

Simultaneous Wireless Information and Power Transfer in Modern Communication Systems

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ABSTRACT

Energy harvesting for wireless communication networks is a new paradigm that allows terminals to recharge their batteries from external energy sources in the surrounding environment. A promising energy harvesting technology is wireless power transfer where terminals harvest energy from electromagnetic radiation. Thereby, the energy may be harvested opportunistically from ambient electromagnetic sources or from sources that intentionally transmit electromagnetic energy for energy harvesting purposes. A particularly interesting and challenging scenario arises when sources perform simultaneous wireless information and power transfer (SWIPT), **as strong signals not only increase power transfer but also interference.** This article provides an overview of SWIPT systems with a particular focus on the hardware realization of rectenna circuits and practical techniques that achieve SWIPT in the domains of time, power, antennas, and space. The article also discusses the benefits of a potential integration of SWIPT technologies in modern communication networks in the context of resource allocation and cooperative cognitive radio networks.

INTRODUCTION

Recently, there has been a lot of interest in integrating energy harvesting technologies into communication networks. Several studies have considered conventional renewable energy resources, such as solar and wind, and have investigated optimal resource allocation techniques for different objective functions and topologies. However, the intermittent and unpredictable nature of these energy sources makes energy harvesting critical for applications where quality of service (QoS) is of paramount importance, and most conventional harvesting technologies are only applicable in certain environments. An energy harvesting technology

that overcomes the above limitations is wireless power transfer (WPT), where the nodes charge their batteries from electromagnetic radiation. In WPT, green energy can be harvested from either ambient signals opportunistically or a dedicated source in a fully controlled manner; in the latter case, green energy transfer can take place from more powerful nodes (e.g., base stations) that exploit conventional forms of renewable energy.

Initial efforts on WPT have focused on long-distance and high-power applications. However, both the low efficiency of the transmission process and health concerns with such high-power applications prevented their further development. Therefore, most recent WPT research has focused on near-field energy transmission through inductive coupling (e.g., used for charging cell phones, medical implants, and electrical vehicles). In addition, recent advances in silicon technology have significantly reduced the energy demand of simple wireless devices. WPT is an innovative technology and attracts the interest from both academia and industry; some commercial WPT products already exist (e.g., [1]), and several experimental results for different WPT scenarios are reported in the literature [2].

With sensors and wireless transceivers getting ever smaller and more energy-efficient, we envision that radio waves will not only become a major source of energy for operating these devices, but their information and energy transmission aspects will also be unified. Simultaneous wireless information and power transfer (SWIPT) can result in significant gains in terms of spectral efficiency, time delay, energy consumption, and interference management by superposing information and power transfer. For example, wireless implants can be charged and calibrated concurrently with the same signal, and wireless sensor nodes can be charged with the control signals they receive from the access point. In the era of the Internet of Things, SWIPT technologies can be of fundamental

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importance for energy supply to and information exchange with numerous ultra-low-power sensors, which support heterogeneous sensing applications. Also, future cellular systems with small cells, massive multiple-input multiple-output (MIMO), and millimeter-wave technologies will overcome current path loss effects; in this case, SWIPT could be integrated as an efficient way to jointly support high throughput and energy sustainability.

In this article, we give an overview of the SWIPT technology, and discuss recent advances and future research challenges. More specifically, we explain the rectifying antenna (rectenna) circuit, which converts microwave energy into direct current (DC) electricity and is an essential block for the implementation of WPT/SWIPT technology. Due to practical limitations, SWIPT requires the splitting of the received signal into two orthogonal parts. Recent SWIPT techniques that separate the received signal in the domains of time, power, antenna, and space are presented. On the other hand, SWIPT entails fundamental modifications for the operation of a communication system, and motivates new applications and services. From this perspective, we discuss the impact of SWIPT on the radio resource allocation problem as well as sophisticated cognitive radio (CR) scenarios that enable information and energy cooperation between primary and secondary networks.

WPT MODULE COMPONENTS

Exchanging electromagnetic power wirelessly can be classified into three distinct cases:

- Near field power transfer employing inductive, capacitive, or resonant coupling that can transfer power in the range of tenths of Watts, over short distances of up to one meter (sub-wavelength)
- Far field directive power beaming, requiring directive antennas, that can transfer power in the range of several milliwatts at distances of up to several meters in indoor and outdoor environments
- Far field, low-power, ambient RF power scavenging involving receivers that opportunistically scavenge the power transmitted from public random transmitters (cell phone base stations, TV broadcasting stations) for communication with their peer nodes

For this last case the collected power is in the range of several microWatts, and the communication range can be up to several kilometers assuming there is adequate power density. While there are several applications related to near field wireless charging, such as wireless charging of electric cars, cell phones, or other handheld devices, the main focus of this article is on far field WPT, which involves the use of antennas communicating in the far field.

WIRELESS POWER RECEIVER MODULE

A wireless power scavenger or receiver consists of the following components: a receiver antenna or antenna array, a matching network, a radio frequency to direct current (RF-DC) converter or rectifier, a power management unit (PMU),

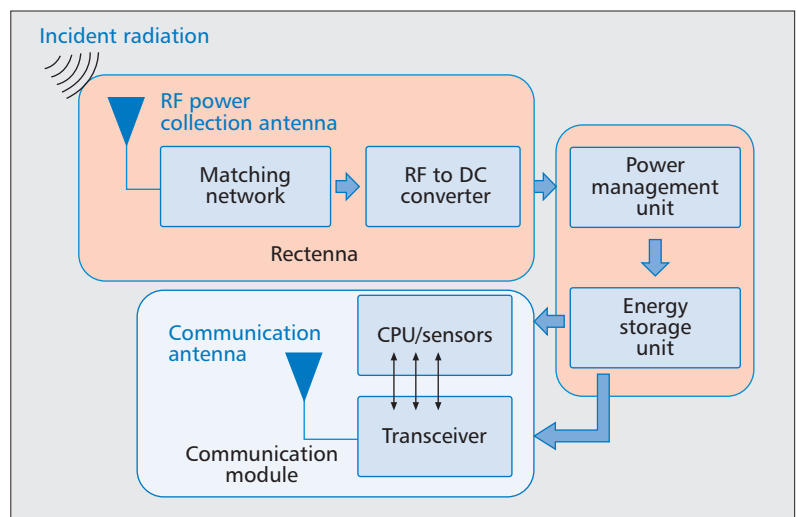


Figure 1. Block diagram of a typical power scavenging module powering a communication transceiver.

and the energy storage unit [3]. Upon the successful charging of the energy storage unit, the storage unit, usually a rechargeable battery or a super capacitor, will provide power to the central processing unit (CPU), the sensors, and the low duty cycle communication transceiver. The schematic of this module is presented in Fig. 1, and a successful implementation of a WPT system that scavenges ambient power 6.3 km away from a Tokyo TV tower is shown in Fig. 2.

CONDITIONS FOR EFFICIENT WPT

Based on the Friis free space equation, the received RF power at the terminals of the antenna depends on the available power density and the antennas' effective area $A_e = (\lambda^2 G_R)/(4\pi)$ and is given by

$$P_R = \cos^2 \phi \frac{P_T G_T}{4\pi R^2} A_e, \quad (1)$$

where P_T and P_R are the transmitted and received power, respectively, G_T and G_R are the transmitter and receiver gains (functions of the spatial variables), respectively, λ denotes the wavelength, and $\cos \phi$ is the polarization loss factor, which accounts for the misalignment (angle ϕ) of the received electric intensity vector E and the receiver antenna linear polarization vector. From Eq. 1 we can deduce that in order to ensure maximum received power, the receiver antenna needs to have high gain, has to be directed toward the transmitter (maximum directivity direction), and must be aligned with the received E -field ($\phi = 0$). However, these conditions cannot be ensured in practice. For example, in a Rayleigh multipath propagation environment the received signal has random polarization. Consequently, the optimum polarization for a receiver antenna is dual, linear, orthogonal polarization because it ensures the reception of the maximum average power regardless of the received signal's polarization. If the maximum gain direction cannot be guaranteed, omnidirectional antennas are preferred instead. The Friis equation is frequency-depen-

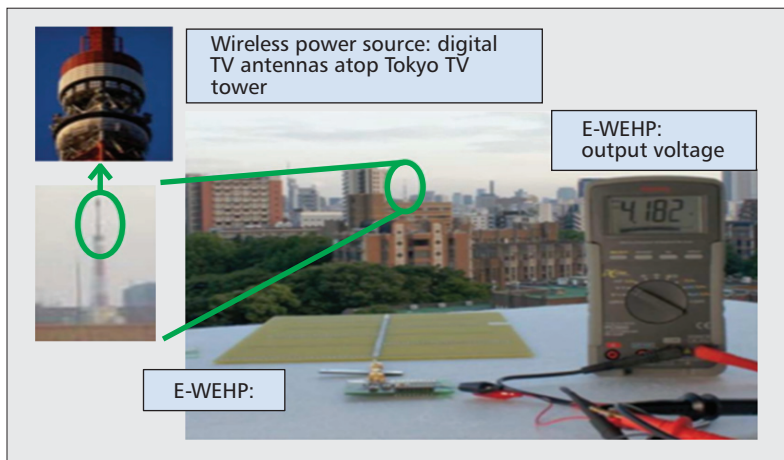


Figure 2. Field measurement in downtown Tokyo, Japan, with prototype device [4] harvesting wireless energy from multicarrier wireless digital TV signals broadcasted from atop the Tokyo TV tower 6.3 km away.

dent and applicable to narrowband signals. The total received power is calculated by integrating the received power P_R over frequency; therefore, a broadband antenna will receive more power than a narrowband one. As a result, wideband antennas or multi-band antennas are preferred.

The RF-to-DC converter or rectifier is probably the most critical component of a WPT module, and its design is the most challenging task [5]. A rectifier consists of at least one nonlinear device. Most rectennas (antenna and rectifier co-design) reported in the literature consist of only one diode. Ideally, the conversion efficiency of a rectifying circuit with a single nonlinear device can reach up to 100 percent. Unfortunately, this can only happen for specific values of P_{RF} and R_{DC} , where P_{RF} denotes the level of the RF power input at the rectifier, and R_{DC} is the delivered load. In more detail, the rectenna structure consists of a single shunt full-wave rectifying circuit with one diode, a $\lambda/4$ distributed line, and a capacitor to reduce the loss in the diode. Depending on the requirements, more complicated and sophisticated rectifier topologies can be used which are based on the well-known Dickson charge pump that can provide both rectification and impedance transformation. Typically, Schottky diodes are used as the nonlinear devices because they have low forward voltage drop and allow very fast switching action, features useful for rectifiers. Low forward voltage drop is needed because the received power is rather small, and fast switching action is needed to follow the relatively high RF frequency of the received signal. Alternatively, it is possible to use complementary metal oxide semiconductor (CMOS) transistors or other transistors as the nonlinear rectifying elements, especially when integrated solutions are preferred. The major problem with RF-to-DC converters is that their efficiency, defined as $\eta_R = P_{RF}/(V_{DC}^2/R_{DC})$, depends on P_{RF} , R_{DC} , and the DC voltage, V_{DC} , across the load. Generally, the higher the incident RF power, the higher the efficiency. For low power levels, efficiency can even drop to zero because the diodes' forward voltage drop is too high. This is why the reported high efficien-

cies cannot be seen in actual RF scavenging scenarios. As an example, the ambient power density measured 6.5 km away from the Tokyo TV tower was approximately $1 \mu\text{W}/\text{cm}^2$ and the received power was about $50 \mu\text{W}$, whereas high efficiency rectifiers require input powers between 0.5–5 mW, 10 to 100 times higher. As a result, the measured efficiency was rather small.

The final stage of the WPT module is the power management unit (PMU), which is responsible for maintaining the optimum load at the terminals of the rectifier despite the changing received RF power levels, and at the same time ensures the charging of the energy storage unit without additional loss.

TECHNIQUES FOR SWIPT

Early information theoretical studies on SWIPT have assumed that the same signal can convey both energy and information without losses, revealing a fundamental trade-off between information and power transfer [10]. However, this simultaneous transfer is not possible in practice, as the energy harvesting operation performed in the RF domain destroys the information content. **To practically achieve SWIPT, the received signal has to be split in two distinct parts, one for energy harvesting and one for information decoding.** In the following, the techniques that have been proposed to achieve this signal splitting in different domains (time, power, antenna, space) are discussed.

TIME SWITCHING

If time switching (TS) is employed, the receiver switches in time between information decoding and energy harvesting [6]. In this case, signal splitting is performed in the time domain, and thus the entire signal received in one time slot is used either for information decoding or power transfer (Fig. 3a). The TS technique allows for a simple hardware implementation at the receiver but requires accurate time synchronization and information/energy scheduling.

POWER SPLITTING

The power splitting (PS) technique achieves SWIPT by splitting the received signal into two streams of different power levels using a PS component; one signal stream is sent to the rectenna circuit for energy harvesting, and the other is converted to baseband for information decoding (Fig. 3b) [6]. **The PS technique entails higher receiver complexity compared to TS and requires the optimization of the PS factor α ;** however, it achieves instantaneous SWIPT, as the signal received in one time slot is used for both information decoding and power transfer. Therefore, it is more suitable for applications with critical information/energy or delay constraints and closer to the information theoretical optimum.

ANTENNA SWITCHING

Typically, antenna arrays are used to generate DC power for reliable device operation. Inspired by this approach, the antenna switching (AS) technique dynamically switches each antenna element between decoding/rectifying to achieve SWIPT in the antenna domain (Fig. 3c). In the

AS scheme, the receiving antennas are divided into two groups where one group is used for information decoding and the other group for energy harvesting [6]. The AS technique requires the solution of an optimization problem in each communication frame in order to decide the optimal assignment of the antenna elements for information decoding and energy harvesting. For a MIMO decode-and-forward (DF) relay channel, where the relay node uses the harvested energy in order to retransmit the received signal, the optimization problem was formulated as a knapsack problem and solved using dynamic programming in [7].

Because optimal AS suffers from high complexity, low-complexity AS mechanisms have been devised that use the principles of generalized selection combining (GSC) [7]. The key idea of GSC-AS is to use L out of N_T antennas with the strongest channel paths for either energy (GSCE technique) or information (GSCI technique) and the rest for the other operation.

SPATIAL SWITCHING

The spatial switching (SS) technique can be applied in MIMO configurations and achieves SWIPT in the spatial domain by exploiting the multiple degrees of freedom (DoFs) of the interference channel [8]. Based on the singular value decomposition (SVD) of the MIMO channel, the communication link is transformed into parallel eigenchannels that can convey either information or energy (Fig. 3d). At the output of each eigenchannel there is a switch that drives the channel output to either the conventional decoding circuit or the rectification circuit. Eigenchannel assignment and power allocation in different eigenchannels is a difficult nonlinear combinatorial optimization problem; in [8] an optimal polynomial complexity algorithm has been proposed for the special case of unlimited maximum power per eigenchannel.

Numerical Example — The performance of the discussed SWIPT techniques is illustrated in Fig. 4 for the MIMO relay channel introduced earlier, assuming a normalized block fading Rayleigh. In the considered setup, a single-antenna source communicates with a single-antenna destination through a battery-free MIMO relay node, which uses harvested energy in order to power the relaying transmission. We assume that the source transmits with power P and spectral efficiency $r_0 = 2$ b/channel use (BPCU); the relay node has global channel knowledge, which enables beam-forming for the relaying link. An outage event occurs when the destination is not able to decode the transmitted signal, and the performance metric is the outage probability. The first observation is that GSCI outperforms GSCE scheme for $L = 1$ and $L = 2$, respectively. This result shows that diversity gain becomes more important than energy harvesting due to the high RF-to-DC efficiency η . In addition, the GSCI scheme with $L = 1$ is the optimal GSC-based strategy and achieves a diversity gain equal to two. It can also be seen that the PS scheme outperforms the AS scheme with a gain of 2.5 dB for high P , while the TS scheme provides poor performance due to the required time division.

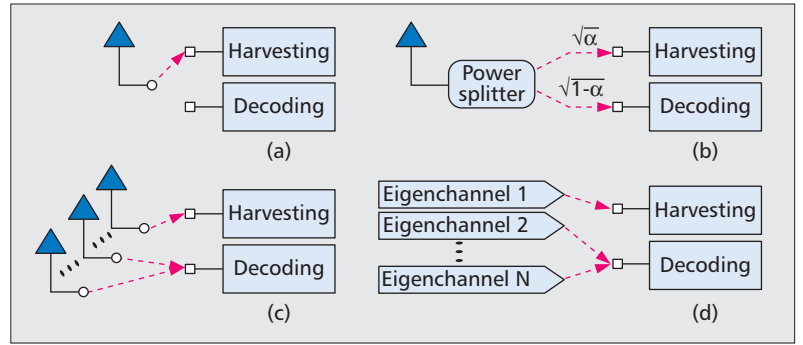


Figure 3. SWIPT transmission techniques in different domains: a) time; b) power; c) antenna; d) space.

RESOURCE ALLOCATION FOR SYSTEMS WITH SWIPT

This section discusses the benefits of employing SWIPT on resource allocation applications. Utility-based resource allocation algorithm design has been heavily studied in the literature [9] for optimizing the utilization of limited resources in the physical layer such as energy, bandwidth, time, and space in multiuser systems. In addition to the conventional QoS requirements such as throughput, reliability, energy efficiency, fairness, and delay, the efficient transfer of energy plays an important role as a new QoS requirement for SWIPT [10, 11]. Resource allocation algorithm design for SWIPT systems includes the following aspects:

Joint power control and user scheduling: The RF signal acts as a dual-purpose carrier for conveying information and energy to the receivers simultaneously. However, the wide dynamic range of the power sensitivity for energy harvesting (−10 dBm) and information decoding (−60 dBm) is an obstacle to realizing SWIPT. As a result, joint power control and user scheduling is a key aspect for facilitating SWIPT in practice. For instance, idle users experiencing high channel gains can be scheduled for power transfer to extend the lifetime of the communication network. Besides, opportunistic power control can be used to exploit the channel fading for improved energy and information transfer efficiency [10–12]. Figure 5 depicts an example of power control in SWIPT systems. We show the average system capacity vs. the average total harvested energy in a downlink system. In particular, a transmitter equipped with N_T antennas is serving one single-antenna information receiver and K single-antenna energy harvesting receivers. As can be observed, with optimal power control, the trade-off region of the system capacity and the harvested energy increases significantly with N_T . Besides, the average harvested energy improves with the number of energy harvesting receivers.

Energy and information scheduling: For passive receivers such as small sensor nodes, uplink data transmission is only possible after the receivers have harvested a sufficient amount of energy from the RF in the downlink. The physical constraint on the energy usage motivates a “harvest-then-transmit” design. Allocating more

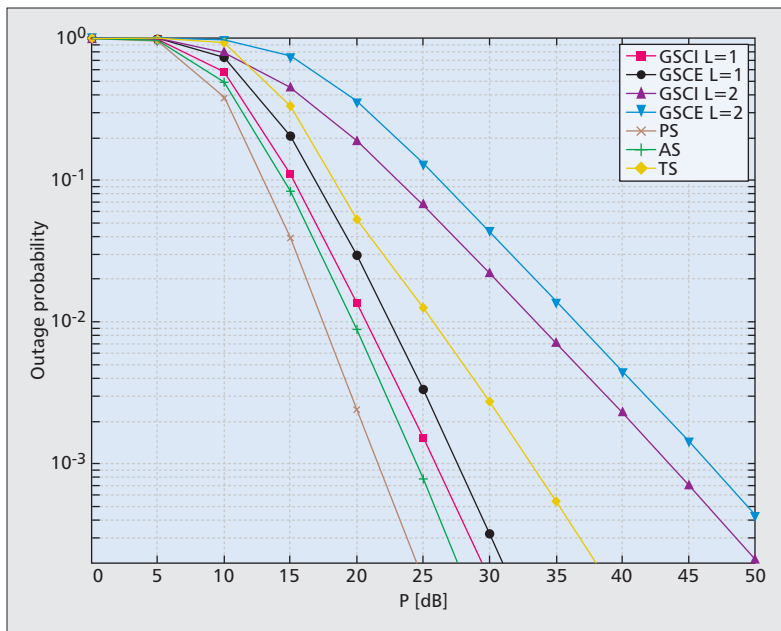


Figure 4. Outage probability versus P for GSCI, GSCE, PS, AS and TS; the simulation setup is $r_0 = 2$ BPCU, $N_T = 3$ antennas, $L = \{1, 2\}$ and RF-to-DC efficiency $\eta = 1$.

time for energy harvesting in the downlink leads to a higher amount of harvested energy, which can then be used in the uplink. However, this also implies that there is less time for uplink transmission which may result in a lower transmission data rate. Thus, by varying the amounts of time allocated for energy harvesting and information transmission, the system throughput can be optimized.

Interference management: In traditional communication networks, co-channel interference is recognized as one of the major factors that limits the system performance and is suppressed or avoided via resource allocation. However, in SWIPT systems, the receivers may embrace strong interference since it can act as a vital source of energy. In fact, injecting artificial interference into the communication network may be beneficial for the overall system performance, especially when the receivers do not have enough energy for supporting their normal operations, since in this case, information decoding becomes less important compared to energy harvesting. Besides, by exploiting interference alignment and/or interference coordination, a “wireless charging zone” can be created by concentrating and gathering multicell interference in certain locations.

JOINT INFORMATION AND ENERGY COOPERATION IN CR NETWORKS

SWIPT also opens up new opportunities for cooperative communications. We present one example where SWIPT improves the traditional system design of cooperative CR networks (CCRN). CCRNs are a new paradigm for improving spectrum sharing by having the primary and secondary systems actively seek opportunities to cooperate with each other [13, 14]. The

secondary transmitter (ST) helps relay the traffic of the primary transmitter (PT) to the primary user (PU), and in return can utilize the primary spectrum to serve its own secondary user (SU). However, to enable this cooperation, the ST should both possess a good channel link to the primary system and have sufficient transmit power. While the former can be achieved by proper placement, the latter requirement cannot be easily met especially when the ST is a low-power relay node rather than a powerful base station (BS), which renders this cooperation unmeaningful.

SWIPT may provide a promising solution to address this challenge by encouraging the cooperation between the primary and secondary systems at both the information and energy levels [15]. That is, the PT will transmit both information and energy to the ST; in exchange, the low-power ST relays the primary information. Compared to the traditional CCRN, this approach creates more incentives for both systems to cooperate and therefore improves the system overall spectrum efficiency without relying on external energy sources.

We illustrate the performance gain by studying a joint information and energy cooperation scheme using the amplify-and-forward protocol and the power splitting technique. Two channel phases are required to complete the communication. In phase I, the PT broadcasts its data and both the ST and the PU listen. The ST then splits the received RF signal into two parts: one for information processing then forwarding to the PU, and the other for harvesting energy, with relative power ratio of α and $1 - \alpha$, respectively. In phase II, the ST superimposes the processed primary data with its own precoded data, then transmits it to both the PU and the SU. The ST jointly optimizes power allocation factor α and the precoding vectors to the PU and SU to achieve the maximum rates.

In Fig. 6, we show the achievable rate region of the proposed information and energy cooperation schemes, and compare it with the conventional information cooperation only scheme [14]. We consider a scenario where the distances from the ST to all the other terminals are 1 m, while the distance from the PT to the PU is 2 m, and thus assistance from the ST is usually preferred by the PT. We assume that the ST has four transmit antennas and all other terminals have a single antenna. The primary energy is set to 20 dB, while the available secondary energy is 10 dB. The path loss exponent is 3.5, and the K factor for the Rician channel model is set to 5 dB. The RF-to-DC efficiency is equal to $\eta = 0.1, 0.5$, and 1. It is seen that the achievable rate regions are greatly enlarged thanks to the extra energy cooperation even with RF-to-DC efficiencies as low as $\eta = 0.1$. When the required PU rate is 2 b/s/Hz, the SU can double or triple its rate compared to the case without energy cooperation as η varies from 0.1 to 1. When the SU rate is 1.5 b/s/Hz, the PU enjoys a 75 percent higher data rate when $\eta = 1$. The proposed additional energy cooperation clearly introduces a substantial performance gain over the existing information cooperation only CR scheme, and could be a promising solution for future CCRNs.

CONCLUSION AND FUTURE WORK

This survey provides an overview of SWIPT technology. Different SWIPT techniques that split the received signal in orthogonal components have been discussed. We have shown that SWIPT introduces fundamental changes in the resource allocation problem and influences basic operations such as scheduling, power control, and interference management. Finally, a sophisticated CR network that enables information/energy cooperation between primary and secondary systems has been discussed as an example of new SWIPT applications. SWIPT imposes many interesting and challenging new research problems and will be a key technology for the next-generation communication systems. In the following, we discuss some of the research challenges and potential solutions.

Path loss: The efficiency of SWIPT is expected to be unsatisfactory for long-distance transmission unless advanced resource allocation and antenna technology can be combined. Two possible approaches to overcome this problem include the use of massive MIMO and coordinated multipoint systems. The former increase the DoF offered to harvest energy and create highly directive energy/information beams steered toward the receivers. The latter provides spatial diversity for combating path loss by reducing the distance between transmitters and receivers. Besides, the distributed transmitters may be equipped with traditional energy harvesters (e.g., solar panels) and exchange their harvested energy over a power grid to overcome potential energy harvesting imbalances in the network.

Communication and energy security: Transmitters can increase the energy of the information carrying signal to facilitate energy harvesting at the receivers. However, this may also increase their susceptibility to eavesdropping due to the broadcast nature of wireless channels. On the other hand, receivers requiring power transfer may take advantage of the transmitter by falsifying their reported channel state information. Therefore, new QoS concerns regarding communication and energy security naturally arise in SWIPT systems.

Hardware development: Despite the wealth of theoretical techniques for SWIPT, so far, hardware implementations have mostly been limited to WPT systems that opportunistically harvest ambient energy. Thus, the development of SWIPT circuits is fundamental to investigate the trade-off between SWIPT techniques occurring due to inefficiencies of different circuit modules. For example, the TS technique is theoretically less efficient than PS, but the latter suffers from power splitting losses that are not accounted for in theoretical studies.

Applications: SWIPT technology has promising applications in several areas that can benefit from ultra-low-power sensing devices. Potential applications include structure monitoring by embedding sensors in buildings, bridges, roads, and so on; healthcare monitoring using implantable bio-medical sensors; and building automation through smart sensors that monitor and control different building processes. However, for successful realization of such SWIPT

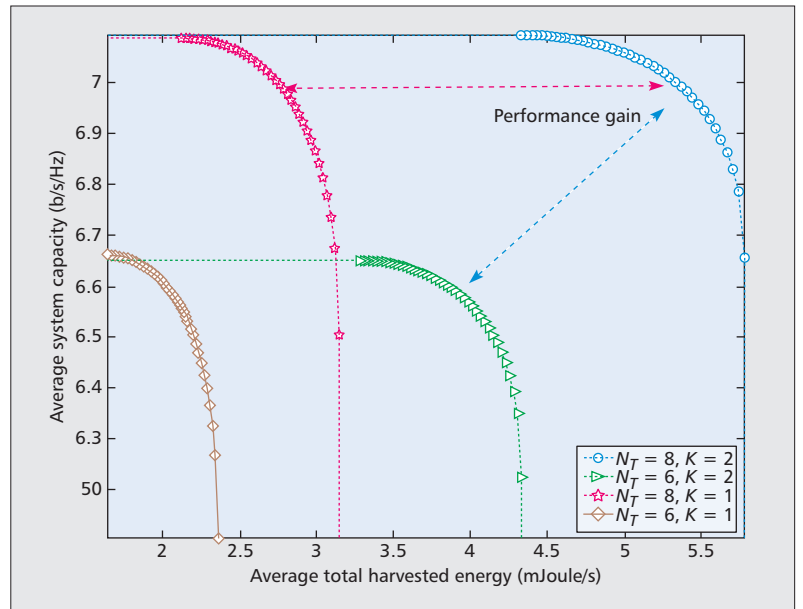


Figure 5. The trade-off region of the average system capacity (b/s/Hz) and the average total harvested energy (mJ/s) for different numbers of receivers. The carrier frequency is 915 MHz, and the information receiver and energy harvesting receivers are located at 30 m and 10 m from the transmitter, respectively. The total transmit power, noise power, transceiver antenna gain, and RF-to-DC conversion loss are set to 10 W, -23 dBm, 10 dBi, and 3 dB, respectively.

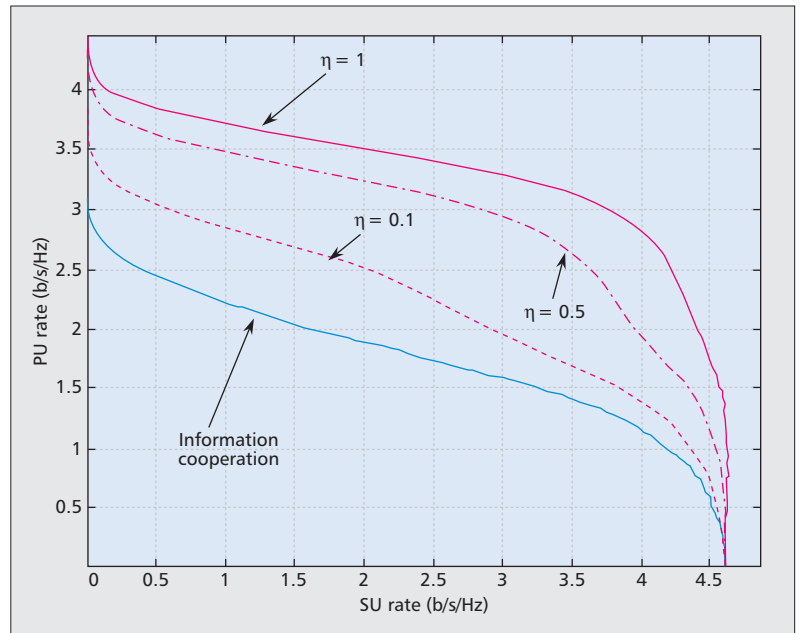


Figure 6. PU-SU rate region with different values of RF-DC efficiency.

applications, several challenges must be overcome at various layers from hardware implementation over protocol development to architectural design.

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SWIPT technology has promising applications in several areas that can benefit from ultra-low power sensing devices. However, for the successful realization of such SWIPT applications, several challenges have to be overcome at various layers.

REFERENCES

- [1] www.powercastco.com.
- [2] N. Shinohara, "Development of Rectenna with Wireless Communication System," *Proc. Euro. Conf. Ant. Prop.*, Rome, Italy, Apr. 2011, pp. 3970–73.
- [3] Z. Popovic, "Cut the Cord: Low-Power Far-Field Wireless Powering," *IEEE Microwave Mag.*, vol. 14, 2013, pp. 55–62.
- [4] R. J. Vyas et al., "E-WEHP: A Batteryless Embedded Sensor Platform Wirelessly Powered from Ambient Digital-TV Signal," *IEEE Trans. Microwave Theory and Tech.*, vol. 61, June 2013, pp. 2491–2505.
- [5] P. Nintanavongsa et al., "Design Optimization and Implementation for RF Energy Harvesting Circuits," *IEEE J. Emerging Sel. Topics Circuit Sys.*, vol. 2, Mar. 2012, pp. 24–33.
- [6] R. Zhang and C. K. Ho, "MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer," *IEEE Trans. Wireless Commun.*, vol. 12, May 2013, pp. 1989–2001.
- [7] I. Krikidis et al., "A Low Complexity Antenna Switching for Joint Wireless Information and Energy Transfer in MIMO Relay Channels," *IEEE Trans. Commun.*, vol. 62, no. 5, May 2014, pp. 1577–87.
- [8] S. Timotheou and I. Krikidis, "Joint Information and Energy Transfer in the Spatial Domain with Channel Estimation Error," *Proc. IEEE Online Conf. Green Commun.*, Oct. 2013, pp. 115–20.
- [9] G. Song and Y. Li, "Utility-based Resource Allocation and Scheduling in OFDM-Based Wireless Broadband Networks," *IEEE Commun. Mag.*, vol. 43, Dec. 2005, pp. 127–34.
- [10] P. Grover and A. Sahai, "Shannon Meets Tesla: Wireless Information and Power Transfer," *Proc. IEEE Int'l. Symp. Info. Theory*, June 2010, Austin, TX, pp. 2363–67.
- [11] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless Information and Power Transfer: Energy Efficiency Optimization in OFDMA Systems," *IEEE Trans. Wireless Commun.*, vol. 12, no. 12, Dec. 2013, pp. 6352–70.
- [12] D. W. K. Ng, E. S. Lo, and R. Schober, "Robust Beamforming for Secure Communication in Systems with Wireless Information and Power Transfer," *IEEE Trans. Wireless Commun.*, vol. 13, Aug. 2014, pp. 4599–4615.
- [13] O. Simeone et al., "Spectrum Leasing to Cooperating Secondary Ad Hoc Networks," *IEEE JSAC*, vol. 26, no. 1, Jan. 2008, pp. 203–13.
- [14] G. Zheng et al., "Cooperative Cognitive Networks: Optimal, Distributed and Low-Complexity Algorithms," *IEEE Trans. Signal Proc.*, vol. 61, no. 11, June 2013, pp. 277–90.
- [15] G. Zheng et al., "Information and Energy Cooperation in Cognitive Radio Networks," *IEEE Trans. Sig. Proc.*, vol. 62, no. 9, May 2014, pp. 2290–2303.

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