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# Research Issues, Challenges, and Opportunities of Wireless Power Transfer-Aided Full-Duplex Relay Systems

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**ABSTRACT** We present a comprehensive review for wireless power transfer (WPT)-aided full-duplex (FD) relay systems. Two critical challenges in implementing WPT-aided FD relay systems are presented, that is, pseudo FD realization and high power consumption. Existing time-splitting or power-splitting structure based-WPT-aided FD relay systems can only realize FD operation in one of the time slots or only forward part of the received signal to the destination, belonging to pseudo FD realization. Besides, self-interference is treated as noise and self-interference cancellation (SIC) operation incurs high power consumption at the FD relay node. To this end, a promising solution is outlined to address the two challenges, which realizes consecutive FD realization at all times and forwards all the desired signal to the destination for decoding. Also, active SIC, that is, analog/digital cancellation, is not required by the proposed solution, which effectively reduces the circuit complexity and releases high power consumption at the FD relay node. Specific classifications and performance metrics of WPT-aided FD relay systems are summarized. Some future research is also envisaged for WPT-aided FD systems.

**INDEX TERMS** Wireless power transfer, full duplex, relay, algorithms.

## I. INTRODUCTION

Wireless power transfer (WPT)-aided relay communications are appealing in the scenarios where regular battery replacement or recharging is inconvenient or even impossible (e.g., in a toxic environment) [1], [2]. By harvesting energy from source node, a WPT-aided relay can continuously assist communication between source and destination. Thus the network connectivity can be maintained, and the lifetime is prolonged [3].

At the beginning, WPT-aided systems adopted half-duplex (HD) transmission. Since HD needs orthogonal time slots or frequencies for transmission and reception, resource utilization efficiency in HD systems is inevitably degraded [4]. There are two different splitting structures, namely power-splitting [5]–[7] and time-splitting structures [8], [9], to process signal at the receiver end. For the time-splitting structure based WPT-aided HD relay systems, three time slots are needed. In the first two time slots, the source

transmits signal to the relay, and the relay processes signal and harvests energy by using amplify-and-forward (AF) or decode-and-forward (DF) protocol. In the third time slot, the relay consumes the harvested energy to forward the signal to the destination. A similar time-splitting structure based bi-directional HD system was considered in [10]. A dedicated energy harvesting (EH) time slot is assigned at the downlink in the first time slot, in which the base station (BS) and the relay nodes send signal to the multiple users. Then the uplink data transmission is performed by the users using the harvested energy in the remaining time. On the other hand, for the power-splitting structure based WPT-aided HD relay systems, two time slots are needed. The source transmits signal to the relay in the first time slot, however, only part of the received signal at the relay node can be forwarded to the destination while the rest is stored to support the relay's operation in the second time slot [8]. Similar power-splitting structure based HD systems were researched by [11] and [12],

where the receivers adopt power-splitting structure and only part of the desired signal can be fed for decoding. In summary, the aforementioned WPT-aided HD relay systems either need extra time slots or only forward part of the desired signal to the destination, incurring spectral efficiency (SE) loss due to low resource utilization efficiency.

In an effort to overcome the SE loss by HD, full-duplex (FD) has attracted extensive attention. With signal transmitted and received simultaneously over the same frequency, FD can approximately double the SE over HD [13]. This has also led to growing interest in applying FD for WPT-aided systems [14]. Existing WPT-aided FD relay systems are also based on time-splitting [15], [16] and power-splitting [17], [18] structures. For the time-splitting structure based WPT-aided FD relay systems, two time slots are required. In the first time slot, the source sends energy-bearing signal to the relay for EH. In the second time slot, the source sends information-bearing signal to the relay and the relay forwards the received signal to the destination simultaneously [19]. As for the power-splitting structure based WPT-aided FD relay systems, the relay splits part of the received signal for EH, and forwards the remnant signal to the destination for decoding [20].

Two critical challenges, however, need to be addressed for WPT-aided FD relay systems. The first challenge is the pseudo FD realization. It is because time-slitting structure based WPT-aided FD relay systems adopt HD operation in one of the time slots and FD operation is only realized in the remaining time, while power-slitting structure based FD can not forward all the received signal to the destination. The second challenge is the high power consumption for WPT-aided FD relay systems, because additional power is triggered by self-interference cancellation (SIC) at the FD relay. A solution was proposed by [15], [21] to release the high power consumption by utilizing self-interference rather than canceling it, and thus SIC is immune at the relay node. However, the systems proposed by [15], [21] still belong to pseudo FD realization, and FD is only realized in the second time slot. Although a lot of research has been conducted in WPT-aided FD relay systems, it is still unknown how to realize consecutive FD transmission, and at the same time to obtain a simple SIC design to reduce the high power consumption at the FD relay node. Also, there still lacks of a comprehensive survey to specifically identify the research issues, challenges and opportunities for WPT-aided FD relay systems. This motivates the work demonstrated in this article:

1) A comprehensive investigation for WPT-aided FD relay systems is presented. The specific classifications of WPT-aided FD relay systems are discussed according to different configurations, *e.g.*, splitting structures, position of WPT harvester, self-interference processing mode, relay mode, antenna type, and the number of relays and users. Then the research issues of WPT-aided FD relay systems are summarized, *e.g.*, SE, energy efficiency (EE), secrecy rate and outage probability.

2) The critical challenges of WPT-aided FD relay systems are presented, *i.e.*, pseudo FD realization and high power consumption. A promising solution is outlined to realize the real FD operation, where FD can be performed at all time and all the desired signal can be received by the destination for decoding. This is fundamentally different from the existing time-splitting structure based WPT-aided FD relay systems that only operate FD in one of time slots, or power-splitting structure based WPT-aided FD relay systems that only forward part of the desired signal to the destination. Besides, active SIC is not required by the proposed solution, which effectively reduces the circuit complexity and thus is more energy efficient than the conventional WPT-aided FD relay systems.

3) Some potential research on WPT-aided FD systems is envisaged, *e.g.*, WPT-aided FD cooperative non-orthogonal multiple access (NOMA) systems, FD ultra-dense heterogeneous systems and WPT-aided FD systems with non-linear EH efficiency.

## II. OVERVIEW OF WPT-AIDED FD RELAY SYSTEMS

In this section, the classifications of WPT-aided FD relay systems are discussed. Then different self-interference suppression/cancellation schemes and system performance metrics for WPT-aided FD relay systems are described.

### A. CLASSIFICATIONS OF WPT-AIDED FD RELAY SYSTEMS

WPT-aided FD relay systems can be classified in different ways as follows.

#### 1) BY SPLITTING STRUCTURE

WPT-aided FD relay systems can be classified into power-splitting based or time-splitting based structure. As aforementioned, the power-splitting based structure requires a fewer number of time slots compared to the time-splitting based structure, however, it only forwards part of the received signal to the destination.

#### 2) BY POSITION OF WPT HARVESTER

Based on the position of harvester, WPT-aided FD relay systems can be classified into destination harvester [7], [22] or relay harvester [23]. For the former case, the destination harvests energy from the relay and the source (if the direct link is not absent), and the received signal at the destination is processed by the power-splitting or time-splitting receiver. For the latter case, the relay harvests energy from the signal sent by the source, and then the harvested energy is used to forward the signal to the destination.

#### 3) BY SELF-INTERFERENCE PROCESSING MODE

WPT-aided FD relay systems can be classified into utilizing-self-interference [15], [21] or canceling-self-interference structure [16]. Conventionally, self-interference is treated as noise and needs to be canceled as much as possible by SIC schemes. To this end, additional power consumption is required, *e.g.*, by analog or digital domain SIC. Differently,

utilizing-self-interference structure utilizes self-interference for energy recycling [21], because self-interference actually comes from the FD relay's transmitter and is known by the relay node.

4) BY RELAY MODE

Based on the relay mode, WPT-aided FD relay systems can be divided into AF relay systems [19], [21], [22] and DF relay systems [24]. An AF relay amplifies the received signal from the source and forwards the mixed signal, including the desired signal, noise and self-interference, to the destination. Therefore, AF relay systems are featured by simple circuit design and low power consumption. However, noise and self-interference are forwarded to the destination. A DF relay decodes the received signal first, and forwards the re-encoded signal to the destination. Hence, the residual self-interference does not affect the relay-destination link directly. However, a DF relay normally leads to higher power consumption and latency than an AF relay due to its complex signal processing.

5) BY ANTENNA TYPE

According to the type of antennas at the relay node, WPT-aided FD relay systems can be classified as shared-antenna FD relay [4] and separated-antenna FD relay systems [25]. With the shared-antenna, only one antenna set is adopted for both transmission and reception at the relay node. A duplexer (circulator) is needed to route the received signal from the antenna to the receive chain, and route the transmitted signal to the antenna from the transmit chain. With the separated-antenna, the relay can use separated antennas for transmission and reception, respectively. In particular, separated-antenna is preferable when multi-input multi-output (MIMO) is applied at the relay node. This is because the SIC in MIMO is more complex than that in single-input single-output (SISO) systems, whereas the isolation offered by the duplexer may be insufficient.

6) BY THE NUMBER OF USERS AND RELAYS

To improve the strength of the received signal and combat high path loss (PL), a user may be assisted by multiple relays [8], [9]. In this case, one can apply relay selection to explore spatial diversity. Also, multiple users may be served by one relay node. In a multiuser scenario, multiple access technique, such as orthogonal frequency division duplexing access (OFDMA), can be adopted [26]. Importantly, the power of self-interference is different across subcarriers. To achieve a better SIC performance, per-subcarrier SIC [27] is desirable. Apart from OFDMA based multiuser systems, MIMO can be applied to multiuser scenario as well [28], where multiuser interference is canceled by proper beam-forming design.

The time-splitting/power-splitting structure based WPT-aided FD/HD relay systems are summarized in Fig. 1, and the classifications of WPT-aided FD relay systems are illustrated in Fig. 2.

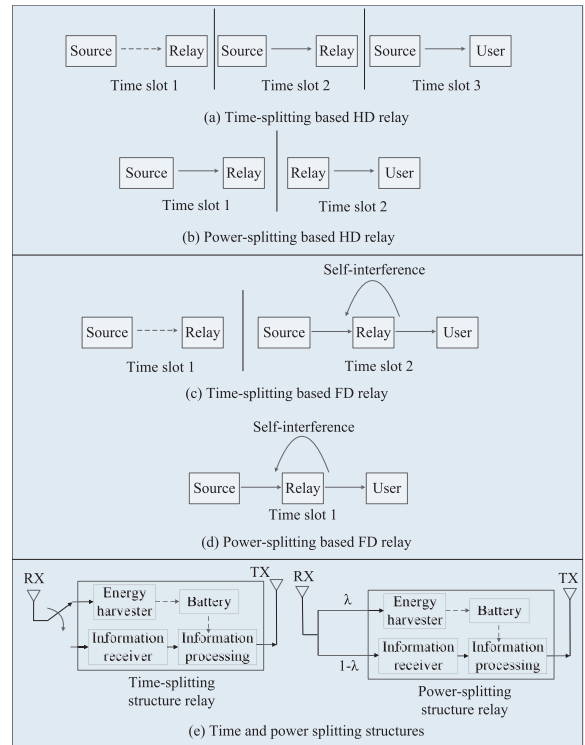


FIGURE 1. Time-splitting/power-splitting structure based WPT-aided FD/HD relay systems.

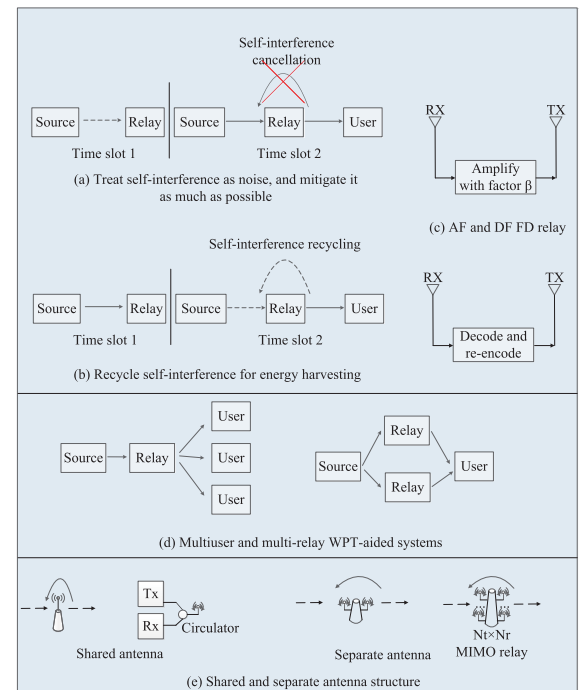


FIGURE 2. Classifications of WPT-aided FD relay systems.

B. SIC IN WPT-AIDED FD RELAY SYSTEMS

SIC is required if self-interference is treated as noise [16], and hereby we give a brief introduction for existing SIC schemes. There are two categories for SIC operation, namely passive

suppression (PS) and active cancellation. Specifically, active cancellation can be further divided into analog cancellation (AC) and digital cancellation (DC).

1) PS

PS, as the first stage of SIC, mitigates self-interference in the propagation domain, via directional antenna, antenna placement and antenna shielding. Recent research has shown that more than 70 dB of SIC amount can be achieved by PS [4]. The advantage of using PS is that no additional power consumption is required. a) A higher PL between relay’s transmitter and receiver leads to a better PS performance. In this case, antenna shielding between the relay’s transmitter and receiver can be adopted. b) Besides, applying high-gain antennas with narrow beamwidth allows the relay to concentrate the radiated energy in the desired directions, and the main lobe of the beam of the relay’s transmitter is not routed into its receiver. c) The application of directional antenna is also beneficial to the cross-polarization, where transmit and receive antennas in orthogonal polarization states (vertically and horizontally polarized) can achieve 20 dB additional SIC amount.

2) AC

After PS, self-interference can be further mitigated by AC before signal goes through low noise amplifier (LNA) [4]. With the ready-made transmit chains and receive chains, there are two kinds of AC designs: direct-conversion architecture AC and non-direct-conversion architecture AC, as illustrated in Figs. 3(a) and (b), respectively. The former deploys the direct-conversion radio architecture to estimate the self-interference and subtracts it at the relay’s receiver end. This kind of AC circuit design does not need additional baseband signal processing at the relay node and thus consumes less power. The relay node processes the transmitted signal from its transmitter to form the predicted self-interference in

the analog-circuit domain. While the non-direct-conversion AC architecture generates the predicted self-interference in digital domain, adjusts the gain/phase digitally, converts the digital signal to analog signal and finally feeds the signal to the receive chain for AC operation. Since baseband signal processing unit, digital-to-analogue converters (DACs), mixers, low pass filters (LPFs), attenuators and adders are required, the incurred power consumption is as high as the equivalent transmit chains.

3) DC

DC is applied at the last stage, which subtracts the residual self-interference after PS and AC in digital domain. It requires accurate estimation of the residual self-interference following PS and AC. Moreover, transmitter and receiver distortions need to be captured by DC. Therefore, complex baseband signal processing unit is required by the DC operation, which also consumes non-negligible power consumption.

C. SYSTEM PERFORMANCE METRICS

1) SE

There have been active research for WPT-aided FD relay systems in terms of SE [19], [22], [23]. Since the FD relay transmits and receives signal simultaneously at the same frequency, WPT-aided FD relay systems can achieve much higher SE compared to its counterpart WPT-aided HD relay systems [29]. In [19] and [23], EH and information transmission are decoupled into two orthogonal time slots. Since the self-interference is treated as noise by the FD relay, SIC is required at the FD relay. In [22], joint optimization design of source and relay beamformers was researched in FD MIMO AF relay systems, where the user is powered through WPT from the relay node.

The authors in [30] and [31] researched the SE oriented resource allocation in bi-directional WPT-aided FD systems, where a FD BS sends the energy-bearing signal to multiple

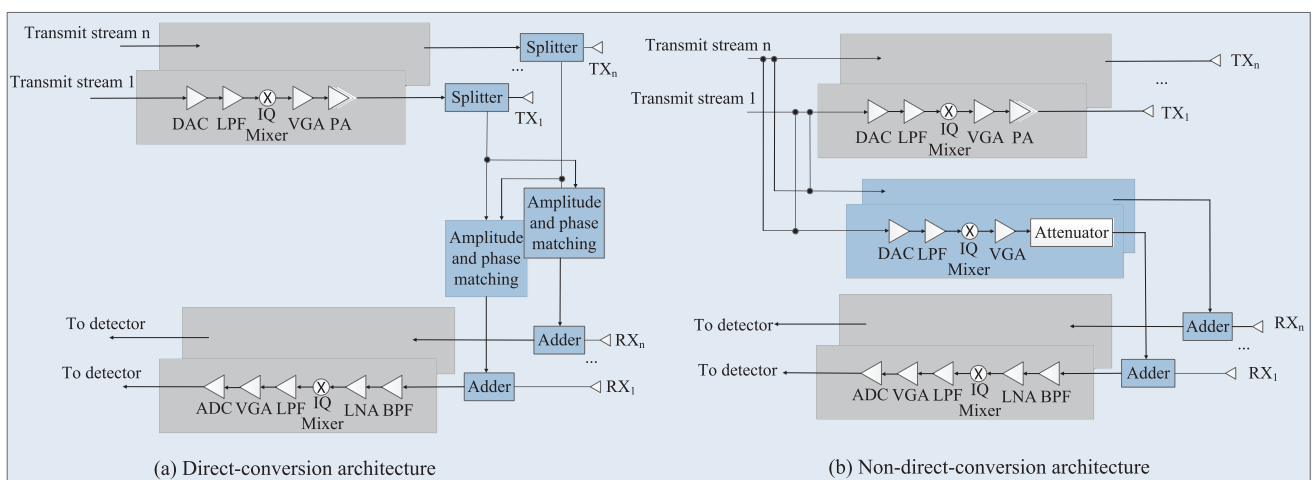


FIGURE 3. Two typical AC designs in WPT-aided FD relay systems.



users while the users send information to the FD BS concurrently. Since the self-interference is introduced at the BS, SIC is required to ensure the uplink reception.

## 2) EE

EE, defined as the ratio between SE and power consumption, makes a proper trade-off between SE and power consumption. EE issue in bi-directional WPT-aided FD systems was considered by [16], where a FD BS sends information-bearing signal to the downlink user and energy-bearing signal to the uplink user in the first time slot. In the second time slot, the BS continues to send information-bearing signal to the downlink user and simultaneously receive information-bearing signal from the uplink user. In [26], WPT in OFDMA based multiuser systems was investigated, where the downlink users split part of the received signal for EH while the remnant signal is fed for decoding.

## 3) SECRECY RATE

Secrecy rate, defined as the difference of mutual information between the normal expectation receiver and the eavesdropper, is used to measure the physical layer security. To optimize the secrecy rate, artificial noise, cooperative jamming and beamforming techniques have been extensively investigated [20], [33]–[36]. Since a FD relay can receive desired signal and transmit jamming signal or artificial noise simultaneously, it is expected to provide high secrecy rate compared to HD relay systems. Also, artificial noise can be generated by other communication nodes [37], [38], such as the source and the destination, to jointly interfere with the passive eavesdropper.

## 4) OUTAGE PROBABILITY

Outage occurs when the received signal-to-interference-and-noise-ratio (SINR) (or achievable rate) is lower than the required SINR (or targeted data rate) [9]. Due to the priority of WPT-aided FD in high SE, WPT-aided FD systems can obtain lower outage probability over its counterpart WPT-aided HD systems [39]. The outage probability in WPT-aided cognitive radio systems was considered in [40], where the cognitive transmitter communicates with the cognitive receiver via an EH relay. Differently, the authors in [41] investigated a three-node system, where a WPT-aided HD relay was positioned to cooperate the communication between the source and the destination. Finally, the splitting factor at the relay node was optimized to minimize outage probability.

The review of WPT-aided FD/HD relay systems is summarized in TABLE 1.

## III. CHALLENGES OF WPT-AIDED FD RELAY SYSTEMS

In this section, we discuss the critical challenges of WPT-aided FD relay systems.

### A. PSEUDO FD REALIZATION

As surveyed in Sections I and II, existing WPT-aided FD relay systems can not realize real FD operation. For the time-splitting structure based WPT-aided FD relay systems, two time slots are required. FD is only realized in one of time slots, while the systems operate in HD mode in the other time slot. For the power-splitting structure based WPT-aided FD relay systems, only part of the desired signal can be forwarded to the destination's decoder. In conclusion, how to realize consecutive FD operation at all time and forward all the desired signal to the destination for decoding is still unknown.

### B. HIGH POWER CONSUMPTION

Since a FD relay transmits or receives signal simultaneously at the same frequency, its transmit and receive chains are active all the time. Therefore, a FD relay naturally consumes higher power than its counterpart HD relay. More importantly, additional power consumption is incurred by SIC at the FD relay node if self-interference is treated as noise [19], [30], [31]. As introduced in Section II, the AC operation design needs DAC, adder, tunable attenuation and delay unit to mitigate self-interference. The incurred power consumption is even comparable with that of the equivalent transmit chains. Also, the power consumed by the DC operation is also non-negligible, which needs digital baseband signal processing unit to calculate the equivalent baseband signal after PS and AC operations, as summarized in TABLE 2.

## IV. REALIZATION OF REAL WPT-AIDED FD RELAY SYSTEMS

### A. SYSTEM MODEL

To address the aforementioned two challenges, in this section, we propose a solution to realize consecutive FD operation at all time and forward all the desired signal to the destination. Differently, conventional WPT-aided FD relay systems only realize FD in one of time slots or only forward part of the desired signal to the destination. Also, conventional WPT-aided FD relay systems suppress self-interference as much as possible [17], [18], [23], [30], [31], giving rise to power consumption.

We consider a classical three-node model, where the communication between the source and the destination is supported by an AF relay. The relay receives the desired signal from the source as well as the self-interference from its own transmit antennas, and simultaneously amplifies the mixed signal to the destination. Thus, at the destination, the desired signal is mixed together with self-interference and noise. Assume that the source transmits  $x[i]$  to the relay with transmission power  $p_s$  in time slot  $i$ . The received signal  $r[i]$  at the relay node can be expressed as

$$r[i] = \sqrt{p_s}h_{sr}x[i] + \sqrt{p_r}h_{si}t[i] + n_r[i], \quad (1)$$

where  $h_{sr}$  and  $h_{si}$  denote the channel responses of the source-relay and the self-interference channels, respectively;  $t[i]$  is the signal transmitted by the relay node with transmission

TABLE 1. Summary of WPT-aided FD/HD relay systems.

References	Duplex Mode	System Model	Splitting Structure	Optimization Metric
[2]	HD	Point-to-point MIMO WPT system at downlink	time splitting	Harvested power
[5]	HD	Three-node model with a WPT-aided AF relay	power/time splitting	SE
[6]	HD	Three-node model with a WPT-aided AF relay	time splitting	SE
[7]	HD	Three-node model. Both the user and relay are WPT-aided.	time/power splitting	SE
[8]	HD	Multi-relay based two-hop systems Relay selection is involved and SI is mitigated as noise.	power splitting	SE
[9]	HD	One source-destination pair and multiple randomly deployed AF relays	power splitting	Outage probability
[10]	HD	Time-splitting based uplink transmission Three time slots are required. Uplink for signal transmission and downlink for WPT	time splitting	SE
[11]	HD	Downlink multiuser system with imperfect SIC	power splitting	Outage probability Power consumption
[12]	HD	Multi-input single-output (MISO) system with a transmitter, an legitimate receiver, an EH receiver, and an eavesdropper	/	Secrecy rate
[26]	HD	Point-to-multi-point OFDMA based system at downlink	power splitting.	SE
[28]	HD	Multiuuser MISO systems Multiple information receivers and EH receivers at downlink	power splitting	Harvested power
[29]	HD	Multiple adjacent AF MIMO multi-way relay networks, each having multiple users and one relay.	time splitting	SE
[33]	HD	MISO AF relay network with one source, one relay, one legitimate destination, one eavesdropper, and one energy receiver	/	Secrecy rate
[39]	HD	Multi-relay cooperative system	time splitting	Outage probability
[40]	HD	Cooperative CR network with a primary receiver, a cognitive transmitter-receiver pair and a WPT-aided relay	power splitting	Outage probability
[41]	HD	Three-node model with a WPT-aided AF relay	power splitting	Outage probability
[42]	HD	AWGN channel with a HD transceiver	time splitting	Delay
[15]	Pseudo FD	Three-node model with a WPT-aided AF relay. Multiple antennas are equipped in source and relay. SI is recycled as energy.	time splitting	SE
[16]	Pseudo FD	Bi-directional FD with a BS, multiple downlink and uplink users. SI is mitigated as noise by the BS.	time splitting	EE/SE
[17]	Pseudo FD	Three-node model with a WPT-aided relay node SI is mitigated as noise.	power splitting	SINR
[18]	Pseudo FD	P-to-P bi-directional FD systems and SI is mitigated as noise.	power splitting	Weighted SE
[19]	Pseudo FD	Dual-hop FD AF relay system The relay harvests energy in the first time slot. FD mode is realized in the second time slot.	time splitting	SE
[22]	Pseudo FD	Beamforming involved at the source and AF relay	power splitting	SE
[23]	Pseudo FD	Two-hop MIMO AF relay system. SI is mitigated as noise by the relay.	time splitting	SE
[21]	Pseudo FD	Three-node models with symmetric time slots SI is recycled by the AF relay node.	time splitting	SE
[30]	Pseudo FD	Multiple users are powered by WPT. Uplink operates in time-division HD and SI is mitigated as noise.	time splitting	SE
[32]	/	Bi-directional FD system with one BS, one uplink user, one downlink user, and one idle user with WPT capability.	/	Secrecy rate
[31]	Pseudo FD	Bi-directional FD with a access point (AP) and multiple users Perfect SIC is assumed and SI is mitigated as noise by the AP.	time splitting	EE

power  $p_r$ .  $n_r[i] \sim \mathcal{CN}(0, \sigma_r^2)$  is the complex additive white Gaussian noise (AWGN) at the relay. Therefore, the received signal at the destination can be expressed as

$$y[i] = \sqrt{p_r}h_{rd}t[i] + n_d[i], \tag{2}$$

where  $h_{rd}$  denotes the channel response of the relay-destination channel;  $n_d[i] \sim \mathcal{CN}(0, \sigma_d^2)$  is the complex AWGN at the destination. In AF relay systems, the transmitted signal  $t[i]$  by the relay node is

$$t[i] = \beta r[i - 1], \tag{3}$$

where  $\beta$  is amplification factor by the AF protocol. Based on the AF protocol, the amplification factor is generally set to  $\beta = \sqrt{\frac{p_r}{p_s|h_{sr}|^2 + p_r|h_{si}|^2 + \sigma_r^2}}$  [43]. Substituting (3) into

(2) yields

$$y[i] = \beta\sqrt{p_r}h_{rd}(\sqrt{p_s}h_{sr}x[i - 1] + h_{si}t[i - 1] + n_r[i - 1]) + n_d[i]. \tag{4}$$

The SINR at the destination is calculated by

$$\begin{aligned} SINR &= \frac{p_s p_r |h_{sr}|^2 |h_{rd}|^2}{p_r |h_{rd}|^2 (p_r |h_{si}|^2 + \sigma_r^2) + (p_r |h_{si}|^2 + \sigma_r^2) \sigma_d^2 + p_s |h_{sr}|^2 \sigma_d^2} \end{aligned} \tag{5}$$

The first term in the denominator in (5) is the power of the self-interference, while the sum of the second and the third terms in the denominator is the power of the noise introduced at the relay and the destination. Since the self-interference

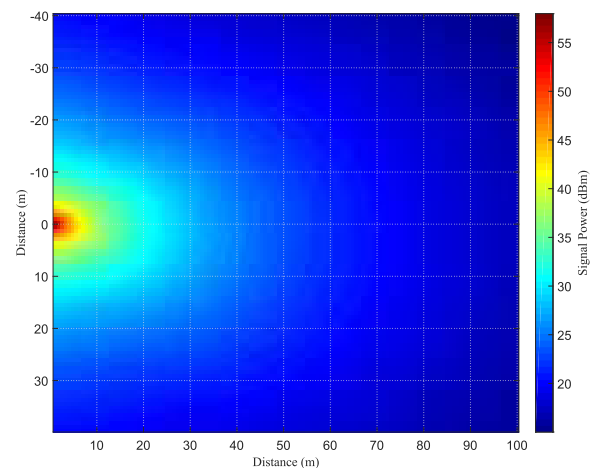
**TABLE 2. Summary of power consumption and EE challenges for different SIC schemes.**

SIC schemes	Hardware Component	Power Consumption	Approaches	Features	Drawbacks
PS	PL	Nil	Benefiting from high PL between relay's transmitter and receiver	Higher PL is preferable.	Sensitive to environment; Increased frequency selectivity of self-interference channel
	Shield, obstacle	Nil	Antenna shielding	Better performance with smaller signal wavelength	
	Directional transmission	Nil	Directional antenna	Widely used in 5G communications; Relay's transmitter pointing to destination	
AC	Balun, attenuators and adders, etc.,	Relative Low	Direct-conversion architecture	Aware to the reflected self-interference	Sensitive to wideband self-interference
	DACs, mixers, LPFs, attenuators and adders, etc.,	Relative high	Non-direct-conversion architecture	Unaware to the reflected self-interference	Not feasible in AF relay system
DC	Digital-band processor	High	Mitigate self-interference in digital domain.	Inefficient given good performance by PS and AC. Additional power is consumed.	May cause negative effect to system (the introduced noise power is higher than the power of the self-interference canceled).
	Beamformer	Nil	Mitigate self-interference by creating null-space of self-interference channel.	Joint transmit and receive beamforming design at relay is preferable.	Trade-off is needed between mitigating self-interference at relay and maximizing received SINR at destination.

is treated as noise by the conventional methods, the self-interference is mitigated as much as possible to obtain a tiny value of  $|h_{si}|^2$ .

By the proposed solution, the self-interference is utilized and harvested by the destination, and thus a tiny value of  $|h_{si}|^2$  is not desirable. However, to guarantee that the desired signal is not overwhelmed by the self-interference, we need to make the power of the desired signal at the destination comparable with that of the self-interference. Hence, we obtain an inequality that  $p_s p_r |h_{sr}|^2 |h_{rd}|^2 \gtrsim p_r |h_{rd}|^2 (p_r |h_{si}|^2 + \sigma_r^2)$  based on (5), which can be further derived into  $p_s |h_{sr}|^2 \gtrsim p_r |h_{si}|^2$ . To make the inequality hold, PS and power adaptation can be applied.

According to the state-of-the-art PS technique [45], more than 70 dB can be achieved by applying PS at the relay node, which does not consume additional power as surveyed in Subsection II-B. On the other hand, Fig. 4 shows the signal propagation from the source to the relay via the source-relay channel  $h_{sr}$ , featured by the 3GPP technical specification group [44] at 2 GHz. As seen from Fig. 4, the propagation attenuation of the channel  $h_{sr}$  is lower than 70 dB within a reasonable communication distance, meaning that the channels  $h_{sr}$  and  $h_{si}$  have similar magnitudes and the desired signal is not overwhelmed by the self-interference. Besides, joint transmission power adaptation at the source and relay can also guarantee the relative power of the desired signal and the self-interference. In AF FD relay systems, since the transmission power  $p_r$  has much higher impact on the self-interference than the transmission power at the source  $p_s$  [43], one can



**FIGURE 4. Signal propagation from the source to the relay node via the channel  $h_{sr}$ , featured by the 3GPP technical specification group at 2 GHz [44]. Transmission power at the source  $p_s = 100$  dBm.**

properly improve the transmission power  $p_s$  at the source and reduce the transmission power at the relay  $p_r$ , which also helps  $p_s |h_{sr}|^2 \gtrsim p_r |h_{si}|^2$  hold. As a result, by PS technique and joint power adaptation, the proposed solution can control the power of the self-interference to the level comparable with that of the desired signal.

**B. SIGNAL SEPARATION AT THE DESTINATION**

At the destination, the received signal consists of the desired signal, self-interference and noise, which can be separated

and extracted by applying blind or semi-blind equalization method. Then the desired signal is routed to the destination's decoder to recover the original transmitted signal, while the self-interference is used for EH.

The proposed solution realizes consecutive FD operation at all time, which reduces the number of the required time slots compared to the time-splitting structure based FD systems. Besides, all the desired signal from the source can be forwarded to the destination and extracted for decoding, while the power-splitting structure based WPT-aided FD relay systems only feed part of the desired signal to the destination, leading to low SE and EE. Last but not least, active SIC, *i.e.*, AC and DC, is not required by the relay node and the self-interference is utilized rather than canceled, which is much more energy-efficient than the existing systems in [17], [18], [23], [30], [31].

### V. POTENTIAL FUTURE RESEARCH

#### A. WPT-AIDED FD COOPERATIVE NOMA SYSTEMS

In the research on WPT-aided FD systems, it has been assumed that orthogonal multiple access is adopted. In fifth generation (5G) communications, NOMA has received considerable attention due to its potential on high SE, where users are operated to transmit at the same time, code and frequency, but with different power levels [46]. The key concept of NOMA is that users' signals are linearly superimposed at the BS with different transmission power. At the receiver end, successive interference cancellation is applied to remove the multiuser interference before detecting its own signal [46]. Normally, two users are clustered in each group to reduce the complexity at the receiver end. By incorporating MIMO and NOMA, additional degrees of freedom are obtained and multiple users can be clustered into different groups by beamforming design [47]. For example, NOMA can be used for inter-grouping while MIMO can be adopted for canceling inter-cluster interference, as shown by Fig.5 (a).

In order to further improve the SE performance of NOMA technique, cooperative NOMA systems have been proposed recently. Different from the conventional non-cooperative NOMA in [46]–[55], cooperative NOMA derives from the fact that the strong user can always decode the weak user's data, due to its better receiving condition than the weak user. Therefore, the strong user can act as a relay node and forward signal to the weak user to improve the system SE via diver-

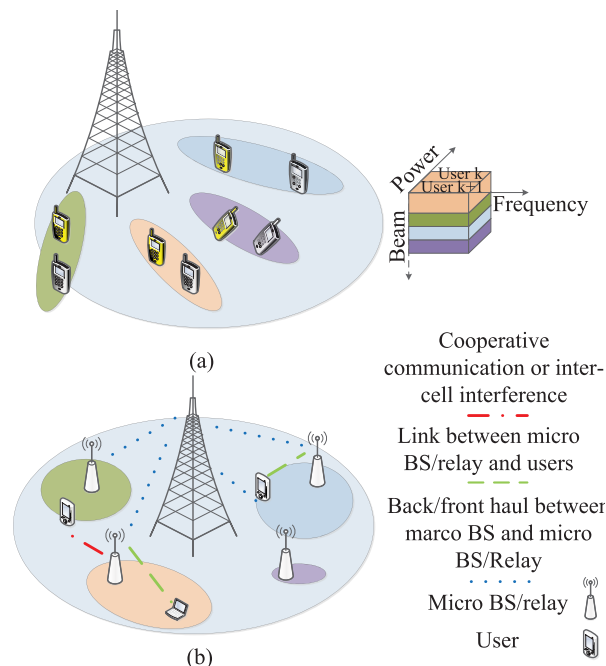


FIGURE 5. a) WPT-aided FD cooperative NOMA systems. b) FD ultra-dense heterogeneous systems.

sity techniques. Related research has been conducted in HD cooperative NOMA systems in terms of outage probability [56], [57] and SE performances [58], [59]. In the first time slot, the BS sends the superimposed signal to both strong user and weak user, while the strong user forwards the signal to the weak user in the second time slot. However, since the aforementioned cooperative NOMA systems assume that the strong user operates in HD mode, additional time slot is required and significant SE loss is generated. To this end, FD can be integrated into cooperative NOMA systems to recover the SE loss [60], [61]. In [61], the user pairing issue in FD cooperative NOMA systems was investigated, while the outage probability was analyzed for FD cooperative NOMA systems in [60]. The literature review of WPT-aided FD cooperative NOMA systems is summarized in TABLE 3.

There are more fundamental challenges that need to be addressed in FD cooperative NOMA systems. For example, how to achieve high EE transmission is still challenging, which requires a trade-off between SE and power consumption. By applying FD cooperative NOMA, additional power

TABLE 3. Summary of FD/HD cooperative/non-cooperative NOMA systems.

References	Cooperative Mode	Duplex Mode	Optimization Metric
[47] [50] [52]	Non-cooperative NOMA	/	SE
[46]	Non-cooperative NOMA	/	SE and fairness
[48] [49] [51]	Non-cooperative NOMA	/	Outage probability
[53]	Non-cooperative NOMA	/	Power consumption
[54] [55]	Non-cooperative NOMA	/	EE
[56] [57]	Cooperative NOMA	HD (Strong user acts as relay node)	Outage probability
[58] [59]	Cooperative NOMA	HD (Strong user acts as relay node)	SE
[60]	Cooperative NOMA	FD (Strong user acts as relay node)	Outage probability
[61]	Cooperative NOMA	FD (Strong user acts as relay node)	User pairing



TABLE 4. Summary of EH efficiency models in WPT-aided systems.

References	EH Efficiency Model	Duplex Mode	Drawbacks
[2], [5]- [12], [26], [28], [29], [33], [39]- [42] [15]- [19] [21]- [23] [30]- [32]	Linear EH model	HD  Pseudo FD	In Ignorance of the saturation and diode breakdown effects
[66]	Taylor series expansion based EH model	/	In Ignorance of the saturation effects
[67]- [69]	Logistic function based EH model	HD in downlink	High complexity to algorithm design

is consumed at the strong user end, while the existing research ignores the additional power consumption on the transmit chain, which is even higher than the consumed transmission power.

### B. FD ULTRA-DENSE HETEROGENEOUS SYSTEMS

Ultra-dense heterogeneous small cell communication is one of characteristics of 5G systems to provide seamless coverage [62]. Small cells are formed by micro, pico or femto nodes, which are featured by low cost and low power consumption. With ultra-dense small cells, users are easier to capture signal and thus high SE is obtained, as shown by Fig.5 (b). The authors in [63] pointed that by applying FD small cells, SE can be significantly improved due to the shortened communication distance. FD MIMO systems with heterogeneous cells were researched in [64] and [65] to improve SE. In [64], FD was applied to small cell BS while HD was applied to macro cell BS to relax the coverage reduction. In [65], the performance of massive MIMO wireless backhaul systems was investigated, where small cells adaptively work in FD or HD mode and each macro cell BS serves its small cell BS by using zero forcing beamforming. However, high density of small cells increases the possibility of inter-cell interference, and system performance may be significantly degraded by inter-cell interference and multiuser interference. How to determine the density of small cells, and how to organize adjacent small cells for cooperative communications, interference management and WPT are challenging.

### C. WPT-AIDED FD SYSTEMS WITH NON-LINEAR EH EFFICIENCY

Linear EH efficiency has been extensively assumed in the current research. With a linear harvesting efficiency  $\zeta$ , the harvested power can be calculated as  $P_{harvest} = \zeta P_{rec}$ , where the harvested power  $P_{harvest}$  is proportional to the received signal power  $P_{rec}$ . Due to the simple expression, the linear model has been extensive adopted in algorithm design [21], [30], [32]. However, as verified by the field measurement, the actual harvesting circuit demonstrates a non-linear behavior. The authors in [66] proposed a non-linear model by adopting the Taylor series expansion of the diode current. The harvested power is calculated by  $P_{harvest} = aP_{rec}^2 + bP_{rec} + c$ , where  $a$ ,  $b$  and  $c$  are constants related to the specific EH circuit, respectively. However, the model does not capture the saturation effect of the harvesting circuit at a high power level.

To further improve the accuracy of EH model, the authors in [67] adopted a logistic function based model  $P_{harvest} = \frac{P_{max}(1-e^{-aP_{rec}})}{1+e^{-a(P_{rec}-b)}}$ , where  $P_{max}$  denotes the maximum harvested power when the harvesting circuit is saturated. The values of  $P_{max}$ ,  $a$  and  $b$  are related to the specific EH circuit design and can be determined by the curve fitting method, such as the turn-on voltage of the diode and the maximum output power of the rectifier. Compared to the first two models, the logistic function based model well captures the saturation and the diode breakdown effects.

With the non-linear EH models, several algorithms were proposed to maximize the total harvested power or SE for HD systems [67]–[69]. However, how to apply the non-linear EH model into FD systems is still untouched, which makes algorithm design more complicated. The literature review of EH efficiency models is summarized in TABLE 4.

## VI. CONCLUSION

This article presents an overview of the research issues, challenges and opportunities for WPT-aided FD relay systems. The two critical challenges, pseudo FD realization and high power consumption, are demonstrated. We further outline a technical solution to enhancing the performance of WPT-aided FD relay systems, which can realize FD operation at all time with self-interference recycling and forward all the desired signal to the destination. Different WPT-aided FD relay classifications and performance metrics are discussed, such as SE, EE, secrecy rate and outage probability. Finally, we envisage the future research for WPT-aided FD systems, such as WPT-aided FD cooperative NOMA systems, FD ultra-dense heterogeneous systems and WPT-aided FD systems with non-linear EH efficiency.

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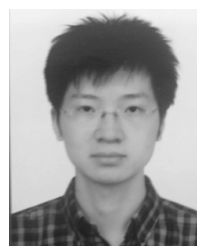
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