Simultaneous Wireless Information and Power Transfer: Technologies, Applications, and Research Challenges

Jun Huang, Cong-Cong Xing, and Chonggang Wang

The authors survey the current architectures and enabling technologies for SWIPT and identify technical challenges to implement SWIPT. Following an overview of enabling technologies for SWIPT and SWIPT-assisted wireless systems, they showcase a novel SWIPT-supported power allocation mechanism for D2D communications to illustrate the importance of the application of SWIPT.

ABSTRACT

Energy efficiency will play a crucial role in future communication systems and has become a main design target for all 5G radio access networks. The high operational costs and impossibility of replacing or recharging wireless device batteries in multiple scenarios, such as wireless medical sensors inside the human body, call for a new technology by which wireless devices can harvest energy from the environment via capturing ambient RF signals. SWIPT has emerged as a powerful means to address this issue. In this article, we survey the current architectures and enabling technologies for SWIPT and identify technical challenges to implement SWIPT. Following an overview of enabling technologies for SWIPT and SWIPT-assisted wireless systems, we showcase a novel SWIPT-supported power allocation mechanism for D2D communications to illustrate the importance of the application of SWIPT. As an ending note, we point out some future research directions to encourage and motivate more research efforts on SWIPT.

INTRODUCTION

Energy-constrained wireless devices are typically powered by batteries that suffer from limited lifetime. While replacing or recharging wireless device batteries can sustain the network's normal operations, it either incurs high operational costs or is even impossible in some scenarios.

This situation calls for a new technology by which wireless devices can constantly replenish themselves with energy from the ambient environment. Simultaneous wireless information and power transfer (SWIPT), which exploits the same emitted electromagnetic wave field to deliver both energy and information, has emerged as a powerful means to address the above issue. SWIPT promises three types of gain. First, wireless devices with SWIPT support are able to scavenge energy when receiving data, thereby prolonging their lifetime. Second, compared to the conventional time-division multiplexing mechanism, where the transmissions of power and information are separate, the transmission efficiency under SWIPT is improved. Third, with SWIPT, the interference to the communications is kept under control and can even be beneficial for energy harvesting (EH).

SWIPT is applicable to various wireless systems. One of its notable applications is RF identification (RFID) tags, which are passive devices and battery-free. Although RFID technology has been extensively investigated, its potential is not fully exploited due to the small reading range of RFID readers and constrained power. Another SWIPT application can be found in relay-assisted wireless communication systems where energy is transferred to remote terminals via one or more intermediate relays. In this situation, with SWIPT, the high path loss rate of energy-bearing signals can be mitigated.

The purpose of this article is to provide a brief overview of the current SWIPT architectures, enabling technologies, and applications, and some technical challenges in realizing SWIPT. Specifically, multiple technologies whose integration is needed to enable SWIPT in wireless systems are surveyed. As a case study to illustrate the importance of the application of SWIPT, a novel SWIPT power allocation mechanism for device-to-device (D2D) communications is presented. Also, future SWIPT research directions are comprehensively discussed in this article.

SWIPT ARCHITECTURES

A significant advance in wireless power transfer is the rectifying-antenna (rectenna), which is a diode-based circuit that converts RF signals into direct current voltage. Early research efforts on wireless power transfer focused on the design of compact and efficient rectennas or similar energy harvesters.

With the ever increasing amount of wireless devices in today's society, substantial research efforts in both academia and industry have recently focused on SWIPT due to its dual roles in transferring information and energy. Typical SWIPT architectures are shown in Fig. 1, where the time switching refers to the architecture in which each receiving antenna periodically switches between the energy harvester and the information decoder, and the power splitting refers to the architecture, where the received signal is divided into two separate signal streams, with one being sent to the energy harvester and the other to the information decoder. To realize SWIPT in practical wireless systems, sophisticated receivers have been designed based on these two architectures. In

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particular, *antenna switching* [1] is devised where the receiving antennas are separated into two groups with one group dedicated to information decoding and the other to EH. Nevertheless, this design is essentially a special case of the power splitting architecture with binary splitting power ratios. Another notable practical receiver design is *dynamic power splitting* [2] where an adjustable power ratio for EH and information decoding is designed.

Given these architectures, corresponding technologies need to be developed to successfully implement SWIPT in wireless systems. These technologies are summarized in the next section.

Enabling Technologies for SWIPT

Enabling SWIPT in wireless systems requires the integration of multiple technologies such as multi-antenna transmission, EH, resource allocation, and signal processing. The state of the art of these technologies is briefly discussed in this section.

Multi-Antenna Transmission

Among the efforts searching for a solution to reducing the transmission range of SWIPT, the idea of installing multiple antennas on devices appears to be sound and feasible, as multiple antennas not only can increase the antenna aperture, but also can attain higher gain. In order to arrange multiple antennas into a small pocket-sized device, a higher communication frequency would be useful for SWIPT systems. Incidentally, equipping a SWIPT system with multiple antennas enables two different signal processing techniques: analog domain beamforming and digital domain precoding. The former can be realized by a complex weighting phase shifter, and the latter can be specially designed to satisfy some predefined power or rate conditions/constraints.

An issue that arises and needs to be addressed in multi-antenna transmissions is co-channel interference, because the system consists of multiple users. In this regard, various existing interference alleviation techniques (e.g., block diagonalization precoding [3], which sends information to interference-free receivers and energy to others) may be applied in SWIPT systems to deal with this issue.

Efficient Energy Harvesting

Toward achieving a green and self-sustaining system that requires less energy from fixed sources, efficient EH methods and techniques need to be considered in SWIPT systems. Unlike traditional EH sources such as solar power, wind, and tide, the location of a transceiver has a great impact on the EH performance in SWIPT. A SWIPT-enabled transmitter can work in either a periodic manner or a time-varying manner. When most of the nodes in the system have a strong power level, SWIPT may be turned off by the system for reduced overhead. On the other hand, when most of the nodes in the system suffer from a lack of power, SWIPT may be turned on to power the nodes.

EH for SWIPT has been explored in opportunistic and cooperative ways. An optimal time switching rule for a point-to-point wireless link over the flat-fading channel subject to the time-varying

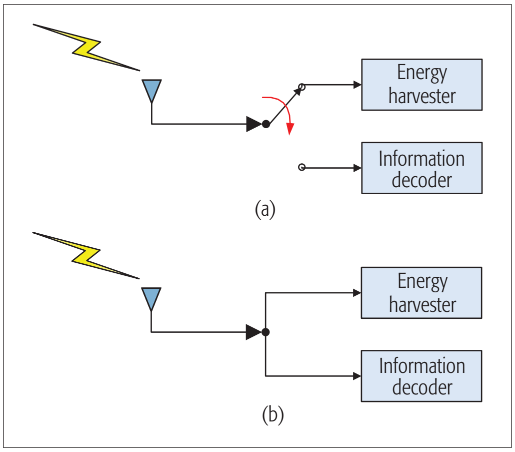

Figure 1. SWIPT architectures at the receiving antenna: a) time switching; b) power splitting..

Resource allocation in SWIPT systems refers to, primarily, the optimization of the utilization of various limited resources in the system, such as energy, bandwidth, time, and space. Of course, any required or predefined constraints with respect to relevant parameters must be satisfied.

co-channel interference was derived in [4], where the receiver was assumed to have no fixed power supplies, and thus needs to replenish energy from the unintended interference and/or the intended signal sent by the transmitter. Relay selection for achieving a trade-off between the efficiency of the information transmission to the receiver and the amount of energy transferred to the energy harvesters has been studied recently, and a relay selection policy that yields the optimal trade-off was proposed in [5]. The latest progress on efficient EH techniques in SWIPT implementation can be found in [6].

Resource Allocation

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Due to the dual identities of RF signals, transmitting information and power simultaneously calls for joint consideration of resource allocation with power control and user scheduling, which entails the following two things. First, opportunistic power control can be used to improve the energy and information transfer efficiency by exploiting the channel fading feature. Second, idle users who have high channel gains can be scheduled for power transfer to prolong the network lifetime. It has been discovered that with optimal power control consideration, both the system capacity and the harvested energy increase significantly, and the average harvested energy can be improved as well.

Moreover, resource allocation is an effective way to mitigate the interference in wireless systems. With SWIPT, harmful interference to a system can be turned into useful energy for the system. An interference-based resource allocation mechanism can gather the interference and direct it to specific energy-hungry devices, thereby enhancing the system's performance.

Signal Processing

A main concern for SWIPT is the growing decay in energy transfer efficiency, caused by the propagation of path loss when the transmission distance increases. Beamforming, as an advanced signal

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processing technique, can be applied to SWIPT to improve its power transfer efficiency without additional bandwidth or increased transmitting power. Indeed, beamforming has been deemed a primary technique for feasible implementations of SWIPT.

In addition to beamforming, the transmitted power in a wireless power transfer system varies over time provided that the average power delivered to the receiver is above a certain required threshold. Because of this, information can be encoded in the energy signal by varying its power levels over time, thereby achieving continuous information transfer without degrading the power transfer efficiency. To emphasize this dual use of energy signal in both wireless power transfer and wireless information transfer, the resulting modulation scheme is called energy modulation.

A new general modulation mechanism that is influenced by the spatial modulation was proposed in [7]. This new modulation uses multiple antennas, is suitable for SWIPT, and, notably, carries information via energy patterns. With regard to pulse position modulation (PPM) and pulse amplitude modulation (PAM), the following two energy patterns can be conceived [8]:

(1) A PPM-resembling position-based energy pattern that is used in the spatial domain
(2) A PAM-resembling intensity-based energy pattern that completely depends on positive values

Potentially, some other modulation techniques may also be of possible inspirational value in devising additional energy patterns for energy-pattern-based transmissions in integrated receivers.

Wireless Systems with SWIPT

As SWIPT-enabled devices can function dually, that is, they can decode information and harvest energy from the same stream of signals simultaneously, the SWIPT technology can be applied to various wireless systems. In this section, typical wireless networks with SWIPT are summarized by organizing them into the following five types: wireless sensor networks (WSNs), relay networks, coordinated multipoint (CoMP) networks, collaborative mobile clouds (CMCs), and cognitive radio networks.

Wireless Sensor Networks

One of the essential features of the Internet of Things (IoT) is that all (small) physical objects around us will be connected via some WSN in which a small, inexpensive, and low-power sensor is attached to each physical object to collect information from the immediate surrounding environment and transmit it to other nodes in the network, thereby enabling future smart homes, smart cities, smart hospitals, and so forth. For a long time, the notable bottleneck for any WSN, which consists of a large number of sensors as the "skin" of the IoT structure, is the (short) period of time in which the network can be functional. Since sensors are typically powered by batteries, those batteries need to be recharged or replaced on a regular basis. Even worse, it is sometimes very difficult or impossible to replace sensor batteries [9].

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Relay Networks

Relay networks are devised to improve the efficiency and reliability of signal/data transmissions by setting up intermediate network nodes and requiring them to relay signals/data in a cooperative manner to reduce the fading and attenuation of signals. Relay networks present a particularly appropriate scenario to which the SWIPT technology can be applied, in the sense that the relay network itself can benefit from the relayed and cooperative transmissions in terms of saving energy, and the harvested energy can be used to charge relay nodes as compensation for their role of data forwarding [10]. Generally speaking, current research on relay-assisted systems in the literature studies the following two scenarios: the SWIPT scenario and the multihop energy transfer scenario. The former refers to the scheme where the employed relay and the source terminal seek energy from each other's radiated signals, and the latter refers to the situation where energy needs to be transferred to some remote terminals through multiple relays.

Also, studies in the literature on SWIPT relay networks primarily focus on performance enhancement of the physical layer, the medium access control layer, and the network layer. For instance, there are issues related to relay operation, power allocation, and relay selection. With regard to relay selection, the mechanism of SWIPT in fact poses a new challenge for the design of relay networks, since the demanded relay for data transmission may not be the same relay that has the most powerful channel for EH. As such, a trade-off between the efficiencies of information transfer and energy transfer must be considered when devising relay selections.

CoMP Networks

At present, CoMP networks can be categorized into the following two types: joint transmission (JT), where multiple base stations serve an edge user simultaneously and the edge user's data is shared commonly, and coordinated beamforming (CB) where, in contrast to JT, an edge user is served only by one base station, and its data is locally owned. Pragmatically, CB-CoMP networks are more preferable than JT-CoMP networks since they require much less data exchanging overhead.

It is an emerging practice to investigate the benefits and challenges of integrating CoMP networks with the SWIPT technology, with the proven fact that full-scale integration/cooperation can reduce the total amount of required transmitting power in a CoMP network [11]. Note, however, that an enormous backhaul capacity will be needed for a CoMP network integrated with SWIPT if all base stations participate in energy transfer and information sharing with respect to all EH terminals and information-receiving terminals.

Collaborative Mobile Clouds

A CMC is a cooperative content distribution architecture in mobile computing where users share acquired multimedia information in a collaborative and complementary manner [12]. A CMC, unlike conventional cloud computing or cloud radio access networks, constitutes a set of mobile terminals that, in a way similar to the peer-to-peer mechanism, completes the desired tasks distributively, cooperatively, and collaboratively.

A CMC constituted by a set of SWIPT mobile terminals can be expected to be more energy-efficient than a CMC of regular mobile terminals due to the fact that the SWIPT technology allows a terminal to harvest energy and receive information simultaneously. Furthermore, integrating SWIPT with CMCs not only can result in more efficient energy utilizations, but can restructure the formation of the CMC as well. Considering that the data transmission performed by a CMC member can cost that member/user/terminal a considerable amount of energy, the selfish nature of a user/terminal may consequently prevent it from being willing to join a CMC. Thus, applying the SWIPT technology to CMCs may act as an incentive for users to join CMCs, as doing so may benefit users with extra energy.

Cognitive Radio Networks

Cognitive radio networks refer to systems of spectrum sharing between primary users (PUs) and secondary users (SUs), where the PUs share their underutilized licensed spectrum with the SUs under the condition that the SUs' communications do not generate harmful interference to PUs' communications. Specifically, the following spectrum sharing methods are available: interweave, overlay, and underlay. Interweave spectrum sharing requires the SU transmit data over the silent intervals of PU's communications; overlay spectrum sharing enables the SU to exchange available spectrum with the PU; and underlay spectrum sharing allows the SU and the PU to coexist on the spectrum band by requesting the SU to restrict its transmitting power to a certain extent.

Because of the ways in which cognitive radio networks and the SWIPT technology work, making a cognitive radio network SWIPT can be expected to enhance the spectrum utilization and the EH efficiency [8]. To see this, consider a SWIPT-enabled PU network that shares its licensed spectrum with an SU network. While the spectrum utilization efficiency in the PU network can be improved, the energy transfer efficiency in the PU network can be augmented due to the extra energy source from the SU.

Power Allocation for D2D with SWIPT

The most challenging issue in successfully implementing D2D communications underlaying cellular networks lies in the mutual interference between D2D and cellular communications.

Power allocation plays a vital role in addressing such an issue. While numerous research studies have been conducted on D2D power allocation, most of them have assumed that the interference is harmful, and little work has been done for D2D power allocation in the presence of SWIPT. In this section, we address the D2D power allocation problem with SWIPT by using game theory.

System Model

Consider a single cell in cellular networks that D2D communications underlay. Within the cell, there are one base station (BS), one cellular user, and n D2D links. As D2D communications are implemented as an underlay to cellular communications, D2D links nonorthogonally reuse cellular uplink resources, and thus they will cause interference to cellular users and among themselves as well.

Each D2D user is installed with a SWIPT power splitting unit, which allows simultaneous information and power transfer. Hence, the D2D device is able to harvest energy from signals, interference, and noise. As noted earlier, a D2D pair will be interfered not only by the cellular user, but also by the other D2D links; that is, a D2D receiver can scavenge energy from the associated D2D transmitter and cellular users as well as other D2D links.

It is true that higher transmitting power of a D2D link will lead to an increased signal-to-interference-plus-noise ratio (SINR), but this increase will certainly cause stronger interference to other D2D links. Meanwhile, increased power will result in more energy harvested by D2D receivers and more power consumption. The objective is to determine the appropriate amount of power for all D2D pairs in the presence of SWIPT.

Utility Formulation

Game theory is leveraged to model the power allocation among D2D communication transmitters. Specifically, we define the utility of the D2D link i as

$$U_i = \omega_1 \cdot SINR_i + \omega_2 \cdot E_i - \omega_3 \cdot F_i, \qquad (1)$$

where E_i is the total amount of energy harvested by D2D link i, F_i signifies the negative impacts of link i including the interference (caused by i) to other D2D links and its own power consumption, and ω_1, ω_2, and ω_3 are (positive) weights reflecting the importance of each term, and $\Sigma_{i=1}^{3} \omega_i = 1$.

Note that the power of a D2D transmitter, p_i, should not be so high that it would consume more power and generate harmful interference to other D2D links. Figure 2 illustrates the correlation between U_i and p_i, and between $SINR_i$ and p_i. As can be seen, the utility would not increase unlimitedly with the increase of power, which shows the rationality of the formulation of utility.

Distributed Power Allocation Mechanism

To solve the power allocation problem, we assume that any D2D link only knows its own power and link status and has no way of knowing those of any other D2D links. However, the interference and the harvested energy from the interference are known by this link, and U_i is concave with respect to p_i based on the previous discussion. Here, we give an iterative algorithm for computing the Nash equilibrium where the computation of the Nash-equilibrium-leading power $p_i[t + 1]$ for link i at the $(t + 1)$th iteration amounts to finding the optimal power for link i. That is,

$$p_i[t+1] = \arg \max_{p_i[t] \in [0,\infty]} \{(U_i[t])\}, \qquad (2)$$

where the right side can be obtained by solving the equation

$$\frac{\partial U_i[t]}{\partial p_i[t]} = 0.$$

The major steps of the algorithm for computing the desired Nash equilibrium power p_i^* for each

CMC, unlike the conventional cloud computing or cloud radio access networks, constitutes a set of mobile terminals which, in a way similar to the peer-to-peer mechanism, completes the desired tasks distributively, cooperatively, and collaboratively.

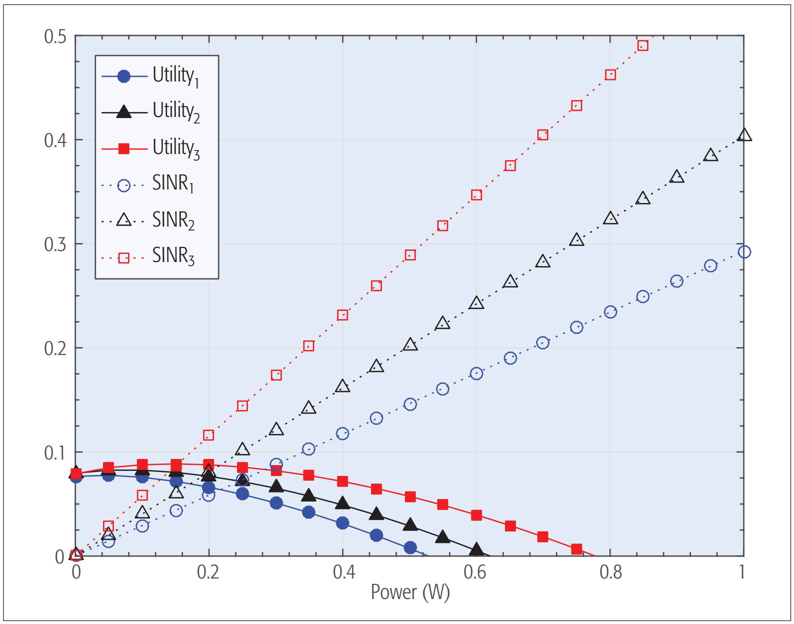

Figure 2. Correlations between U_i and p_i, and $SINR_i$ and p .

D2D link i are shown as follows:

- Each D2D link takes an initial value for its power $p_i[0]$, where $i = 1, 2, ..., n$.
- Each D2D link computes its subsequent powers by Eq. 2, and updates its power value. We use $p_i[t]$ to denote the tth updated power value for link i.
- If $|U_i[t] - U_i[t-1]| \leq \varepsilon$ for a predefined threshold ε at the tth round; then the computation terminates and $p_i^* = p_i[t]$; otherwise, the computation continues by starting the next round.

It can be proven that this approach converges to the Nash equilibrium strategy. The detailed proof is omitted here due to space limitation.

Simulations

To validate the proposed power allocation mechanism, comparisons for the mechanism with/without SWIPT and node mobility are thoroughly investigated in this section. We assume that three D2D links reuse the same spectrum with one cellular user in the cell. $p_i \in [0, 2]$ W, and the *Rician* fading model is employed, the weights for each terms of Eq. 1 are set to be the same (i.e., 1/3), meaning that they are equally important, all the experiments are run in MATLAB, and the simulation results are statistically collected by averaging 1000 trials.

With vs. Without SWIPT: Comparisons are performed between the power allocation with SWIPT and that without SWIPT. For the latter case, the utility function of each D2D link i is defined as $U_i = SINR_i - F_i$, where

$$\frac{(1-\delta)p_i h_{ii}}{(1-\theta)(N_0+I)+(1-\eta)\sum_{j\neq i} p_j h_{ji}}$$

and $F_i = p_i^{1.5}$ [13]. It is obvious to see that this definition has almost the same form as the previous utility except for the EH term

$$E_i = \delta \cdot p_i h_{ii} + \eta \cdot \sum_{j\neq i} p_j h_{ji} + \theta \cdot (N_0 + I),$$

where δ, η, and θ are the power conversion efficiencies, which are all set to 0.2. Moreover, $N_0 + I$ is set to 0.4 throughout all the simulations.

The comparison results in terms of power and utility are shown in Fig. 3. As expected, we can see from Fig. 3a that the power of each D2D link with SWIPT is at least 11 percent greater than that without SWIPT. In parallel, the utility of each D2D link with SWIPT is higher than that without SWIPT, as evidenced by Fig. 3b. Thus, we claim that SWIPT plays an important role in improving the system performance, and thus our proposed power allocation mechanism is of practical significance.

With vs. Without Mobility: Using the same parameter settings used in the previous experiments, comparisons are also conducted between power (and utility, respectively) with node mobility and without mobility. The error scaling factors for

$$J[t-1] = \sum_{j\neq i} p_j[t-1]h_{ji}$$

are employed to reflect the mobility. Specifically, the perceived interference from other D2D links at the tth iteration is assumed to be a random variable that is evenly distributed in the interval from $0.8 \cdot J[t-1]$ to $1.3 \cdot J[t-1]$ instead of exact $J[t-1]$ due to mobility.

The results are shown in Fig. 4, where for the case with mobility, the mean value of 1000 trials and standard deviation at each iteration are given. As can be observed from this figure, the gap between results of without mobility and with mobility is small, indicating that mobility may have little impact on the algorithm if it is guaranteed to converge. In addition, we can see that the algorithm can converge very fast even with mobility, and it has the same convergence speed as in the case without mobility. This insight further validates the correctness of the proposed mechanism.

Conclusion and Future Research Directions

In this article, with respect to the emerging complex mechanism of SWIPT, we have surveyed its current architectures and enabling technologies, and have identified some technical challenges in implementing this mechanism. Following an overview of enabling technologies for SWIPT and SWIPT-enabled wireless systems, we have showcased a novel SWIPT-supported power allocation mechanism for D2D communications to illustrate the importance of the application of SWIPT. Toward encouraging more research efforts on SWIPT to forthcome, we point out the following issues that may be worth investigations as future research topics on SWIPT.

Mobility of SWIPT: While the notion that mobility would be a desired feature of any SWIPT systems, as is readily seen by considering the fact that information transmission and EH as well as network status all have a dynamic and time-varying nature, note that the mobility itself will largely affect the availability of channel state information of the network, and therefore it is not an easy task to obtain the precise channel state information in SWIPT systems. Given this situation, devising robust beamformers to cope with the mobility issue in systems with SWIPT is a both needed and challenging task.

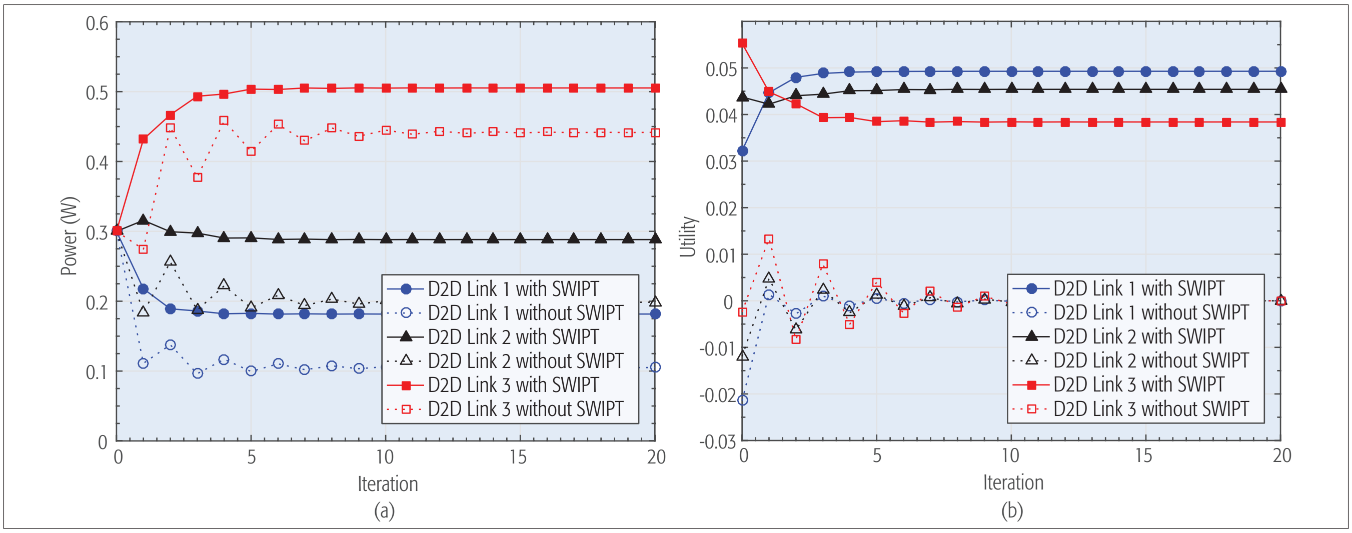

Figure 3. Performance comparisons with/without SWIPT: a) power comparison; b) utility comparison.

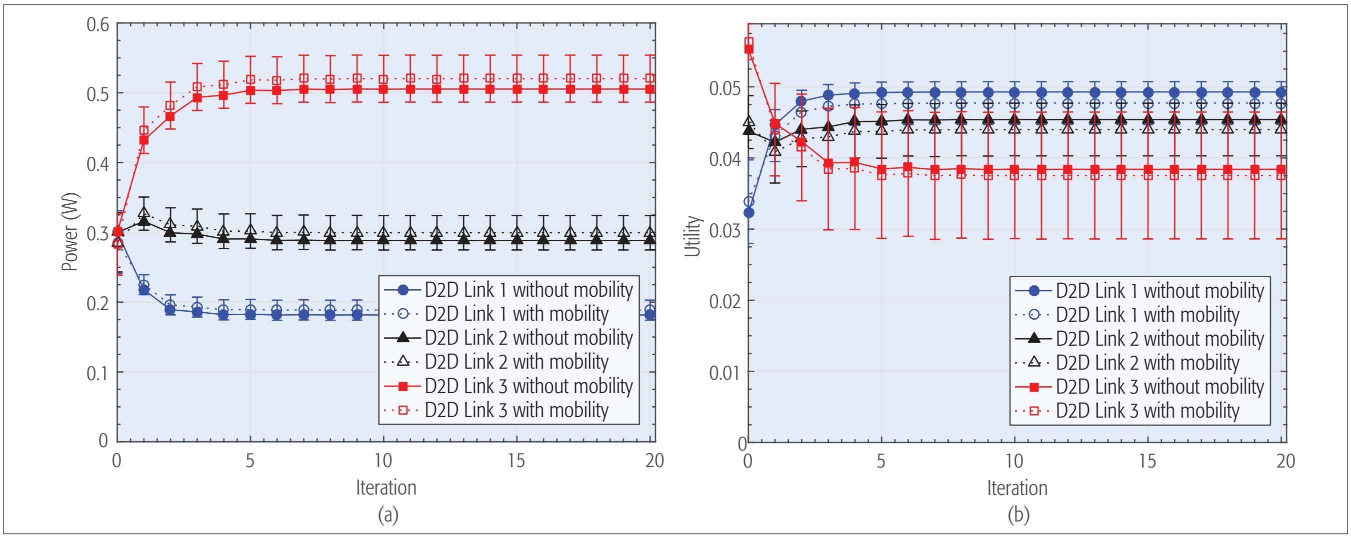

Figure 4. Performance comparisons with/without mobility; a) power comparison; b) utility comparison.

Security of SWIPT: The dual effects of increasing the transmitting power of signals — doing so not only can enhance the desired energy transfer from a transmitter (Alice) to a legitimate receiver (Bob), but can escalate the undesired risk of information stealth by an eavesdropper (Eve) as well — present a security concern in SWIPT systems. Noticing the recognized effectiveness of physical layer security measures, which essentially work by optimizing the secrecy rate, it would be a release to the aforementioned security concern if we are able to find an effective way to increase the signal strength on the legitimate channel and reduce the signal strength on the wiretap channel at the same time.

SWIPT in Multihop Networks: The trade-off issue between the efficiencies of information transmission and energy transfer in SWIPT is manifested when SWIPT is integrated into a multihop relay network, since a relay node that is most suitable for information transmission may not be most suitable for energy transfer. Hence, how to appropriately select relay nodes in terms of the efficiencies of information transmission and energy transfer needs to be further investigated. Considering that network coding is known for its capability to increase the amount of transmitted information per time slot and for allowing receivers to receive messages simultaneously, which now means an increased amount of surrounding energy, it would be an interesting approach to tie network coding, SWIPT, and multihop networks together in this context.

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