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Application of Smart Antenna Technologies in Simultaneous Wireless Information and Power Transfer

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ABSTRACT

Simultaneous wireless information and power transfer (SWIPT) is a promising solution to increase the lifetime of wireless nodes and hence alleviate the energy bottleneck of energy constrained wireless networks. As an alternative to conventional energy harvesting techniques, SWIPT relies on the use of radio frequency signals, and is expected to bring some fundamental changes to the design of wireless communication networks. This article focuses on the application of advanced smart antenna technologies to SWIPT, including multiple-input multiple-output and relaying techniques. These smart antenna technologies have the potential to significantly improve the energy efficiency and also the spectral efficiency of SWIPT. Different network topologies with single and multiple users are investigated, along with some promising solutions to achieve a favorable trade-off between system performance and complexity. A detailed discussion of future research challenges for the design of SWIPT systems is also provided.

INTRODUCTION

In wireless power transfer, a concept originally conceived by Nikola Tesla in the 1890s, energy is transmitted from a power source to a destination over the wireless medium. The use of wireless power transfer can avoid the costly process of planning and installing power cables in buildings and infrastructure. One of the challenges for implementing wireless power transfer is its low energy transfer efficiency, as only a small fraction of the emitted energy can be harvested at the receiver due to severe path loss and the low efficiency of radio frequency (RF)–direct current (DC) conversion. In addition, early electronic devices, such as first generation mobile phones, were bulky and suffered from high power consumption. For the aforementioned reasons, wireless power transfer had not received much attention until recently, although Tesla had already provided a successful demonstration to light electric lamps wirelessly in 1891.

In recent years, a significant amount of research effort has been dedicated to reviving the old ambition of wireless power transfer, which is motivated by the following two reasons [1, 2]. The first reason is the tremendous success of wireless sensor networks (WSNs) which have been widely applied for intelligent transportation, environmental monitoring, etc. However, WSNs are energy constrained, as each sensor has to be equipped with a battery that has a limited lifetime in most practical cases. It is often costly to replace these batteries and the application of conventional energy harvesting (EH) technologies relying on natural energy sources is problematic due to their intermittent nature. Wireless power transfer can be used as a promising alternative to increase the lifetime of WSNs. The second reason is the now widespread use of low-power devices that can be charged wirelessly. For example, Intel has demonstrated the wireless charging of a temperature and humidity meter as well as a liquid-crystal display using the signals of a TV station 4 km away [4].

This article considers the combination of wireless power transfer and information transmission, a recently developed technique termed simultaneous wireless information and power transfer (SWIPT), in which information carrying signals are also used for energy extraction. Efficient SWIPT requires some fundamental changes in the design of wireless communication networks. For example, the conventional criteria for evaluating the performance of a wireless system are the information transfer rates and the reception reliability. However, if some users in the system perform EH by using RF signals, the trade-off between the achievable information rates and the amount of harvested energy becomes an important figure of merit [1]. In this context, an ideal receiver, which has the capability to perform information decoding (ID) and EH simultaneously, was considered in [1]. In [2] a more practical receiver architecture was proposed, in which the receiver has two circuits to perform ID and EH separately.

This article focuses on the application of smart antenna technologies in SWIPT systems, namely multiple-input multiple-output (MIMO)

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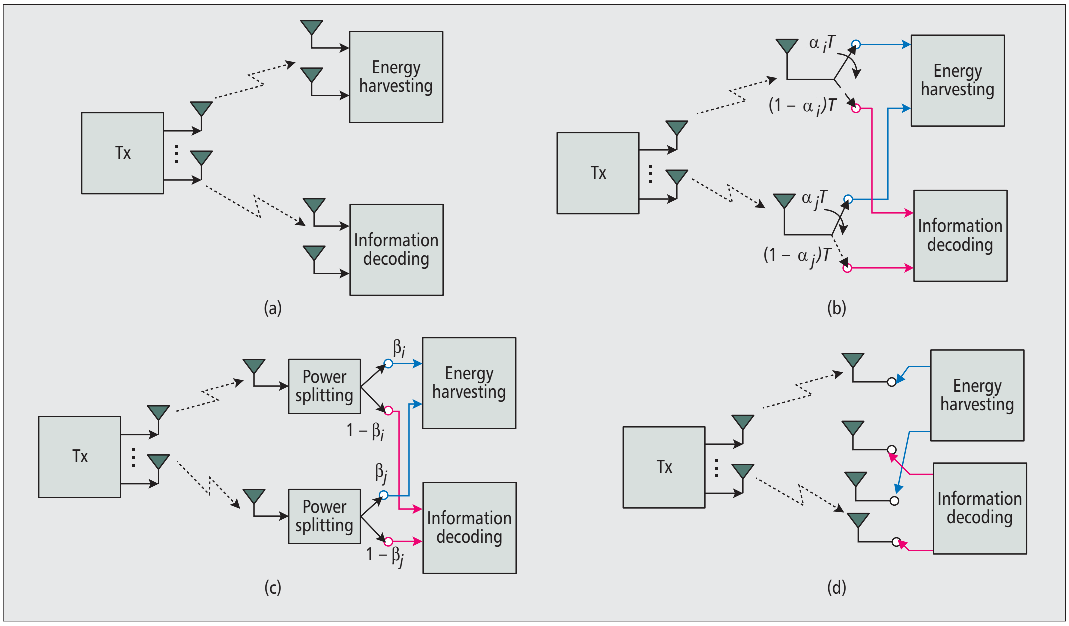

Figure 1. Illustration of the described SWIPT receiver structures. α_i denotes the time switching factor, β_i denotes the power splitting factor, i denotes the antenna index, and T denotes the transmission block duration.

By taking into account the channel statistics and the quality of service requirements regarding the energy transfer, the time switching sequence and the transmit signal can be jointly optimized for different system design objectives.

and relaying. The use of these smart antenna technologies is motivated by the fact that they have the potential to improve the energy efficiency of wireless power transfer significantly. For example, MIMO can be used to increase the lifetime of energy constrained sensor networks, in which a data fusion center is equipped with multiple antennas with which it can focus its RF energy on sensors that need to be charged wirelessly, leading to a more energy efficient solution compared to a single-antenna transmitter. Furthermore, a relay can harvest energy from RF signals from a source and then use the harvested energy to forward information to the destination, which not only facilitates the efficient use of RF signals but also provides motivation for information and energy cooperation among wireless nodes [3]. The application of smart antenna technologies to SWIPT opens up many new exciting possibilities, but also brings some challenges for improving spectral and energy efficiency in wireless systems.

The organization of this article is as follows. Some basic concepts of SWIPT are introduced first. Then the separate and joint application of MIMO and relaying in SWIPT is discussed in detail. Finally, some future research challenges for the design of multi-antenna and multi-node SWIPT systems are provided.

SWIPT: BASIC RECEIVER STRUCTURES

In SWIPT systems, ID and EH cannot be performed on the same received signal in general. Furthermore, a receiver with a single antenna typically may not be able to collect enough energy to ensure a reliable power supply. Hence, centralized/distributed antenna array deployments, such as MIMO and relaying, are required to generate sufficient power for reliable device operation. In the following, we provide an overview of MIMO SWIPT receiver structures, namely the power splitting, separated, time-switching, and antenna-switching receivers, as shown in Fig. 1.

SEPARATED RECEIVER

In a separated receiver architecture, an EH circuit and an ID circuit are implemented as two separate receivers with separated antennas, which are served by a common multiple antenna transmitter [2]. The separated receiver structure can be easily implemented using off-the-shelf components for the two individual receivers. Moreover, the trade-off between the achievable information rate and the harvested energy can be optimized based on the channel state information (CSI) and feedback from the two individual receivers to the transmitter. For instance, the covariance matrix of the transmit signal can be optimized for capacity maximization of the ID receiver subject to a minimum required amount of energy transferred to the EH receiver.

TIME SWITCHING RECEIVER

This receiver consists of an information decoder, an RF energy harvester, and a switch at each antenna [2]. In particular, each receive antenna can switch between the EH circuit and the ID circuit periodically based on a time switching sequence for EH and ID, respectively. By taking into account the channel statistics and the quality of service requirements regarding the energy transfer, the time switching sequence and the transmit signal can be jointly optimized for different system design objectives.

POWER SPLITTING RECEIVER

Employing a passive power splitting unit, this receiver splits the received power at each antenna into two power streams with a certain power

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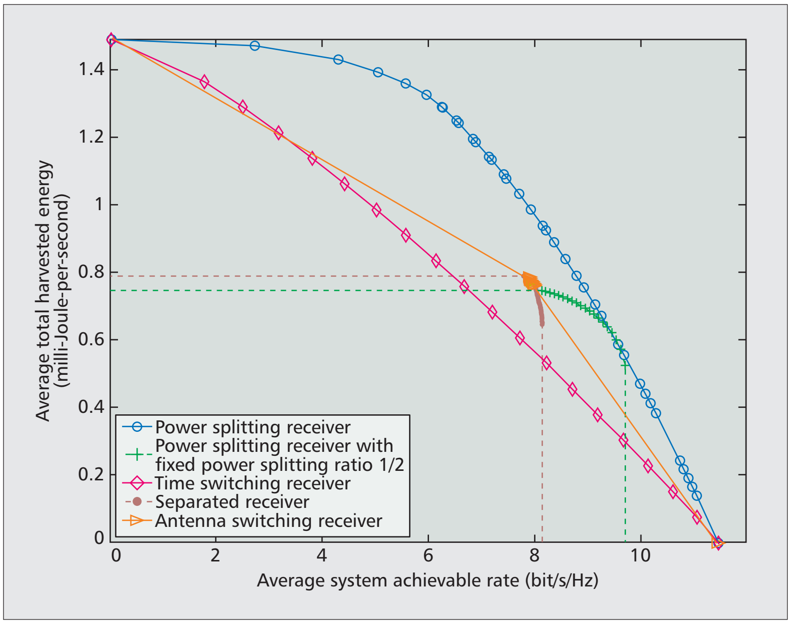

Figure 2. The trade-off region of the average total harvested energy (mJ/s) and the average system achievable rate (bit/s/Hz) for the different receivers. The carrier frequency is 915 MHz and the receiver is located 10 meters from the transmitter. The total transmit power, noise power, transceiver antenna gain, and RF-to-electrical energy conversion loss are set to 10 Watt, –23 dBm, 10 dBi, and 3 dB, respectively. The multipath fading coefficients are modelled as independent and identically distributed Rician random variables with a Rician *K*-factor of 6 dB.

splitting ratio before any active analog/digital signal processing is performed. Then the two streams are sent to an energy harvester and an information decoder, respectively, to facilitate simultaneous EH and ID [2, 5, 6]. The power splitting ratio can be optimized for each receive antenna. In particular, a balance can be struck between the system achievable information rate and the harvested energy by varying the value of the power splitting ratios. Further performance improvement can be achieved by jointly optimizing the signal and the power splitting ratios.

ANTENNA SWITCHING RECEIVER

With multiple antennas, low-complexity antenna switching between decoding/rectifying can be used to enable SWIPT [7]. For instance, given N_R antennas, a subset of L antennas can be selected for ID, while the remaining ($N_R - L$) antennas are used for EH. Unlike the time switching protocol which requires stringent time synchronization and the power splitting protocol where performance may degrade in case of hardware imperfections, the antenna switching protocol is easy to implement, and attractive for practical SWIPT designs. From a theoretical point of view, antenna switching may be interpreted as a special case of power splitting with binary power splitting ratios at each receive antenna.

Figure 2 illustrates the performance trade-offs of the considered SWIPT receiver structures. In particular, we show the average total harvested energy versus the average system achievable information rate in a point-to-point scenario with one transmitter and one receiver. A transmitter equipped with $N_T = 2$ antennas is serving a receiver equipped with $N_R = 2$ receive antennas. Resource allocation is performed to achieve the respective optimal system performance in each case [15]. For a fair comparison, for the separated receiver, the EH receiver, and the ID receiver are equipped with a single antenna, respectively, which results in $N_R = 2$. Besides, we also illustrate the trade-off region for a suboptimal power splitting receiver with a fixed power splitting ratio of 1/2 at each antenna. It can be observed that the optimized power splitting receiver achieves the largest trade-off region among the considered receivers at the expense of incurring the highest hardware complexity and the highest computational burden for resource allocation.

MIMO SWIPT NETWORKS

MIMO can be exploited to bring two distinct benefits to SWIPT networks. On the one hand, due to the broadcast nature of wireless transmission, the use of additional antennas at the receiver can yield more harvested energy. On the other hand, the extra transmit antennas can be exploited for beamforming, which could significantly improve the efficiency of information and energy transfer. The impact of MIMO on point-to-point SWIPT scenarios with one source, one EH receiver, and one ID receiver was studied in [2], where the trade-off between the MIMO information rate and power transfer was characterized. The benefits of MIMO are even more obvious for the multiuser MIMO scenario illustrated in Fig. 3a. Specifically, a source equipped with multiple antennas serves multiple information receivers, where the RF signals intended for the ID receivers can also be used to charge EH receivers wirelessly. Since there are multiple users in the system, co-channel interference (CCI) needs to be taken into account, and various interference mitigation strategies can be incorporated into SWIPT implementations, e.g. block diagonalization precoding as in [8], where information is sent to receivers that are interference free, and energy is transmitted to the remaining receivers. Furthermore, it is beneficial to employ user scheduling, which allows receivers to switch their roles between an EH receiver and an ID receiver based on the channel quality in order to further enlarge the trade-off region between the information rate and the harvested energy.

The multi-source multiuser MIMO scenario illustrated in Fig. 3b is another important SWIPT application, where multiple source–destination pairs share the same spectrum and the associated interference control is challenging. Since in interference channels, interference signals and information bearing signals co-exist, issues such as interference collaboration and coordination bring both new challenges and new opportunities for the realization of SWIPT, which are very different from those in the single source-destination pair scenario. For example, with antenna selection and interference alignment as illustrated in [9], the received signal space can be partitioned into two subspaces, where the subspace containing the desired signals is used for infor-

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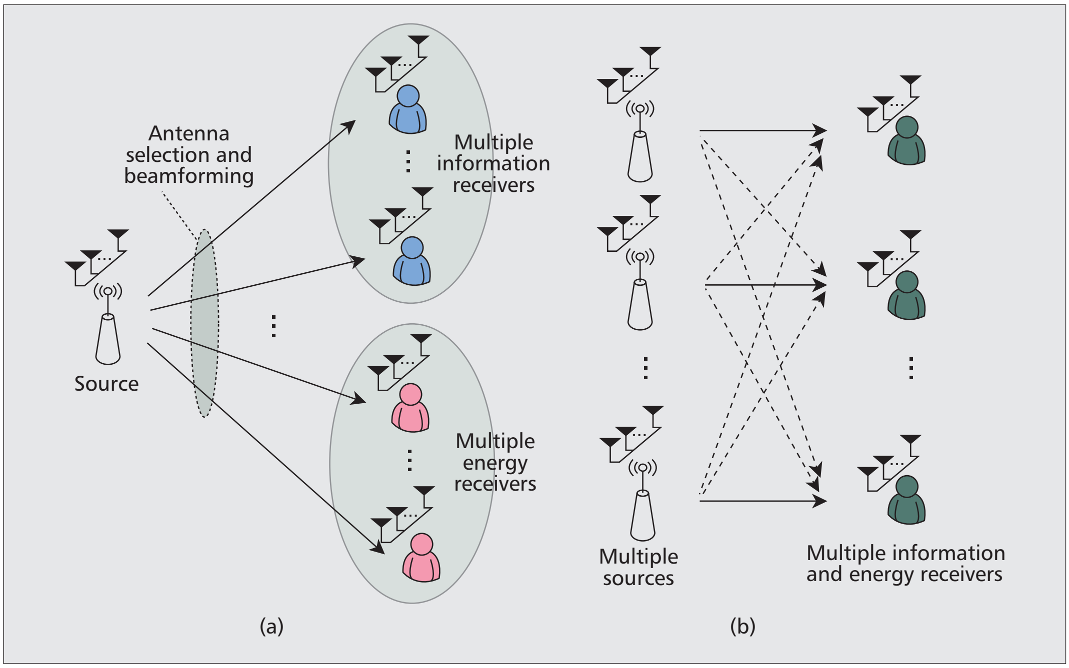

Figure 3. Two typical multiuser MIMO scenarios.

It is beneficial to employ user scheduling, which allows receivers to switch their roles between an EH receiver and an ID receiver based on the channel quality in order to further enlarge the trade-off region between the information rate and the harvested energy.

mation transfer, and the other subspace containing the aligned interference is used for power transfer. This design is a win-win strategy since the information transfer is protected from interference, and the formerly discarded interference can be utilized as an energy source. More importantly, this approach offers a new look at interference control, since the formerly undesired and useless interference can be used to enhance the performance of SWIPT systems. On the other hand, the use of RF EH introduces additional constraints to the design of transmit beamforming. Hence, the solutions well known from conventional wireless networks, such as zero forcing and maximum ratio transmission, need to be suitably modified to be applicable in SWIPT systems, as shown in [10].

Relay Assisted SWIPT Systems

Centralized MIMO as described above may be difficult to implement due to practical constraints, such as the size and cost of mobile devices. This motivates the use of relaying in SWIPT networks. In addition, the use of wireless power transfer will encourage mobile nodes to participate in cooperation, since relay transmissions can be powered by the energy harvested by the relay from the received RF signals and hence the battery lifetime of the relays can be increased. The benefits of using EH relays can be illustrated based on the following example. Consider a relaying network with one source–destination pair and a single decode-and-forward (DF) relay. SWIPT is performed at the relay by using the power splitting receiver structure shown in Fig. 1. In Fig. 4, the performance of the scheme using this EH relay is compared to that of direct transmission, i.e. when the relay is not used. As can be observed from the figure, the use of an EH relay can decrease the outage probability from 7×10^{-1} to 5×10^{-2}, a more than tenfold improvement in reception reliability, compared to direct transmission.

The performance of time sharing and power splitting SWIPT systems employing amplify-and-forward (AF) and DF relays was analyzed in [11], and the impact of power allocation was investigated in [12]. These existing results demonstrate that the behavior of the outage probability in relay assisted SWIPT systems is different from that in conventional systems with self-powered relays. For example, in the absence of a direct source–destination link, the outage probability with an EH relay decays with increasing signal-to-noise ratio (SNR) at a rate of log SNR/SNR, i.e. slower than the rate of 1/SNR in conventional systems. The reason for this performance loss is that the relay transmission power fluctuates with the source-relay channel conditions. This performance loss can be mitigated by exploiting user cooperation. For example, in a network with multiple user pairs and an EH relay, advanced power allocation strategies, such as water filling based and auction based approaches, can be used to ensure that the outage probability decays at the faster rate of 1/SNR [12]. This performance gain is obtained because allowing user pairs to share power can avoid the situation in which some users are lacking transmission power whereas the others have more power than needed.

Relay selection is an important means to exploit multiple relays with low system complexity, and the use of EH also brings fundamental changes to the design of relay selection strategies. In conventional relay networks, it is well known that the source-relay and relay-destination channels are equally important for relay selection, which means that the optimal location of the relay is the middle of the line connecting the source and the destination, i.e. (2.5 m,0) for

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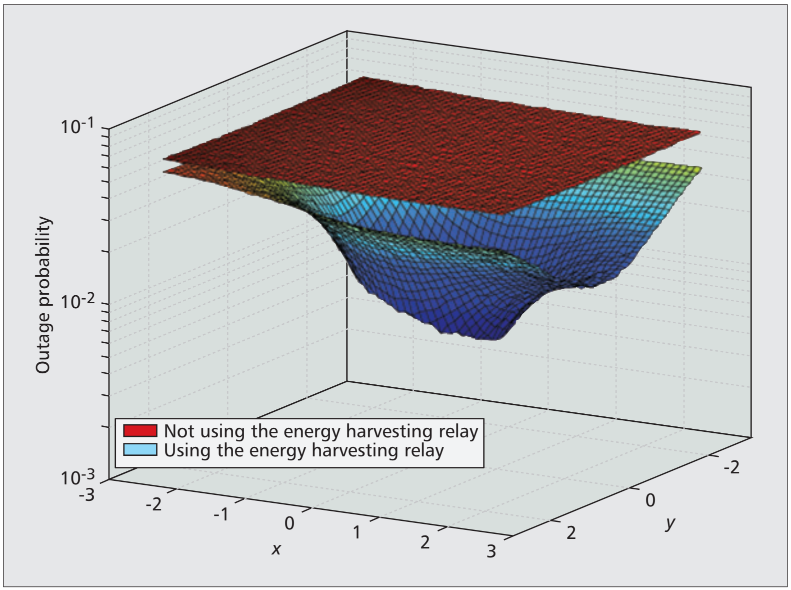

Figure 4. Outage performance of a relaying network with one source, one relay, and one destination. The source is located at (0, 0), the destination is located at (5 m,0), and the x-y plane shows the location of the relay. The carrier frequency is 915 MHz. The total transmit power, noise power, transceiver antenna gain, and RF-to-electrical energy conversion loss are set to 10 Watt, −17 dBm, 0 dBi, and 3 dB, respectively. We assume that the multipath fading coefficients are modelled as independent and identically distributed Rayleigh random variables. The targeted data rate is 0.1 bit/Hz/s. The path loss exponent is 3.

the scenario considered in Fig. 4. Nevertheless, Fig. 4 shows that an EH relay exhibits different behavior than a conventional relay, i.e. moving the relay from the source toward the middle point (2.5 m,0) has a detrimental effect on the outage probability. We note that this observation is also valid for SWIPT systems with AF relays. This phenomenon is due to the fact that in EH networks, the quality of the source-relay channels is crucial since it determines not only the transmission reliability from the source to the relays, but also the harvested energy at the relays. In [13] it was shown that the max-min selection criterion, a strategy optimal for conventional DF relaying networks, can only achieve a small fraction of the full diversity gain in relaying SWIPT systems.

THE COMBINATION OF MIMO AND COOPERATIVE RELAYING IN SWIPT

MIMO and cooperative relaying represent two distinct ways of exploiting spatial diversity, and both techniques can significantly enhance the system's energy efficiency, which is of paramount importance for SWIPT systems. Hence, the combination of these two smart antenna technologies is a natural choice for SWIPT systems. The benefits of this combination can be illustrated using the following example.

Consider a lecture hall packed with students, in which there are many laptops/smart phones equipped with multiple antennas as well as some low-cost single-antenna sensors deployed for infrastructure monitoring. This hall can be viewed as a heterogeneous network consisting of mobile devices with different capabilities. Inactive devices with MIMO capabilities can be exploited as relays to help the active users in the network, particularly the low-cost sensors. Since the relays have multiple antennas, more advanced receiver architectures, such as antenna switching receivers, can be used. In addition, the use of these MIMO relays opens the possibility of serving multiple source-destination pairs simultaneously. In this context, it is important to note that the use of SWIPT will encourage the inactive MIMO users to serve as relays since helping other users will not reduce the lifetime of the relay batteries. Therefore, the MIMO relays can be exploited as an extra dimension for performance improvement, and can achieve an improved trade-off between the information rate and the harvested energy [7].

As discussed earlier, one unique feature of SWIPT systems is the energy efficient use of CCI, which is viewed as a detrimental factor that limits performance in conventional wireless systems. In particular, CCI can be exploited as a potential source of energy in MIMO relay SWIPT systems. To illustrate this point, let us consider the following example. An AF relay with N antennas is employed to help a single-antenna source that communicates with a single-antenna destination. The relay first harvests energy from the received RF signals with the power splitting architecture, and then uses this energy to forward the source signals. Two separate cases are considered, i.e. without CCI and with CCI. To exploit the benefits of multiple antennas, linear processing of the information stream is performed to facilitate ID. Since the optimal linear processing matrix $\mathbf{W}$ is difficult to characterize analytically, a heuristic rank-1 processing matrix $\mathbf{W}$ is adopted. As such, in the case without CCI, the processing matrix is designed based on the principle of maximum ratio transmission, i.e. $\mathbf{W} = a\mathbf{h}\mathbf{g}^{\dagger}$, where the vectors $\mathbf{h}$ of size $N \times 1$ and $\mathbf{g}$ of size $1 \times N$ are chosen to match the first and second hop channels, respectively, and a is a scaling factor to ensure the relay transmit power constraint. On the other hand, in the presence of CCI, the relay first applies the minimum mean square error criterion to suppress the CCI, and then forwards the transformed signal to the destination using maximum ratio transmission. Figure 5 illustrates the achievable ergodic rate as a function of the average strength of the CCI ρ_I, with the optimized power splitting ratio. We observe that increasing the number of relay antennas significantly improves the achievable rate. For instance, increasing the number of antennas from three to six nearly triples the rate. Moreover, we see that when the CCI is weak ($\rho_I \leq -10$dB), the rate difference is negligible compared to the case without CCI. However, when the CCI is strong, a substantial rate improvement is realized. In fact, the stronger the CCI, the higher the rate gain. For example, in some applications the relays will operate at the cell boundaries and the benefit of exploiting CCI will be significant in such situations.

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RESEARCH CHALLENGES

In the following, we discuss some research challenges for future MIMO and relay assisted SWIPT.

Energy Efficient MIMO SWIPT: Because of severe path loss attenuation, the energy efficiency of MIMO SWIPT systems may not be satisfactory for long distance power transfer unless advanced green technologies, such as EH technologies relying on natural energy sources, and MIMO resource allocation are combined. We now discuss two possible approaches to address this problem.

- EH transmitter: In this case the transmitter can harvest energy from natural renewable energy sources such as solar, wind, and geothermal heat. Then the energy harvested at the transmitter can be transferred to the desired receiver over the wireless channel, thereby reducing substantially the operating costs of the service providers and improving the energy efficiency of the system, since renewable energy sources can be exploited virtually for free. However, the time varying availability of the energy generated from renewable energy sources may introduce energy outages in SWIPT systems, and efficient new techniques have to be developed to overcome them.
- MIMO energy efficiency optimization: Energy efficient MIMO resource allocation can be formulated as an optimization problem in which the degrees of freedom in the system such as space, power, frequency, and time are optimized for maximization of the energy efficiency. By taking into account the circuit power consumption of all nodes, the finite energy storage at the receivers, the excess spatial degrees of freedom in MIMO systems, and the utilization of the recycled transmit power and the interference power, the energy efficiency optimization reveals the operating regimes for energy efficient SWIPT systems. Yet, the non-convexity of the energy efficiency objective function [6] is an obstacle in designing algorithms for achieving the optimal system performance and low-complexity but efficient algorithms are yet to be developed.

Energy Efficient SWIPT Relaying: The concepts of SWIPT and relaying are synergistic since the use of SWIPT can stimulate node cooperation and relaying is helpful to improve the energy efficiency of SWIPT. In the following, several research challenges for relay assisted SWIPT are discussed:

- Practical relaying systems suffer from spectral efficiency reduction due to half-duplex operation. One possible approach to overcome this limitation is to use the idea of successive relaying, where two relays listen and transmit in succession. When implemented in a SWIPT system, the inter-relay interference, which is usually regarded as detrimental, can now be exploited as a source of energy. Another promising solution is to adopt full-duplex transmission. In the ideal case, full-duplex relaying can double the spectral efficiency, but the loopback interference corrupts the information signal in practice. Advanced MIMO solutions can be designed to exploit such loopback interference as an additional source of energy.

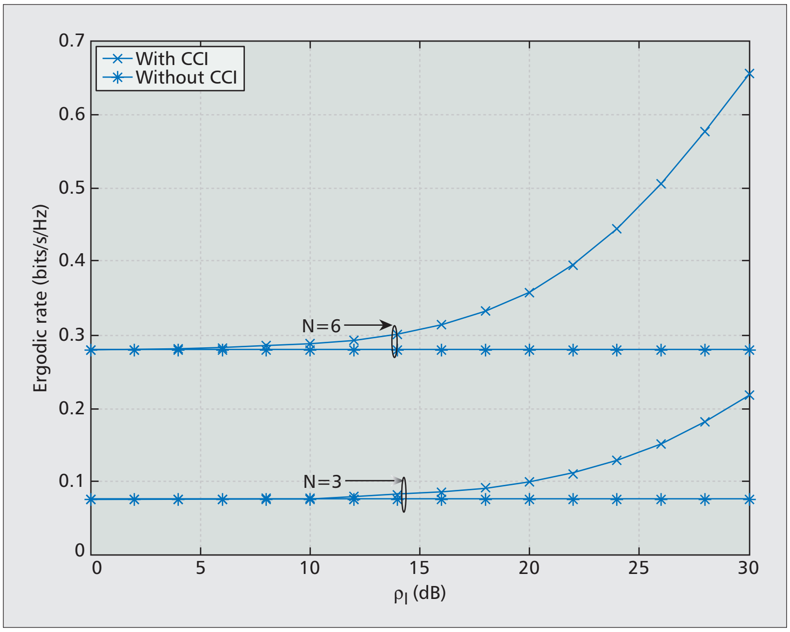

Figure 5. Achievable ergodic rate of a SWIPT relay system with a single-antenna source, a single-antenna destination, and a relay with N antennas. The distances from source to relay, relay and destination, and interferer to relay are set to 2 m, 3 m, and 5 m, respectively. The path loss exponent is 3. The total transmit power, noise power, transceiver antenna gain, and RF-to-electrical energy conversion efficiency are set to 10 Watt, 3 dBm, 0 dBi, and 80%, respectively.

- Relay assisted SWIPT is not limited to the case of EH relays, and can be extended to scenarios in which RF EH is performed at the source and/or the destination based on the signals sent by the relay. For example, in WSNs, two sensors may communicate with each other with the help of a self-powered data fusion center. For this type of SWIPT relaying, the relaying protocol needs to be carefully redesigned, since an extra phase for transmitting energy to the source and the destination is needed.
- Most existing works on SWIPT relaying have assumed that all the energy harvested at the relays can be used as relay transmission power. In practice, this assumption is difficult to realize due to non-negligible circuit power consumption, power amplifier inefficiency, energy storage losses, and the energy consumed for relay network coordination, which need to be considered when new SWIPT relaying protocols are designed. In addition, the superior performance of MIMO/relay SWIPT is often due to the key assumption that perfect CSI knowledge is available at the transceivers; however, a large amount of signalling overhead will be consumed to realize such CSI assumptions. Therefore, for fair performance evaluation, future works should take into account the extra energy cost associated with CSI acquisition [14].

Communication Security Management: Energy transfer from the transmitter to the receivers can be facilitated by increasing the transmit power of the information carrying signal. However, a higher transmit power leads to a larger susceptibility for information leakage due to the broadcast nature of wireless channels. Therefore, communication security is a critical issue in systems with SWIPT.

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The application of smart antenna technologies, such as MIMO and relaying, in SWIPT systems has been investigated for different network topologies. In addition, future research challenges for the design of energy efficient MIMO and relay assisted SWIPT systems have been outlined.

- Energy signal: Transmitting an energy signal along with the information signal can be exploited for expediting EH at the receivers. In general, the energy signal can utilize arbitrary waveforms such as a deterministic constant tone signal. If the energy signal is a Gaussian pseudo-random sequence, it can also be used to provide secure communication since it serves as interference to potential eavesdroppers [5]. On the other hand, if the sequence is known to all legitimate receivers, the energy signal can be cancellated at the legitimate receivers before ID. However, to make such cancellation possible, a secure mechanism is needed to share the seed information for generating the energy signal sequence, to which MIMO precoding/beamforming can be applied.
- Jamming is an important means to prevent eavesdroppers from intercepting confidential messages; however, performing jamming also drains the battery of mobile devices. The use of SWIPT can encourage nodes in a network to act as jammers, since they can be wirelessly charged by the RF signals sent by the legitimate users. However, the efficiency of this harvest-and-jam strategy depends on the network topology, where a harvest-and-jam node needs to be located close to legitimate transmitters to harvest a sufficient amount of energy. Advanced multiple-antenna technologies are needed to overcome this problem.

CONCLUSIONS

In this article the basic concepts of SWIPT and corresponding receiver architectures have been discussed along with some performance tradeoffs in SWIPT systems. In particular, the application of smart antenna technologies, such as MIMO and relaying, in SWIPT systems has been investigated for different network topologies. In addition, future research challenges for the design of energy efficient MIMO and relay assisted SWIPT systems have been outlined.

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REFERENCES

[1] L. R. Varshney, "Transporting Information and Energy Simultaneously," *Proc. IEEE Int'l. Symp. Inf. Theory (ISIT)*, Toronto, Canada, July 2008, pp. 1612–16.

[2] 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.

[3] G. Zheng *et al.*, "Information and Energy Cooperation in Cognitive Radio Networks," *IEEE Trans. Wireless Commun.*, vol. 62, no. 9, May, 2014, pp. 2290–303.

[4] A. Sample and J. R. Smith, "Experimental Results with Two Wireless Power Transfer Systems," *Proc. IEEE Radio and Wireless Symp. (RWS)*, San Diego, CA, Jan. 2009, pp. 16–18.

[5] 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. 4599–615.

[6] 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, Dec. 2013, pp. 6352–70.

[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] W. Wang *et al.*, "Power Allocation in Multiuser MIMO Systems for Simultaneous Wireless Information and Power Transfer," *Proc. IEEE Vehic. Tech. Conf. (VTC)*, Las Vegas, NV, Sept. 2013, pp. 1–5.

[9] B. Koo and D. Park, "Interference Alignment and Wireless Energy Transfer via Antenna Selection," *IEEE Commun. Lett.*, vol. 18, no. 4, Apr. 2014, pp. 548–51.

[10] S. Timotheou, I. Krikidis, G. Zheng, and B. Ottersten, "Beamforming for MISO Interference Channels with QoS and RF Energy Transfer," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, May 2014, pp. 2646–58.

[11] A. A. Nasir *et al.*, "Relaying Protocols for Wireless Energy Harvesting and Information Processing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, July 2013, pp. 3622–36.

[12] Z. Ding *et al.*, "Power Allocation Strategies in Energy Harvesting Wireless Cooperative Networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, Feb. 2014, pp. 846–60.

[13] Z. Ding and H. V. Poor, "'User Scheduling in Wireless Information and Power Transfer Networks," *Proc. IEEE Int. Conf. on Commun. Systems (ICCS)*, Macau, China, Nov. 2014, pp. 1–5 (a journal version available at http://arxiv.org/abs/1403.0354).

[14] S. Yatawatta, A. P. Petropulu, and C. J. Graff, "Energy Efficient Channel Estimation in MIMO systems," *Proc. IEEE Int'l. Conf. Acoustics, Speech, and Signal Processing (ICASSP)*, Las Vegas, NV, Mar. 2005, pp. iv/317–iv/320.

[15] X. Lu *et al.*, "Resource Allocation in Wireless Networks with RF Energy Harvesting and Transfer," *IEEE Network*, to appear in 2014.

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