DOI: 10.3969/j.issn.1673-5188.2018.01.005

Recent Advances of Simultaneous Wireless Information and Power Transfer in Cellular Networks

LIU Binghong, PENG Mugen, and ZHOU Zheng
(Beijing University of Posts and Telecommunications, Beijing 100876, China)

Abstract

As a promising solution to alleviating the energy bottleneck in wireless devices with limited battery capacity, simultaneous wireless information and power transfer (SWIPT) techniques have been widely researched in cellular networks. To further improve the spectral and energy efficiency of wireless information and power transfer, the combination of SWIPT and new techniques in cellular networks has drawn much attention recently. In this paper, we comprehensively survey the key techniques for SWIPT, the combination of SWIPT and new techniques in cellular networks, challenges and open issues. The key techniques for SWIPT including traditional power splitting, time switching, etc., and joint receiving and transmitting techniques such as eigenchannels and mixed signals are provided in detail. Furthermore, the applications of SWIPT to recent techniques such as SWIPT-assisted non-orthogonal multiple access, SWIPT-assisted device-to-device communication, and SWIPT-assisted full-duplex communication, are comprehensively summarized in this paper. The potential open issues including the management of dynamic harvested energy, trading between wireless power transfer and traffic offloading, and effects of the mode switching at energy harvesting devices, are outlined as well.

Keywords

SWIPT; non-orthogonal multiple access; device-to-device communication; full-duplex communication

1 Introduction

Limited device battery life has always been a key consideration in the energy-constrained wireless network and largely confines the performance of the network. In order to prolong the battery life, a sustainable power supply has to be considered. In the near-field communication, techniques such as inductive coupling and magnetic resonance coupling contribute to high power density and conversion efficiency. However, because of the non-radiative property, the power transfer distance of these techniques is limited. As a result, in the far-field communication, the radio frequency (RF) signal is chosen as a continuous and stable power supply. Recently, the dual use of RF signals including information transmitting and power delivering has been studied. Simultaneous wireless information and power transfer (SWIPT) [1] is an emerging technology to utilize RF signals to transmit information and energy concurrently and offers a promising solution to above problems.

In recent years, attention on SWIPT in mobile communication networks has been growing significantly. For instance, in [2], a two-user Multiple-Input Single-Output (MISO) interference channel with SWIPT is discussed, in which different transmission strategies are proposed to maximize the achievable sum rate. And in [3], multiuser Multiple-Input Multiple-Output (MIMO) systems with SWIPT are studied. There are two scenarios, including separated information decoding (ID) and energy harvesting (EH) receivers and co-located ID and EH receivers, and optimal transmission strategies are proposed to achieve different tradeoffs between maximal information rate and energy transfer for the separated scenario. In addition, in [4], SWIPT is also applied into broadband wireless systems. In this system, the integration of SWIPT and microwave power transfer has been considered as a convenient power supply, freeing the wireless devices from the limited battery capacities. The optimization of power control for different system configurations (i.e. single-user/multiple-user and downlink/uplink information transfer) is studied and the optimal algorithm is used to sequentially allocate required decoding power for mobile devices in ascending order until all the budgeted power is spent.

Nowadays, to further improve the transmission performance, the combination of SWIPT and 5G key techniques has been considered to improve the spectral efficiency (SE) and energy efficiency (EE). As a key technique for the 5G wireless network, massive MIMO is used to satisfy the demand for the ever-increasing data traffic and enhance the spectral efficiency and radiated energy efficiency. Therefore, the surveys [5] and [6] investigate the existing work of massive MIMO with SWIPT. In particular, [5] describes the general architecture of distributed massive MIMO, including receiver/transmitter design and beamforming in the uplink/downlink. Then, it proposes future directions based on interference management and power allocation. Furthermore, the survey [6] introduces relay in MIMO SWIPT networks and investigate different network topologies with single and multiple users.

The existing surveys about SWIPT to 5G key techniques involve massive MIMO and relaying [5], [6]. However, surveys about combination of SWIPT with key techniques in 5G networks such as non-orthogonal multiple access (NOMA), device-to-device (D2D) and full-duplex (FD) are still open. Therefore, to fill in this gap, we provide a comprehensive survey about the applications of SWIPT with the key techniques for 5G networks in this paper.

The contributions of this work are three-folds, which are summarized as follows:

- A comprehensive survey on SWIPT techniques is presented, besides the popular receiving techniques for SWIPT, such as power splitting, time switching and antenna switching. Recent advantages on joint transmitting and receiving techniques for SWIPT based on the designs of Eigen-channels or mixed signals are also concluded.
- The 5G key techniques that have been applied to SWIPT are comprehensively surveyed in this paper. In particular, as shown in **Table 1**, SWIPT with NOMA, with D2D communication, and with FD communication are illustrated respectively, which improve the SE and EE of communication in cellular networks.
- The future directions and open problems related to SWIPT in cellular networks are identified, as the management of dynamic harvested energy, trading between wireless power transfer and traffic offloading, and effects of the mode switching at energy harvesting devices, which are vital for the future development of SWIPT.

The rest of this survey is organized as follows. Section 2 introduces practical techniques to realize SWIPT, including receiver design techniques and joint transmitter and receiver design techniques. Section 3 discusses the combination of SWIPT and some 5G key techniques including NOMA, D2D and FD based on the realizing technologies mentioned in Section 2. Section 4 provides some future challenges and open issues. Finally, Section 5 concludes the survey.

▼**Table 1. Contributions of survey**

Aspects	Survey papers	Contributions
Realizing techniques for SWIPT	[7], [8]	Surveys about wireless energy transfer technology, its applications, and three types of practical SWIPT receivers.
	[9]	A survey about receiving and transmitting techniques, and resource allocation for SWIPT.
	[10]	A hybrid receiver design to maximize the achievable rate in relay channels.
	This Article	A comprehensive survey on techniques for SWIPT, including receiving techniques and joint transmitting and receiving techniques.
SWIPT with NOMA	[12], [13]	Performance analysis on SWIPT with NOMA for single user pair.
	[14], [15]	Performance analysis on SWIPT with NOMA for multiple user pairs.
	[16], [17]	Performance analysis on NOMA with wireless powered relay.
	This Article	A comprehensive survey of NOMA with SWIPT, including pairing schemes, with/without relay, relaying protocols, the node and receiving techniques for SWIPT.
SWIPT with D2D	[18], [19]	Techniques for wireless powered D2D communication.
	[20]–[22]	Techniques for wireless powered D2D relay.
	This Article	A comprehensive survey of D2D with SWIPT, including with/without relay, receiving techniques for SWIPT and relaying protocols.
SWIPT with FD	[24]–[28]	Transmission schemes for two-phase FD relaying systems with SWIPT.
	[29], [30]	Transmission schemes for one-phase FD uplink and downlink communications with SWIPT.
	This Article	A comprehensive survey of two types of FD, including with/without relay, relaying protocols, the node and receiving techniques for SWIPT.

D2D: device-to-device
FD: full-duplex
NOMA: non-orthogonal multiple access
SWIPT: simultaneous wireless information and power transfer

2 Techniques for SWIPT

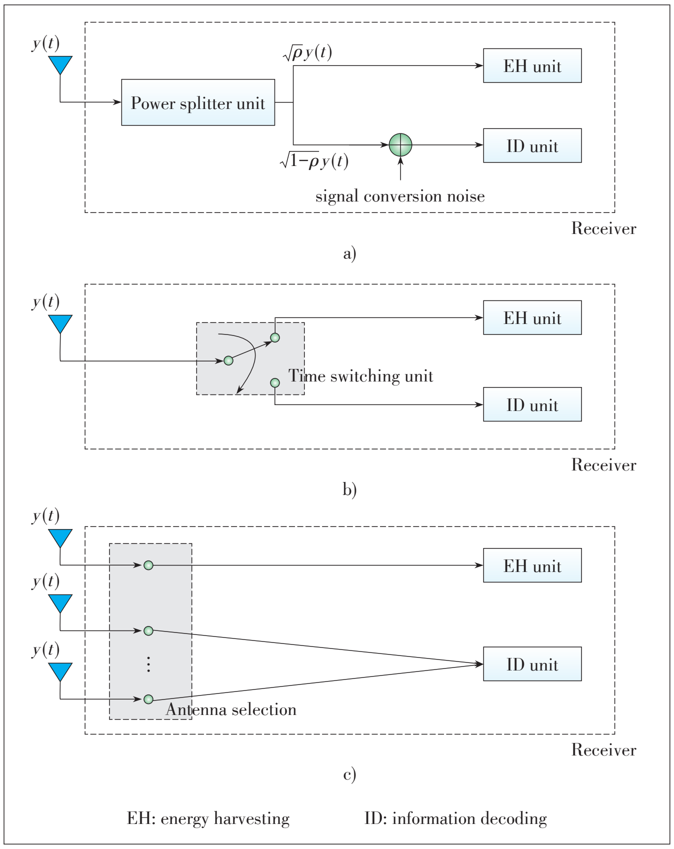
In SWIPT systems, dual use of RF signals is exploited to simultaneously transmit information and energy. Therefore, the receiver of SWIPT has to be split into EH receiver and ID receiver to deal with the information and energy respectively. This section considers practical receiver designs for SWIPT. Furthermore, based on techniques at the receiver, joint transmitting and receiving techniques are proposed, which can improve the performance of energy harvesting and information decoding by designing the transmitted channel or signal.

2.1 Receiving Techniques for SWIPT

Practical receiver design techniques include power splitting (PS), time switching (TS) and antenna switching (AS) [7] (**Fig. 1**). These three techniques split the RF signal resources from the energy domain, the time domain and the space domain respectively.

2.1.1 Power Splitting

As shown in Fig. 1a, the PS receiver consists of a EH receiver and an ID receiver. By using PS ratio ρ, the PS receiver splits the received signal $y(t)$ into two streams with different



▲Figure 1. Receiving techniques for SWIPT, including a) power splitting, b) time switching and c) antenna switching.

power, namely $\sqrt{\rho}y(t)$ and $\sqrt{1-\rho}y(t)$. One is used for harvesting energy at the EH receiver, while the other is used for decoding information at the ID receiver at the same time. It should be noted that there is a signal conversion noise added to the ID receiver, which is produced by RF band to baseband conversion. Different rate-energy trade-offs can be achieved by adjusting the PS ratio ρ.

2.1.2 Time Switching

In this case, the transmitter divides the transmission block into two orthogonal time slots based on the TS factor. One slot is used for data transmission and the other is used for power transmission. At each time slot, the transmitter can optimize its transmission waveforms to achieve better transmission for information or energy.

2.1.3 Antenna Switching

There are multiple antennas at the AS receiver. These antennas are divided into two groups, one group for information decoding and the other for energy harvesting [8]. To decide the optimal assignment of the antenna elements for information decoding and energy harvesting, the solution of an optimization problem in each communication frame is required. Furthermore, antenna switching can be regarded as a special case of power splitting, which the PS ratio at each antenna is binary.

Based on the techniques mentioned above, a comprehensive SWIPT architecture, i.e., the hybrid time-switching/power-splitting (TS/PS) energy harvesting receiver or the hybrid time-switching/antenna-switching (TS/AS) energy harvesting receiver and the hybrid power-splitting/antenna-switching (PS/AS) [9] can be further considered.

2.2 Joint Transmitting and Receiving Techniques for SWIPT

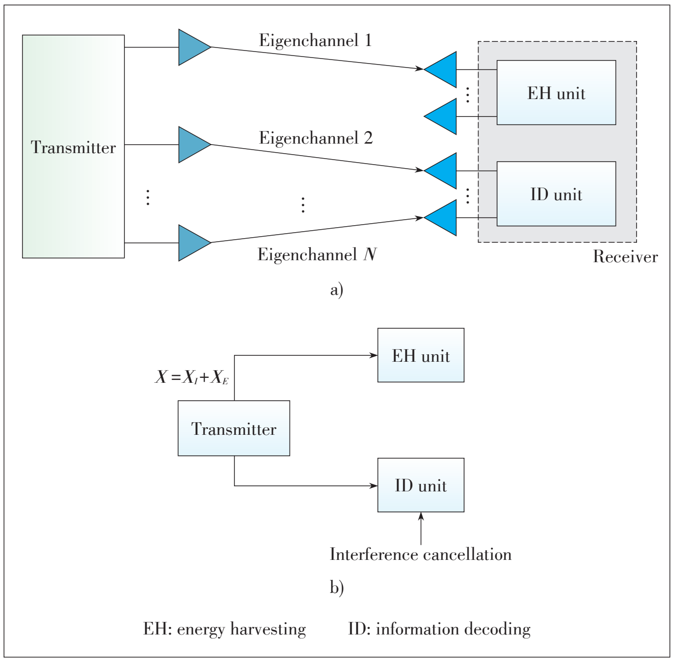
In this section, we mainly focus on the design of the transmitter, including decomposing the transmission channel into multiple sub-channels: eigenchannels and using mixed-signals for transmission (**Fig. 2**).

2.2.1 Eigenchannels

As referred in [10], the communication link is decomposed into multiple eigenchannels, which can be used either to convey information or to transfer energy. As shown in Fig. 2a, at the output of each eigenchannel, there is a switch that switches the channel output either to the information decoding receiver or to the energy harvesting receiver.

2.2.2 Mixed Signals

There is an information signal X_I sent to the ID receiver and an energy signal X_E sent to the EH receiver. The mixed signal includes both of them. Then we can perform the beamforming for the mixed transmission signal to achieve better performance at the ID and EH receivers. To be more specific, by designing the mixed signal at the transmitter, i.e. using the pseudo random signal as the energy signal, which is known by the



▲Figure 2. Joint transmitting and receiving techniques for SWIPT.

receiver, the ID receiver can use successive interference cancellation (SIC) to remove the energy signal. Meanwhile, the information signal can also be used as a source of energy, which increases the energy harvested at the EH receiver and enhances its performance.

3 Combination of SWIPT and Recent Techniques in Cellular Networks

Except for massive MIMO, recent techniques in cellular networks include NOMA, D2D and full-duplex, which contribute to the enhancement of spectrum efficiency and network capacity. NOMA is to realize multiple access in the power domain. D2D is used to provide proximity services and enable the establishment of high data rate peer-to-peer (P2P) links. And full-duplex allows device to transmit and receive on the same frequency concurrently. However, devices involved in all of these techniques are faced with a limited battery capacity, which leads to a constrained performance. Therefore, the combination of SWIPT and 5G key techniques has a promising prospect in the future network.

3.1 SWIPT with Non-Orthogonal Multiple Access

Non-orthogonal multiple access has been considered as an emerging technology for the 5G network [11], which improves the SE by superposing multiple users in power domain. In NOMA systems, the near NOMA user acts as a relay to help transmit information for the far NOMA user, which shorten the lifetime of the energy-constrained near NOMA users. As a result, cooperative NOMA with SWIPT (SWIPT - CNOMA) is proposed, so that the near user can harvest energy from received signals and then use the harvested energy rather than its own energy to assist the information transmission for the far NOMA user.

In SWIPT-CNOMA, a near user and a far user are chosen to pair. Then there is a two-phase transmission. In the first transmission phase, the access point (AP) broadcasts superposed signals to both of the two users. The near user adopts power splitting scheme to use the part of the received signal for energy harvesting and the rest for information decoding. Particularly, based on SIC, the near user first decodes the message of the far user and then subtracts it from its observation to decode its own information. While the far user just keeps the received signal for jointly decoding in the second phase. In the second phase, the far user forwards the message decoded in the first phase to the weak user by its harvested energy. At the end of the second phase, the far user decodes the message jointly based on the signals received from AP and the near user using maximal-ratio combination (MRC).

Hence, in the following paragraphs, we will introduce three kinds of NOMA with SWIPT (**Fig. 3** and **Table 2**), the first two types are about user pairing including single user pair and mul-

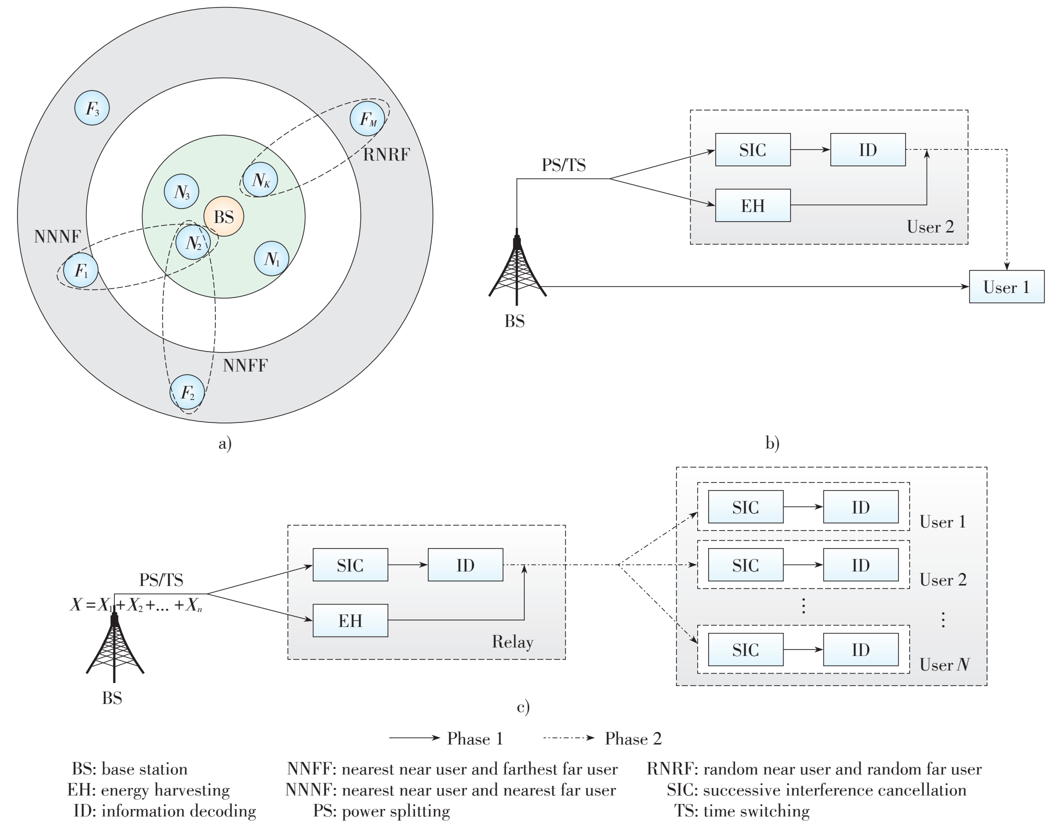


Figure 3. ▶
SWIPT with NOMA: a) pairing schemes for near and far users; b) transmission scheme for NOMA with wireless powered relaying at the near user; c) transmission scheme for NOMA with the EH relay.

▼Table 2. Summary of SWIPT with NOMA

Literature	System model	Transmission protocol	SWIPT technique	Design objective (far/near)
Y. Xu et al. [12]	One BS with single user pair	NOMA with wireless powered DF relaying at the near user	PS at the near user	Maximization of the data rate
N. T. Do et al. [13]	One BS with single user pair	NOMA with wireless powered DF relaying at the near user	Hybrid TS/PS at the near user	Closed-form approximate expressions for the outage probability
Y. Liu et al. [14]	One source with multiple user-pairs	NOMA with wireless powered DF relaying at the near user	PS at the near user	Outage probability and system throughput
Y. Ye et al. [15]	One BS with multiple user-pairs	NOMA with wireless powered DF relaying at the near user	PS at the near user	Ensure target data rates of the relay and the far user are realized prior to harvesting energy
Z. Zhang et al. [16]	One source, an energy-harvesting relay and a user group (2 users)	NOMA with wireless powered DF relaying at the energy-harvesting relay	PS at the energy-harvesting relay	Performance analysis of the outage probability and SNR
W. Han et al. [17]	One BS, an energy-harvesting relay and a user group (multiple users)	NOMA with wireless powered DF relaying at the energy-harvesting relay	PS at the energy-harvesting relay	Performance of the outage probability

BS: base station
DF: decode-and-forward
NOMA: non-orthogonal multiple access
PS: power splitting
SNR: signal-noise ratio
SWIPT: simultaneous wireless information and power transfer
TS: time switching

tiple user pairs, the last is about users with relay.

3.1.1 Single User Pair

In the case of single user pair, there only exists one near-far user pair. Specifically, considering a downlink MISO transmission system in [12]. To achieve the maximization of the near user’s data rate while satisfying the far user’s QoS requirement, the corresponding transmitting beamformers and PS ratio have to be optimized. Demonstrated by simulation, the proposed SWIPT-CNOMA strategy outperforms the existing SWIPT orthogonal multiple access (OMA) strategy, thus marking it a promising candidate for enabling high throughput in IoT and mMTC scenarios.

The author in [13] also considers the situation of single user pair. Furthermore, it takes the impact of the wireless AP with multiple antennas on the transmission performance into consideration. When the source is equipped with multiple antennas, [13] proposes two transmit antenna selection schemes to reduce the complexity of precoding design at the transmitter. The first scheme is selecting an antenna that provides the strongest channel condition of the channel from the AP to the far user. The second scheme is selecting an antenna that maximizes the gain of the channel from the base station (BS) to the near user. The transmission divides into two phases. Different from [12], in the first phase, the near user adopts hybrid time switching and power splitting technologies to obtain information and energy simultaneously, which provides higher flexibility than the conventional power splitting scheme. To be more specific, in the first transmission phase, the AP broadcasts the superposed signals to users, which contain information of the near and far users. In particular, for a near user, the block time T is divided into two sub-blocks. In the first sub-block, the near user harvests energy from its received signal. In the second sub-block, the near user simultaneously utilizes the received power for energy harvesting and information decoding, while the far user just keeps the received signal for jointly decoding in the second phase. The second transmission phase is similar to the process referred in [12]. The authors derive tight closed-form approximate expressions for the outage probability (OP) of near and far users and analyze diversity order of two antenna selection schemes. The results demonstrate that at the high SRN region, the first antenna selection scheme outperforms the second and vice-versa, which exactly reflects the characteristics of the two proposed schemes.

3.1.2 Multiple User Pairs

Considering the situation of multiple user pairs, users are divided into two groups: near users and far users, based on their distance from the BS. Therefore, different near-far user pairing schemes have to be chosen. The work in [14] proposes three user selection schemes based on the user distance from the BS:

- Random near user and random far user (RNRF) selection scheme, in which both the near and far users are randomly selected from the two groups. The advantage of RNRF is that it does not require the knowledge of instantaneous channel state information (CSI).
- Nearest near user and nearest far user (NNNF) selection scheme, in which a near user and a far user closest to the BS are selected from the two groups. This scheme can enable the selected near user to harvest more energy and minimize the outage probability of both the near and far users.
- Nearest near user and farthest far user (NNFF) selection, in which a near user that is closest to the BS is selected and a far user that is farthest from the BS is selected. The transmission in this paper is similar to [12]. The authors derive closed-form expressions for the outage probability and system throughput of three user selection schemes to evaluate the performance. The results confirm that NNNF outperforms other two schemes with the lowest outage probability and the highest throughput for both the near and far users.

The work in [15] also considers the situation of multiple user pairs and the user selection scheme is based on the RNRF scheme referred in [14], which does not need instantaneous CSI and can be easy of implementation. The authors mainly discuss the PS ratio in the first transmission phase. The previous PS protocol in [12] sets that in the first phase, as long as the decoding correctness of far users' information is guaranteed, the rest of the signal is totally used for energy harvesting at the near user (namely the EH relay), which may result that the near user may not be able to decode its own information correctly. Therefore, the new proposed PS protocol sets the PS ratio to firstly ensure the decoding correctness of both near users' information and far users' information at the near user, then use the rest signal for energy harvesting. The impact of the proposed PS protocol for far users on the outage probability of both near and far NOMA users is studied. Simulation results show that comparing with the existing PS protocol in [12], the proposed PS protocol can greatly reduce the outage probability of the near users and enhance system throughput. Meanwhile, it does not affect the outage performance of far users.

3.1.3 Users with Relay

Besides the traditional multiple access scenarios, the combination of SWIPT and NOMA is applied into cooperative non-orthogonal multiple access scenarios, which mainly considers that the source node is far from users and the EH relay is introduced to provides service for users.

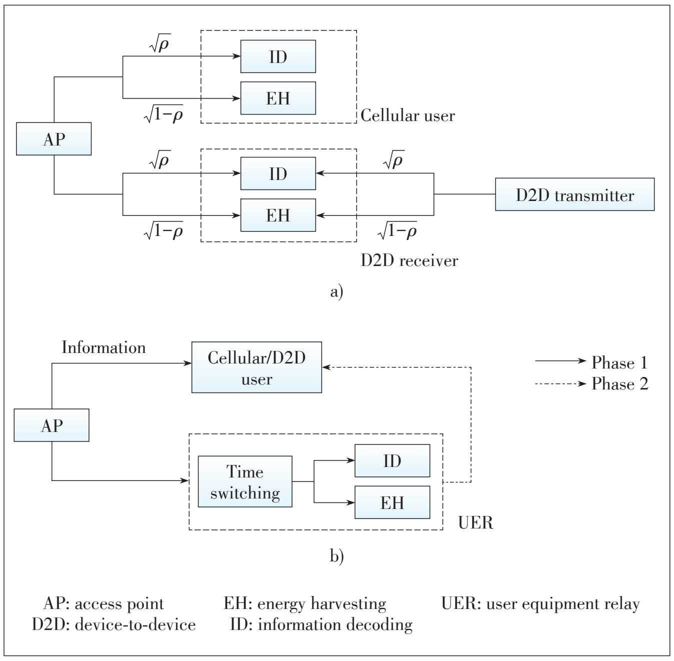
The work in [16] considers a situation that a source node communicates with two users through an energy harvesting relay. The transmission is divided into two phases. In the first phase, the source uses superposition coding to combine two independent signals of near and far users, and the relay receives information and energy from the source simultaneously. Specifically, firstly the relay uses part of the signal for harvesting energy and the rest for decoding information. In the information decoding process, based on SIC, the relay first decodes the far users' information and then, decodes the near user information. In the second phase, the relay uses the energy harvested from the first phase to simultaneously serve two users through NOMA. Specifically, based on decode-and-forward (DF) protocol, the relay transmits the superposed signals to two users. Then the far user will directly decode its own information and the near user will decode the far users' information based on SIC and then decode its own information. In this paper, the effect of power allocation on SWIPT-CNOMA has been investigated. The results show that compared with traditional OMA with SWIPT, NOMA can efficiently lower the outage probability and obtain the same diversity gain.

Similar to the study in [16], [17] considers a source communicating with a group of users through an EH relay. Existing works are mostly focused on single-antenna system and Rayleigh fading channels. However, the work in [17] mainly investigates the impact of multiple antennas and Nakagami-m fading channels on transmission performance of the NOMA EH relay, in which the multiple-antenna technology is used to improve the performance of information and energy transmission. The paper introduces Nakagami-m distribution because it is better at modeling empirical data than Rayleigh distribution. The transmission can also be divided into two phases, while the relay uses the amplify-and-forward (AF) protocol to forward information. To be more specific, in the first phase, the source is equipped with multiple antennas. The transmit antenna that maximizes the channel gain between the source and the relay is chosen for transmitting the superposed signal to the relay, which enhances the performance of the system. On the basis of PS protocol, the received signals at the EH relay are split into two parts, one for harvesting energy and the other for processing information. In the second phase, based on NOMA, the relay uses the energy harvested from the first phase to broadcast the superposed signal. Because the user is equipped with multiple antennas, so the received signals are combined with the rule of MRC. Then, users decode the signals using the optimal order for SIC, which is in the order of the increasing channel gain, where users with better channel conditions are required to decode the signals for others before decoding their own. The paper concentrates on the outage performance of NOMA-EH relaying networks and derives closed-form expressions for the outage probability. Finally, simulation results demonstrate that the worst relay location for both NOMA-EH and OMA-EH relaying networks is the half-way point between users and the BS. Furthermore, it is shown that NOMA-EH outperforms OMA-EH with better performance of outage probability and EE. Meanwhile, NOMA can provide better user fairness and SE since more users can be served at the same time.

3.2 SWIPT with D2D Communications

D2D communication, which provides proximate services by establishing direct links between devices rather than through the BS, has emerged as a key technology for future 5G system to solve the conflict between the limited network bandwidth and the growing demands of users. However, the growing demand for higher data rate and ubiquitous mobile services have caused a high-energy consumption in mobile devices with limited battery capacities, which becomes a bottleneck of the network lifetime. SWIPT enables the receivers to harvest RF energy from the transmitters to extend their lifetimes and improve the EE. What's more, the traditional harmful noise and interference can also be exploited as a source of energy to improve the EE. Therefore, the SWIPT with D2D (**Fig. 4** and **Table 3**) has been proposed, facilitating the deployment of D2D networks by prolonging the network lifetime.

In the following paragraphs, we will talk about SWIPT with D2D mainly from three aspects. Firstly, we will analyze the performance of the energy harvesting-based D2D communications. Then, we will discuss the performance of D2D user equipment relay. Finally, we will investigate the security issue



▲**Figure 4. SWIPT with D2D: a) wireless powered UE communications; b) wireless powered relaying at the D2D transmitter.**

in cooperative D2D communications with SWIPT.

3.2.1 Energy Harvesting-Based D2D Communications

The performance of the energy harvesting-based D2D communications are discussed based on two aspects: the outage probability and the EE performance.

The work in [18] analyzes cognitive and energy harvesting-based D2D communication in cellular networks from the perspective of the outage probability. In this paper, there are multiple macro BSs, multiple cellular users and multiple D2D pairs, in which D2D users can reuse downlink (DL) resource blocks (RBs) occupied by cellular UEs to enhance the system SE. All D2D transmitters are powered by energy harvested from the ambient interference caused by the simultaneous cellular transmissions in the network (i.e., downlink and uplink transmissions), and then use one of the channels allocated to cellular UEs to communicate with the corresponding receivers. Considering the power-hungry characteristic of the user equipment, D2D users with SWIPT communicate with each other only when they harvest enough energy. The authors in [18] propose two spectrum access policies for cellular communication in the uplink or downlink and use tools from stochastic geometry to evaluate the performance of the proposed communication system model with general path-loss exponent in terms of outage probability for D2D and cellular UEs. The results show that energy harvesting can be a reliable alternative to power cognitive D2D transmitters while achieving acceptable performance.

The study in [19] aims to address joint power control and spectrum resource allocation problem in SWIPT-based energy-harvesting D2D underlay networks from the perspective of the EE. In this paper, there are only one BS, multiple users and multiple D2D pairs. Each user can harvest energy from the received desired signals, interference signals and noise. As a result of downlink spectrum reusing, a cellular user can scavenge energy from the BS and the D2D transmitter using the same channel, while a D2D receiver can harvest energy from its corresponding D2D transmitter and the BS. The D2D users with SWIPT can communicate with each other as long as they harvest energy, which improves the EE performance. The purpose of this work is to maximize the EE performance of D2D links and the amount of energy harvested at cellular UEs by designing an efficient resource allocation mechanism. Hence, a joint optimization problem of power control and partner selection between D2D pairs and cellular UEs has to be considered. Simulation results demonstrated that the EH-based energy-efficient stable matching algorithm can achieve the best EE performance under all of the considered scenarios.

3.2.2 User Equipment Relay

Except for the functionality that users in the D2D pair can

▼**Table 3. Summary of SWIPT with D2D**

Literature	Mode	Scenario	SWIPT technique	Design objective
A. H. Sakr et al. [18]	Wireless powered user equipment communication	Multiple macro BSs, multiple users and multiple D2D users	TS at the D2D transmitter	Performance evaluation of the outage efficiency
Z. Zhou et al. [19]	Wireless powered user equipment communication	One BS, multiple cellular users and multiple D2D users	PS at the D2D transmitter	Performance analysis of the energy efficiency
H. H. Yang et al. [20]	Wireless powered DF relaying at the D2D transmitter	Multiple APs, cellular users, D2D users, where the idle D2D transmitter acts as the relay	TS at the D2D transmitter	Performance analysis of the outage probability
R. Atat et al. [21]	Wireless powered DF relaying at the D2D transmitter	One BS, cellular users, D2D users, where the idle D2D transmitter acts as the relay, along with MTC devices	TS at the D2D transmitter	Performance analysis of the spectral efficiency
R. I. Ansari et al. [22]	Wireless powered DF relaying at the D2D transmitter	One BS, cellular users, D2D users, where the idle D2D transmitter acts as the relay	TS at the D2D transmitter	Performance evaluation of the outage probability

AP: access point
BS: base station
D2D: device-to-device
DF: decode-and-forward
PS: power splitting
SWIPT: simultaneous wireless information and power transfer
TS: time switching

communicate directly with each other, D2D UEs can also act as a relay for UEs by cooperative transmission and traffic offloading. Therefore, the concept of mobile user equipment relay (UER) has been introduced to support D2D communications for enhancing communication reliability. However, as the UER needs to use its own power for data transmission of other UEs, relaying information in D2D communication may be undesirable for the UER and UEs are not obligated to provide energy for the UER. Therefore, SWIPT is introduced for energy compensation. Namely, the UER harvests energy from APs and relays information of other UEs in D2D communication using only the harvested energy.

The work in [20] considers a D2D communication provided EH heterogeneous cellular network (HCN), where APs are capable of performing wireless power transfer and UEs can harvest energy from nearby APs. Specifically, the UER can harvest energy from the RF signal transmitted by nearby wireless APs and then store it. When the harvested energy has been accumulated to a certain threshold, the UER will be chosen to achieve the best performance based on the best UER selection strategy. By introducing the EH region (EHR) and modeling the status of harvested energy using Markov chain, the network outage probability is derived in close form to measure the performance of a D2D communication provided EH HCN. The results show that by exploiting EH-D2D communication, the energy can be saved by turning off some APs while maintaining a certain level of expected outage probability. The results also show that there exist the optimal AP transmit power which increases with EH efficiency, and the optimal offloading bias which decreases compared to an HCN without EH-D2D communication.

Considering the future 5G networks, there are massive numbers of machine-type communication (MTC) devices to be scheduling and powering. Offloading MTC traffic onto D2D communication links can better manage radio resources and reduce MTC devices energy consumption. However, it requires D2D users to use their own limited energy to relay MTC traffic. Therefore, the study in [21] proposes using D2D communication to offload MTC traffic and exploiting RF energy harvesting for powering D2D relay transmission. A cellular network consists of cellular users, MTC devices and D2D relays, where D2D users and cellular users (CUs) share the licensed uplink spectrum, while MTC devices use orthogonal spectrum resources. Specifically, to lower MTC devices energy consumption and improve the transmission performance, the EH-D2D user can serve as a D2D relay, which is able to access a fraction of the spectrum occupied by cellular users, to help relay the information of MTC devices to the BS. To protect cellular users, the spectrum available to D2D users needs to be reduced, which limits the number of D2D transmissions, but increases the amount of time that D2D users can spend harvesting energy to support MTC traffic. The authors in [21] analyze the average MTC SE, the average cellular SE and the weighted proportional-fairness SE, in which the last one is used to show the balance between efficiency and fairness among D2D and cellular transmitters. Simulation results have shown that a small spectrum partition factor, combined with an adequate number of available channels in the network, can achieve 1) a balance and fairness in weighted SE among D2D and cellular users that are sharing the spectrum, 2) a higher D2D transmission probability, and 3) a relatively high MTC and D2D SE in a dense cellular environment.

The work in [22] proposes a SWIPT-based cooperative D2D network, where the D2D pairs are distributed in a circular area. Energy-constrained D2D networks calls for multi-hop communications. Therefore, the authors introduce the dual-hop D2D network when the destination is spatially distant from the transmitter. In the system architecture, there are multiple idle D2D nodes between the source and the destination. To be more specific, the idle D2D node can serve as relay to forward the message to the destination using the cooperative DF mechanism. It can also serve as the energy harvesting node to harvest energy from RF signals transmitted by nearby transmitters. A transmission flow mechanism encompassing energy harvesting and decode-and-forward nodes is devised for end-to-end transmission. The results show that for a larger distance between D2D communication nodes, dual-hop D2D network is more suitable for reliable end-to-end communication.

3.2.3 Security

In the cooperative D2D communication with SWIPT, there exist multiple idle D2D users who need to harvest energy from the D2D transmitter signals and store the harvested energy for future use. However, the idle D2D users may decode the cellular message without permission instead of harvesting energy, which results in cellular message security problem. Therefore, in addition to meeting the energy harvesting requirements of the idle D2D users, the cooperative D2D communication system with SWIPT should be optimally designed to guarantee the cellular message security in the presence of potential eavesdropping of the idle D2D users.

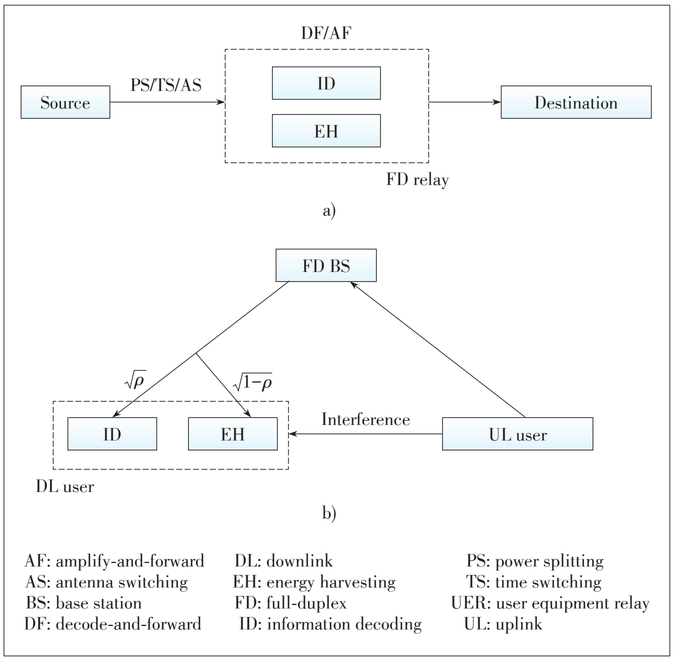
The work in [23] considers cooperation between a cellular downlink communication and a D2D communication. The cellular downlink communication system consists of a source and a CU, while the D2D communication system has a pair of D2D users (DUs). There exists multiple idle DUs. The source transmits the confidential message to the CU, the D2D transmitter (DT) transmits a non-confidential message to the desired DU and assists the source to transmit the confidential message to the CU. To be more specific, the paper considers a two-phase transmission. At the first phase, the source transmits a signal to all the receivers. The DT amplifies the received cellular signal at different receive antennas using MRC receiver. At the second phase, the DT concurrently transmits both the cellular confidential message and its own message to the CU and to the desired DU. The paper aims to design secure beamforming schemes to maximize the D2D users' data rate while guaranteeing the secrecy rate requirements of the cellular users and the minimum required amounts of power transferred to the idle D2D users. Simulation results demonstrate that comparing with the two-suboptimal secure beamforming scheme, the proposed optimal secure beamforming scheme in [23] achieves a significant data rate of the desired DU while provides a high secrecy rate for the cellular users and facilitates the efficient power transfer for the idle DUs.

3.3 SWIPT with Full-Duplex Communication

Recently, FD communication has become a viable option for next generation wireless communication networks. In contrast to conventional half-duplex (HD) transmission, FD communication allows devices to transmit and receive simultaneously on the same frequency, thus potentially doubling the SE. However, the self-interference caused by the own transmit signal impairs the simultaneous signal reception in FD systems severely. In fact, the self-interference can also serve as a vital energy sources for RF energy harvesting. As a result, when considering the self-interference as well as EH, FD SWIPT systems (**Fig. 5** and **Table 4**) have been proposed.

There are mainly two types of FD SWIPT systems; one is FD relaying systems and the other is FD systems.

In FD relaying SWIPT systems, there is a source node communicating with a destination node with the assistance of a SWIPT FD relay node. The FD relay node receives signal from the source node and concurrently transmits information using a portion of the harvested energy. The energy harvested for the relay node comes from the source node and the self-interference link.



▲**Figure 5. SWIPT with full-duplex: a) transmission schemes for two-phase FD relaying systems with SWIPT; b) transmission schemes for one-phase FD uplink and downlink communications with SWIPT.**

The work [24] employs DF protocol and PS for the relay. The relay node splits its received signal into two components for energy harvesting and information decoding, respectively, and forwards the decoded information using a portion of the harvested energy. To maximize the end-to-end transmission rate, the PS ratio and energy consumption proportion at the relay have been jointly optimized. Demonstrated by simulations, increasing the number of transmit antennas at both the source node and the relay node can increase the transmission rates of

▼**Table 4. Summary of SWIPT with full-duplex**

Literature	Transmission scheme	System model	SWIPT technique	Design objective
I. Orikumhi et al. [28]	Two-phase DF	Multiple FD relay nodes, one HD source node and one HD destination node	TS at the FD relay nodes	Management of the degrading effect of the inter-relay-interference on the ID receiver and optimization of the ID and EH receivers
L. Zhao et al. [24]	Two-phase DF	One FD relay node, one HD source and one HD destination	PS at the FD relay	Maximization of the end-to-end transmission rate
H. Liu et al. [25]	Two-phase DF	One FD relay node, one HD source and one HD destination	PS at the FD relay	Maximization of the end-to-end signal-to-interference-plus-noise ratio and optimization the outage probability
Y. Zeng et al. [26]	Two-phase AF	One FD relay node, one HD source and one HD destination	TS at the FD relay	Optimization of power allocation and beamforming design
L. Zhang et al. [27]	Two-phase AF	One FD relay node, one HD source and one HD destination	TS at the FD relay	Minimization of the MSE
S. Leng et al. [29]	One-phase transmission	One FD BS and multiple HD users	PS at HD users	The trade-off between uplink transmit power minimization, downlink transmit power minimization, and total harvested energy maximization.
M. M. Zhao et al. [30]	One-phase transmission	Multiple FD RRHs and multiple HD users	PS at HD users	Minimization of the total power consumption

AF: amplify-and-decode
BS: base station
DF: decode-and-forward
EH: energy harvesting
FD: full-duplex
HD: half-duplex
ID: information decoding
MSE: mean-squared-error
PS: power splitting
RRH: remote radio head
SWIPT: simultaneous wireless information and power transfer
TS: time switching

FD relay systems.

The study in [25] extends the work in [24] by considering the power management of relay-harvested energy. The traditional power management is the harvest-use model, in which the harvested energy has been fully used up for relay transmission. Although the harvest-use model is easy to implement, it is not an efficient technology of power management. Therefore, in [25], the authors consider the situation that storing part of the harvested energy for future usage is good for practical scenarios, and propose a new harvest-use-store model. The results show that the harvest-use-store model outperforms the harvest-use model.

Different from the work in [24], [26] employs a new two-phase protocol for AF based SWIPT. In the first phase, information is transmitted from the source to the relay. In the second phase, the received signal at the relay is amplified and forwarded to the destination, and concurrently, dedicated energy signals are sent from the source to the relay for energy harvesting, which possesses the advantage of uninterrupted information transmission since no time switching or power splitting is needed at the relay for energy harvesting. The simulation results show a significant throughput gain achieved by this two-phase proposed design over the existing time switching based relay protocol.

The study in [26] investigates the design of robust non-linear transceivers in the face of realistic imperfect CSI. The relay node uses the same AF protocol as [26] and TS protocol. In the first phase, the source node transmits information to the relay node, and in the second phase, the relay node harvest energy from the source node and transmits information to the destination node. The proposed nonlinear transceiver relies on a Tomlinson-Harashima (TH) precoder along with an AF relaying matrix and a linear receiver, where the TH precoder is composed of a feedback matrix and a source precoding matrix. The simulation results show that the robust design advocated is capable of alleviating the effects of CSI errors, hence improving the robustness of the system over that of the corresponding linear designs.

The work in [24]–[27] all considers the system with only one relay, while the authors in [28] study the FD relay SWIPT system with multiple relays, which bring about the inter-relay-interference. However, the IRI can serve as an additional source of energy to the relay. Namely, the relay can use energy harvested from the source node and gleaned from self-interference and IRI links. To manage the degrading effect of the IRI on the ID receiver, maximum channel gain transmit antenna selection scheme is proposed at the relay to transmit information to the destination node. In addition, precoding matrices which optimize the ID and EH receivers are jointly designed. The simulated results show that although IRI could be a degrading factor from the information viewpoint, it can be properly managed and exploited for energy harvesting at the relay while maintaining the end-to-end data rate.

In FD SWIPT systems comprising a FD BS and multiple HD users, the BS transmits information and energy simultaneously to receivers and receive information transmitted by HD users.

The work in [29] deals with receivers, where ID receivers and EH receivers are separated, namely some HD users serve as ID receivers and some serve as EH receivers. To study the trade-off between uplink transmit power minimization, downlink transmit power minimization, and total harvested energy maximization, a multi-objective optimization framework has been proposed. Numerical results reveal the improved power efficiency facilitated by FD in SWIPT systems compared to traditional HD systems.

Differently, the authors in [30] study joint transceiver design for a FD cloud radio access network with SWIPT considering integrated receivers. The design aims to minimize the total power consumption with both uplink and downlink quality of service constraints and energy harvesting constraints.

4 Open Problems and Future Directions

SWIPT causes many challenging problems. In the following, we will discuss some of the research challenges and potential solutions.

4.1 Management of Dynamic Harvested Energy

Based on the investigation about SWIPT, we find out that the energy harvested by the energy-harvesting receiver arrives dynamically. Therefore, the available energy at the receiver can be changed over time. As referred in [25], the traditional power management: harvest-and-use model is not an efficient utilization of harvested energy, so that the authors in [25] propose a new harvest-use-store model to store part of the harvested energy in a battery group for future usage. However, the battery capacity is limited, which may lead to two situations:

- Overflowing when there is too much energy stored in the battery;
- Lacking of energy for the following slot when there is too little energy stored in the battery.

Thus, further research on the problems that when to store the energy and how much energy to store is still needed.

Intuitively, the problems proposed above are related to the channel condition. If the channel condition is better in the next slot, we can choose to store more harvested energy in the battery and vice versa. A recent work in [31] considers utilizing statistical properties of CSI to design a scheme of power management.

4.2 Trading Between Wireless Power Transfer and Traffic Offloading

The abilities (including computing, storage and communications) of edge intelligent UEs in the cellular network can be exploited to resolve the network congestion. Specifically, the transmission task can be offloaded on edge intelligent UEs or small BSs. However, existing works usually assume that edge UEs and small BSs are willing to perform this offloading. Actually, the offloading will consume energy of edge UEs which are energy-hungry and degrade the gain brought about by traffic offloading. Then, the edge UEs may not be willing to use their limited power to perform the offloading. Hence, the paper [32] proposes the issue of making a tradeoff between the amount of RF energy needed for the offloading and the price at which edge UEs are willing to participate in the traffic offloading.

4.3 Effect of Mode Switching

There are some wireless powered access points in the network, such as PICO BSs. Based on the time switching technology of SWIPT, they can switch between the energy harvesting mode and the information transmission mode in different part of a time slot. Therefore, access points involved in the information transmission may be different during different time, which leads to the topology change of the wireless access network. Hence, the transmission and resource allocation in cellular network have to be dynamic and adaptive, which need to be further investigated.

5 Conclusions

A comprehensive survey on recent advantages of SWIPT in next generation cellular networks is presented in this paper. Firstly, we provide an overview of popular techniques that realizing SWIPT. Then, we survey the combination of the SWIPT techniques with NOMA techniques, with D2D communication techniques and with FD communication techniques. Finally, we discuss the future research directions for SWIPT in next generation cellular networks.

References

[1] Y. Ma, M. Peng, and Z. Zhao, "Optimization of simultaneous wireless information and power transfer in cloud radio access networks," in *Proc. 2016 IEEE Vehicular Technology Conference (VTC Spring)*, Nanjing, China, 2016, pp. 1-5. doi: 10.1109/VTCSpring.2016.7504391.

[2] C. Shen, W. Li, and T. Chang, "Simultaneous information and energy transfer: a two-user MISO interference channel case," in *Proc. 2012 IEEE Global Communications Conference (GLOBECOM)*, Anaheim, USA, 2012, pp. 3862-3867. doi: 10.1109/GLOCOM.2012.6503719.

[3] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989-2001, May 2013. doi: 10.1109/TWC.2013.031813.120224.

[4] K. Huang and E. Larsson, "Simultaneous information and power transfer for broadband wireless systems," *IEEE Transactions on Signal Processing*, vol. 61, no. 23, pp. 5972-5986, Dec. 2013. doi: 10.1109/TSP.2013.2281026.

[5] F. Yuan, S. Jin, Y. Huang, et al., "Joint wireless information and energy transfer in massive distributed antenna systems," *IEEE Communications Magazine*, vol. 53, no. 6, pp. 109-116, Jun. 2015. doi: 10.1109/MCOM.2015.7120025.

[6] Z. Ding, C. Zhong, D. Wing Kwan Ng, et al., "Application of smart antenna technologies in simultaneous wireless information and power transfer," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 86-93, Apr. 2015. doi: 10.1109/MCOM.2015.7081080.

[7] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: opportunities and challenges," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 117-125, Apr. 2015. doi: 10.1109/MCOM.2015.7081084.

[8] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989-2001, May 2013. doi: 10.1109/TWC.2013.031813.120224.

[9] Z. Zhou, M. Peng, Z. Zhao, and Y. Li, "Joint power splitting and antenna selection in energy harvesting relay channels," *IEEE Signal Processing Letters*, vol. 22, no. 7, pp. 823-829, Jul. 2015. doi: 10.1109/LSP.2014.2369748.

[10] I. Krikidis, S. Timotheou, S. Nikolaou, et al., "Simultaneous wireless information and power transfer in modern communication systems," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 104-110, Nov. 2014. doi: 10.1109/MCOM.2014.6957150.

[11] Z. Ding, M. Peng, and H. Vincent Poor, "Cooperative non-orthogonal multiple access in 5G systems," *IEEE Communication Letters*, vol. 19, no. 8, pp. 1462-1465, Aug. 2015. doi: 10.1109/LCOMM.2015.2441064.

[12] Y. Xu, C. Shen, Z. Ding, et al., "Joint beamforming design and power splitting control in cooperative SWIPT NOMA systems," in *Proc. 2017 IEEE International Conference on Communications (ICC)*, Paris, France, 2017. doi: 10.1109/ICC.2017.7996560.

[13] N. T. Do, D. Benevides da Costa, T. Q. Duong, and B. An, "Transmit antenna selection schemes for MISO-NOMA cooperative downlink transmissions with hybrid SWIPT protocol," in *Proc. 2017 IEEE International Conference on Communications (ICC)*, Paris, France, 2017. doi: 10.1109/ICC.2017.7997005.

[14] Y. Liu, Z. Ding, M. Elkashlan, and H. V. Poor, "Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 938-953, Apr. 2016. doi: 10.1109/JSAC.2016.2549378.

[15] Y. Ye, Y. Li, D. Wang, and G. Lu, "Power splitting protocol design for the cooperative NOMA with SWIPT," in *Proc. 2017 IEEE International Conference on Communications (ICC)*, Paris, France, 2017. doi: 10.1109/ICC.2017.7996751.

[16] Z. Yang, Z. Ding, P. Fan, and N. Al-Dhahir, "The impact of power allocation on cooperative non-orthogonal multiple access networks with SWIPT," *IEEE Transactions on Wireless Communications*, vol. 16, no. 7, pp. 4332-4343, July. 2017. doi: 10.1109/TWC.2017.2697380.

[17] W. Han, J. Ge, and J. Men, "Performance analysis for NOMA energy harvesting relaying networks with transmit antenna selection and maximal-ratio combining over Nakagami-m fading," *IET Communications*, vol. 10, no. 18, pp. 2687-2693, Dec. 2016. doi: 10.1049/iet-com.2016.0630.

[18] A. H. Sakr and E. Hossain, "Cognitive and energy harvesting-based D2D communication in cellular networks: stochastic geometry modeling and analysis," *IEEE Transactions on Communications*, vol. 63, no. 5, pp. 1867-1880, May 2015. doi: 10.1109/TCOMM.2015.2411266.

[19] Z. Zhou, C. Gao, C. Xu, et al., "Energy-efficient stable matching for resource allocation in energy harvesting-based device-to-device communications," *IEEE Access*, vol. 5, pp. 15184-15196, 2017. doi: 10.1109/ACCESS.2017.2678508.

[20] H. H. Yang, J. Lee, and T. Q. S. Quek, "Heterogeneous cellular network with energy harvesting-based D2D communication," *IEEE Transactions on Wireless Communications*, vol. 15, no. 2, pp. 1406-1419, Feb. 2016. doi: 10.1109/TWC.2015.2489651.

[21] R. Atat, L. Liu, N. Mastronarde, and Y. Yi, "Energy harvesting-based D2D-assisted machine-type communications," *IEEE Transactions on Communications*, vol. 65, no. 3, pp. 1299-1302, Mar. 2017. doi: 10.1109/TCOMM.2016.2639507.

[22] R. I. Ansari, S. A. Hassan, and C. Chrysostomou, "A SWIPT-based device-to-device cooperative network," in *Proc. 2017 24th International Conference on Telecommunications (ICT)*, Limassol, Cyprus, 2017. doi: 10.1109/ICT.2017.7998285.

[23] L. Jiang, C. Qin, X. Zhang, and H. Tian, "Secure beamforming design for SWIPT in cooperative D2D communications," *China Communications*, vol. 14, no. 1, pp. 20-33, Jan. 2017. doi: 10.1109/CC.2017.7839755.

[24] L. Zhao, X. Wang, and T. Riihonen, "Transmission rate optimization of full-duplex relay systems powered by wireless energy transfer," *IEEE Transactions on Wireless Communications*, vol. PP, no. 99, pp. 1-1. doi: 10.1109/TWC.2017.2723564.

[25] H. Liu, K. J. Kim, K. S. Kwak, and H. Vincent Poor, "Power splitting-based SWIPT with decode-and-forward full-duplex relaying," *IEEE Transactions on Wireless Communications*, vol. 15, no. 11, pp. 7561-7577, Nov. 2016. doi: 10.1109/TWC.2016.2604801.

[26] Y. Zeng and R. Zhang, "Full-duplex wireless-powered relay with self-energy recycling," *IEEE Wireless Communications Letters*, vol. 4, no. 2, pp. 201–204, April. 2015. doi: 10.1109/LWC.2015.2396516.
[27] L. Zhang, Y. Cai, M. Zhao, B. Champagne, and L. Hanzo, "Nonlinear MIMO transceivers improve wireless-powered and self- interference-aided relaying," *IEEE Transactions on Wireless Communications*, vol. PP, no. 99, pp. 6953–6966, 2017. doi: 10.1109/TWC.2017.2734772.
[28] I. Orikumhi, C. Y. Leow, and Z. Ding, "Wireless information and power transfer in MIMO virtual full duplex relaying system," *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 11001- 11010, 2017. doi: 10.1109/TVT.2017.2720460.
[29] S. Leng, D. W. K. Ng, N. Zlatanov, and R. Schober, "Multi-objective resource allocation in full-duplex SWIPT systems," in *Proc. 2016 IEEE International Conference on Communications (ICC)*, Kuala Lumpur, Malaysia, 2016. doi: 10.1109/ICC.2016.7510760.
[30] M. M. Zhao, Q. Shi, Y. Cai, and M. J. Zhao, "Joint transceiver design for full-duplex cloud radio access networks with SWIPT," *IEEE Transactions on Wireless Communications*, vol. 16, no. 9, pp. 5644–5658, Sept. 2017. doi: 10.1109/TWC.2017.2712693.
[31] Z. Zhou, M. Peng, Z. Zhao, W. Wang, and R. S. Blum, "Wireless-powered cooperative communications: power-splitting relaying with energy accumulation," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 969–982, Apr. 2016. doi: 10.1109/JSAC.2016.2544559.
[32] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: a contemporary survey," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 2, pp. 757- 789, 2015. doi: 10.1109/COMST.2014.2368999.

Manuscript received: 2017-12-17

Biographies

LIU Binghong (2013210720@bupt.edu.cn) received the B.S. degree in communication engineering from Beijing University of Posts and Telecommunications (BUPT), China in 2017. She is currently pursuing the Ph.D. degree at BUPT. Her research interests include energy harvesting and fog radio access networks.

PENG Mugen (pmg@bupt.edu.cn) received the B.E. degree in electronics engineering from Nanjing University of Posts & Telecommunications, China in 2000, and the Ph.D. degree in communication and information system from the Beijing University of Posts & Telecommunications (BUPT), China in 2005. Afterward, he joined BUPT, and became a full professor with the School of Information and Communication Engineering, BUPT, in October 2012. During 2014, he was also an Academic Visiting Fellow at Princeton University, USA. He is leading a research group focusing on wireless transmission and networking technologies in the Key Laboratory of Universal Wireless Communications (Ministry of Education), BUPT. He has authored/coauthored more than 60 refereed IEEE journal papers and over 200 conference proceeding papers. His research interests include wireless communication theory, radio signal processing and convex optimizations, with particular interests in cooperative communication, radio network coding, self-organization networking, heterogeneous networking, and cloud communication.

ZHOU Zheng (nczhouzheng@gmail.com) received the B.S. degree in information engineering from Beijing University of Posts and Telecommunications (BUPT), China in 2012. He is currently pursuing the Ph.D. degree at BUPT. His research interests include simultaneous information and power transfer and cloud radio access networks.