shannon meets Tesla: Wireless information and power transfer. In *Proceedings of.the IEEE international symposium on information theory, ISIT2010 (*pp. 2363–2367).
29. Liu, L., Zhang, R., & Chua, C. K. (2013). Wireless information transfer with opportunistic energy harvesting. *IEEE Transactions on Wireless Communications, 12*(1), 288–300.
30. Xiang, Z., & Tao, M. (2012). Robust beamforming for wireless information and power transmission. *IEEE Wireless Communications Letters, 1*(4), 372–375.
31. Sang, Q. N., & Hyung, Y. K. (2016). Generalized diversity combining of energy harvesting multiple antenna relay networks: Outage and throughput performance analysis. *Annals of Telecommunications, 71*(5), 265–277.
32. Ioannis, K., Shigenobu, S., Stelios, T., & Zhiguo, D. (2014). A low complexity antenna switching for joint wireless information and energy transfer in MIMO relay channels. *IEEE Transactions on Communications, 62*(5), 1577–1587.
33. Perera, T. D. P., Jayakody, D. N. K., Sharma, S. K., Chatzinotas, S., & Li, J. (2018). Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges. *IEEE Communications Surveys & Tutorials, 20*(1), 264–302.
34. Chalise, B. K., Ma, W. K., Zhang, Y. D., Suraweera, H. A., & Amin, M. G. (2013). Optimum performance boundaries of OSTBC based AF-MIMO relay system with energy harvesting receiver. *IEEE Transactions on Signal Processing, 61*(17), 4199–4213.
35. Moritz, G. L., Rebelatto, J. L., Souza, R. D., Ucha-Filho, B. F., & Li, Y. (2014). Time-switching uplink network-coded cooperative communication with downlink energy transfer. *IEEE Transactions on Signal Processing, 62*(19), 5009–5019.
36. Huang, C., Zhang, R., & Cui, S. (2013). Throughput maximization for the Gaussian relay channel with energy harvesting constraints. *IEEE Journal on Selected Areas in Communications, 31*(8), 1469–1479.
37. Son, P. N., Hyung, Y. K., & Alagan, A. (2016). Exact outage analysis of a decode-and-forward cooperative communication network with Nth best energy harvesting relay selection. *Annals of Telecommunications, 71*(5), 251–263.
38. Mahama, S., Asiedu, D. K. P., & Lee, K. (2017). Simultaneous wireless information and power transfer for cooperative relay networks with battery. *IEEE Access, 5,* 13171–13178.
39. Ding, Z., Perlaza, S. M., Esnaola, I., & Poor, H. V. (2014). Power allocation strategies in energy harvesting wireless cooperative networks. *IEEE Transactions on Wireless Communications, 13*(2), 846–860.
40. Chen, H., Yonghui, L., Joao, L. R., Bartolomeu, F. U., & Branka, V. (2015). Harvest-then-cooperate: Wireless-powered cooperative communications. *IEEE Transactions on Signal Processing, 63*(7), 700–1711.
41. Ho, C. K., & Zhang, R. (2012). Optimal energy allocation for wireless communications with energy harvesting constraints. *IEEE Transactions on Signal Processing, 60*(9), 4808–4818.
42. Ding, H., Wang, X., Da costa, D. B., Chen, Y., & Gong, F. (2017). Adaptive time-switching based energy harvesting relaying protocols. *IEEE Transactions on Communications, 65*(7), 2821–2837.
43. Wang, D., Zhang, R., Cheng, X., Quan, Z., & Yang, L. (2017). Joint power allocation and splitting (JoPAS) for SWIPT in doubly selective vehicular channels. *IEEE Transactions on Green Communications and Networking, 1*(4), 494–502.
44. Liu, K. H. (2016). Performance analysis of relay selection for cooperative relays based on wireless power transfer with finite energy storage. *IEEE Transactions on Vehicular Technology, 65*(7), 5110–5121.
45. Zheng, L., Zhai, C., & Liu, J. (2017). Alternate energy harvesting and information relaying in cooperative AF networks. *Telecommunication Systems*. https://doi.org/10.1007/s11235-017-0399-8.
46. Zhai, C., Zheng, L., Lan, P., & Chen, H. (2018). Wireless powered cooperative communication using two relays: Protocol design and performance analysis. *IEEE Transactions on Vehicular Technology, 67*(4), 3598–3611.
47. Hongwu, L., Kyeong, J. K., Kyung, S. K., & Poor, V. H. (2015). Power splitting based SWIPT with decode-and-forward full-duplex relaying. *Cornell University Library*. Arxiv: 1504.04697.
48. Wang, W., Wang, R., Duan, W., Feng, R., & Zhang, G. (2017). Optimal transceiver designs for wireless-powered full-duplex two-way relay networks with SWIPT. *IEEE Access, 5,* 22329–22343.
49. Riihonen, T., Werner, S., & Wichman, R. (2009). Optimized gain control for single-frequency relaying with loop interference. *IEEE Transactions on Wireless Communications, 8*(6), 2801–2806.
50. Hamazumi, H., Imamura, K., Iai, N., Shibuya, K., & Sasaki, M. (2000). A study of a loop interference canceller for the relay stations in an SFN for digital terrestrial broadcasting. In *Proceedings of the*

2000 IEEE global telecommunications conference, GLOBECOM 2000 (pp. 167–171).
51. Krikidis, I., Suraweera, H. A., Smith, P. J., & Yuen, C. (2012). Full-duplex relay selection for amplify-and-forward cooperative networks. *IEEE Transactions on Wireless Communications, 11*(12), 4381–4393.
52. Hongwu, L., Kyeong, J. K., Kyung, S. K., & Poor, V. H. (2016). Power splitting-based SWIPT with decode-and-forward full-duplex relaying. *IEEE Transactions on Wireless Communications, 15*(11), 7561–7577.
53. Okandeji, A. A., Khandaker, M. R. A., & Wong, K. (2016). Wireless information and power transfer in full-duplex communication systems. In *Proceedings of the 2016 IEEE international conference on communications, ICC2016* (pp. 1–6).
54. Ju, H., & Zhang, R. (2014). Optimal resource allocation in full-duplex wireless-powered communication network. *IEEE Transactions on Communications, 62*(10), 3528–3540.
55. Zeng, Y., & Zhang, R. (2015). Full-duplex wireless powered relay with self-energy recycling. *IEEE Wireless Communications Letters, 4*(2), 201–204.
56. Riihonen, T., Werner, S., Wichman, R., & Zacarias, E. B. (2009). On the feasibility of full-duplex relaying in the presence of loop interference. In *Proceedings of the 2009 IEEE 10th workshop on signal processing advances in wireless communications* (pp. 275–279).
57. Bian, H., Fang, Y., Sun, B., & Li, Y. (2013). Co-time co-frequency full duplex for 802.11 WLAN, *IEEE Standard 802.11-13/0765 r2*. (2013, July).
58. Duarte, M., Sabharwal, A., Aggarwal, V., Jana, R., Ramakrishnan, K. K., Christopher, W. R., et al. (2014). Design and characterization of a full-duplex multi-antenna system for WiFi networks. *IEEE Transactions on Vehicular Technology, 63*(3), 1160–1177.
59. Hong, S., Brand, J., Jung, I. C., Jain, M., Mehlman, J., Katti, S., et al. (2014). Applications of self-interference cancellation in 5G and beyond. *IEEE Communications Magazines, 52*(2), 114–121.
60. Deng, Y., Kim, K. J., Duong, T. Q., Elkashlan, M., Karagiannidis, G. K., & Nallanathan, A. (2016). Full-duplex spectrum sharing in cooperative single carrier systems. *IEEE Transactions on Cognitive Communications and Networking, 2*(1), 68–82.
61. George, A., Ropokis, M., Majid, B., Nicola M., & Luiz, A. D. (2017). Optimal power allocation for energy recycling assisted cooperative communications. In *Proceedings of the 2017 IEEE wireless communications and networking conference workshops, WCNCW* (pp. 1–6).
62. Kieu, T. N., Ngoc, L. N., Quoc, H. K., Duy, H. H., Dinh, T. D., Voznak, M., & Mikulec, M. (2016). A performance analysis in energy harvesting full-duplex relay. *2016 39th international conference on telecommunications and signal processing, TSP 2016*, 161–164. https://doi.org/10.1109/TSP.2016.7760850.
63. Zhongxiang, W., Sumei, S., Xu, Z., Yi, H., Linhao, D., & Dong, I. K. (2017). Wireless information and power transfer: Spectral efficiency optimization for asymmetric full-duplex relay systems. *2017 IEEE 85th vehicular technology conference (VTC Spring)* (pp. 1-5).
64. Zheng, G. (2015). Joint beamforming optimization and power control for full-duplex MIMO two-way relay channel. *IEEE Transactions on Signal Processing, 63*(3), 555–566.
65. Chen, H., Li, G., & Cai, J. (2017). Spectral–energy efficiency trade-off in full-duplex two-way relay networks. *IEEE Systems Journal, 99,* 1–10.
66. Zhang, Z., Chen, Z., Shen, M., & Xia, B. (2016). Spectral and energy efficiency of multipair two-way full-duplex relay systems with massive MIMO. *IEEE Journal on Selected Areas in Communications, 34*(4), 848–863.
67. Park, J. J., Moon, J. H., & Kim, D. I. (2016). Time-switching based in-band full duplex wireless powered two-way relay. In *Proceedings of the 2016 URSI Asia-pacific radio science conference, URSI AP-RASC* (pp. 438–441).
68. Okandeji, A. A., Khandaker, M. R. A., & Wong, K. K. (2016). Two-way beamforming optimization for full-duplex SWIPT systems. In *Proceedings of the 2016 European signal processing conference, EUSIPCO* (pp. 2375–2379).
69. Okandeji, A. A., Khandaker, M. R. A., Wong, K. K., & Zheng, Z. (2016). Joint transmit power and relay two-way beamforming optimization for energy harvesting full-duplex communications. *In Proceedings of the 2016 IEEE globecom workshops (GC Wkshps)* (pp. 1–6).
70. Meng-Lin, K., Li, W., Chen, Y., & Liu, K. J. R. (2016). Advances in energy harvesting communications: Past, present, and future challenges. *IEEE Communications Surveys & Tutorials, 18*(2), 1384–1412.

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