

A Survey on Simultaneous Wireless Information and Power Transfer

T D P Perera¹, D N K Jayakody¹, S De², and M A Ivanov¹

¹Department of Control System Optimization, Institute of Cybernetics
National Research Tomsk Polytechnic University, Tomsk 634050, Russia.

²Department of Electrical Engineering, Indian Institute of Technology, Delhi

E-mail: tharindujc@gmail.com

Abstract. This paper presents a comprehensive study related to simultaneous wireless information and power transfer (SWIPT) in different types of wireless communication setups. Harvesting energy using SWIPT is an appealing solution in the context of extending battery life of wireless devices for a fully sustainable communication system. Strong signal power increases power transfer, but also causes more interference in information transfer, causing realization of the SWIPT challenging problem. This article provides an overview of technical evolution of SWIPT. A survey and qualitative comparison of the existing SWIPT schemes is provided to demonstrate their limitations in the current and 5G networks. Open challenges are emphasized and guidelines are provided to adapt the existing schemes in order to overcome these limitations and make them fit for integrating with the modern and emerging next generation communication networks, such as 5G systems.

1. Introduction

The eventual fate of mobile communications is expected to be altogether different from what we are accustomed today. While interest in a versatile mobile broadband will keep on increasing, to a great extent driven by top-notch videos and better screen resolutions, we are now increasingly seeing the effect of the human conceivable outcomes of innovation as the things around us turn out to be always associated. Besides, the rapid growth of wireless data services driven by smart devices, the wireless internet and fundamental challenges of existing cellular networks are the root forcing us to look up the next generation of wireless networks.

Recently, there have been several reports on implementing self-sustained communication systems to support concepts similar to Internet-of-Things (IoT), fifth generation (5G) wireless networks, etc. while maintaining Quality of Service (QoS). Several early studies have been done to use renewable energy resources to harvest energy within communication networks. Nonetheless, the irregular and unforeseeable nature of natural energy sources sometimes can cause a negative impact on QoS and also major harvesting technologies may be only applicable in certain environments. Wireless power transfer (WPT) is one of the energy harvesting technologies that overcomes some of the above-mentioned limitations where devices can charge their batteries (power sources/energy store) from electromagnetic radiation distantly. Techniques of wireless power transfer can be categorized as radiative and non-radiative. In the non-radiative technique, power is transferred by magnetic fields through the inductive coupling between the coil of wires or by electric fields using the capacitive coupling between metal electrodes. In the radiative technique, power is transferred by a beam of



electromagnetic radiation. Different WPT technologies, listed in Table 01, differ in terms of the range in which they can transfer power efficiently.

Table 1. Different Technologies in WPT

WPT Technology	Distance/Range	Antenna
Inductive coupling	Up to one meter - Short distance	Wire coils
Resonant inductive coupling	Several meters in indoor and outdoor environments	Tuned wire coils, resonators
Capacitive coupling	Up to one meter - Short distance	Electrodes
Magnetodynamic coupling	Up to one meter - Short distance	Rotating magnet
Microwaves	Far field -Up to several kilometers	Rectennas, Parabolic dishes
Light waves	Far field - Up to several kilometers	Lasers, lenses, photocells

The concept of simultaneous information and power transfer (SWIPT) was originally proposed in [1]. Later, in [2], SWIPT was considered for transmitting both power and information simultaneously by introducing fundamental changes in the receiver design. The proposed two receiver architecture uses SWIPT techniques to harvest energy and decode information using the radio frequency (RF) signals, which can carry both energy and information at the same time, received from the transmitters in the network. Recent SWIPT technologies separate the received signal in the domains of time, power, antennas, and space etc.

2. SWIPT: A two user MISO Interference Channel

A single antenna is used at both source and destination in typical wireless communication networks, which cause issues in the communication link with multipath effects. Issues caused by multipath wave propagation can be reduced by multiple input single output (MISO) technology, having two or more antennas with the transmission of multiple signals at the source. In MISO, the finest optimal transmission strategy for the best scenario has been studied where the two receivers in the communication system simultaneously harvest energy and decode information [3] to implement self-sustained wireless communication networks. It is also worthwhile to note that cross-link signals are useful in improving energy harvesting of the receivers in spite of the fact that it limits the achievable sum rate [3]. Thereafter, considering the current limitation of circuit technology, we propose two practical schemes based on Time Division Multiple Access (TDMA), where the receiver perform information decoding or energy harvesting at each time slot. The first scheme, TDMA of scheme A, splits each transmission interval into two time slots, where one slot is used to perform energy harvesting by both receivers and afterwards to perform information decoding in the next time slot. The transmission time of TDMA of scheme B divides into two time slots, as in scheme A, with the difference that, in every time slot, one receiver performs information decoding whereas the other receiver performs energy harvesting, simultaneously.

The achievable sum rate of these proposed TDMA schemes A and B in ideal conditions was studied via simulations. It was proved that the ideal scheme, which uses ideal receivers, is sometimes not the best proposition with reference to sum rate maximization [3]. In an interference limited system, TDMA of scheme A offers a better sum rate as compared to the ideal scheme. When one of the receivers requires comparatively higher energy than the other one, TDMA of scheme B provides a higher sum rate than TDMA of Scheme A. Overall simulation results and the conclusion are very different from the previously reported results [6] in the absence of the ideal receiver, which always performs better.

3. SWIPT - Multiuser MIMO systems

In the multiple inputs and multiple outputs (MIMO) network, all receivers/user terminals are battery limited devices, and batteries need to be recharged to extend the network lifetime. Energy harvesting is performed by the individual receivers through dedicated power transmission from the transmitters in the network.

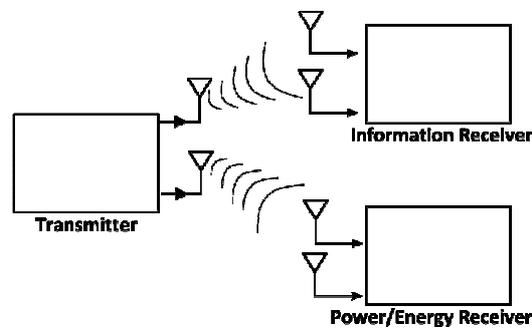


Figure 1. A MIMO broadcast system

Most of the work that tried to integrate SWIPT in MIMO wireless networks assumes that there are two defined groups of users to be served, one for receiving information and another for receiving power to recharge their power sources. To have a better understanding, a three-device (one transmitter and two receivers) MIMO wireless broadcast system is considered, figure 01. Using the signal sent by a transmitter, energy receiver harvests energy while other receiver performs information decoding. Two different scenarios in the MIMO broadcast system have been investigated in [6], namely separate and co-located information decoding and energy harvesting receivers. In the first scenario (separate receivers), the best transmission strategy was designed to attain non-identical tradeoffs in SWIPT. Those trade-offs are characterized by the boundary of the rate-energy region. For the second scenario (co-located receivers), the previous solution can also be applied to the unique MIMO channel from the transmitter to the energy harvesting and information decoding receivers. Furthermore, two SWIPT techniques, time switching and power switching, were investigated for the case of co-located receivers [6].

In the seminal work of [12], SWIPT in massive MIMO enabled multi-way relay networks (MWRNs) and energy constraining amplify-and-forward relays has been investigated by utilizing time switching and power splitting techniques. Once the quantity of relay antennas grows in the network, sum rate expressions and harvested energy have been derived in the significant amount. The effect of co-channel interference (CCI) on the performance metric was also investigated in [12], and the result proved that the existence of CCI, can be utilized in the relay for improving the energy harvesting. Integration of SWIPT and MWRNs with massive MIMO can be a significantly improved tradeoff between the performance of energy constraint AF relaying and the harvest energy.

4. SWIPT - Broadband wireless systems

A wireless broadband is a wireless network technology that addresses the “last mile” problem in telecommunication. It provides the high-speed internet and data services via a wireless local area or a wide area network (WLAN or WWAN). The local multipoint distribution system and the multichannel multipoint distribution service are fixed wireless broadband technologies for broadband microwave wireless transmission heading from a local antenna to the destinations. Integration of SWIPT with epy Microwave power transfer (MPT) within a broadband wireless system had been considered as a promising technique for need of convenient energy supply in wireless networks [7]. The broadband wireless system with limited interference contains multi-antenna base stations for information transfer and power transfer to free the wireless devices from the limitation of restricted battery capacities. Far field MTP has been used to support SWIPT with the understanding of the quality of service (QoS). In this approach, using orthogonal frequency division multiplexing (OFDM), the broadband channel is split into multiple orthogonal sub-channels where the base station in the communication network transmits/receives one data stream per sub-channel created. Depending on the transmission policy, each stream is encoded at a fixed rate or with one of the variable rates, according to the reported received signal-to-noise ratios (SNRs). It is noted that without beamforming, OFDM alone can decouple only an information transfer link, not an MPT link. Based on OFDMA, this work considers both single user and multi user systems, where the mobile device is assigned either to all sub-channels or to a single sub-channel. Depending on the direction of information transfer, downlink or the uplink, two practical courses of events for SWIPT are considered. In the first scenario, SWIPT with downlink information transfer use an OFDM signal which is transmitted by the base station in the broadband wireless network, for both information and power transfer. The second approach deals with uplink information transfer, and information and power transfer proceeds in opposite directions. Downlink MPT depends on the transmission of power tones categorized as unmodulated, while uplink data signals are OFDM modulated.

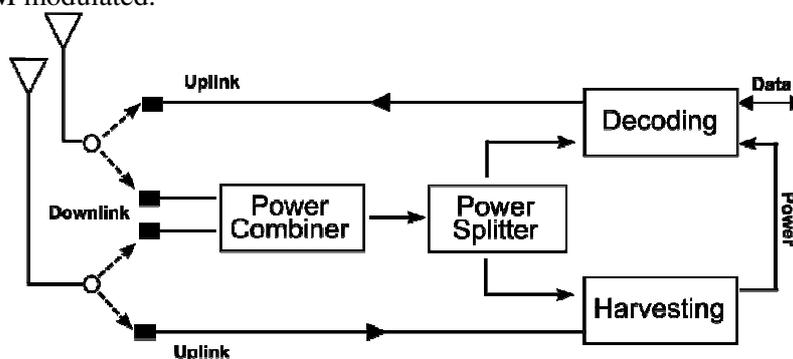


Figure 2. Dual mode SWIPT supports the mobile architecture

SWIPT enabled the dual antenna to support the mobile architecture (Figure 02), which can be reconfigured depending on the direction of information transfer [7]. The proposed architecture contains a transceiver based on downlink or uplink information transfer, which either demodulates and decodes or encodes and modulates received data, and a component of harvested energy converts an input signal to DC power. Once the architecture is configured for downlink, the outputs of the antenna are logically combined to improve the power of received signals. Thereafter, combiner output is splitted into two by the power splitter and is sent to both the transceiver and the energy harvester. Following this, the architecture configured for uplink by having attached two antennas separately to support the full-duplex operation, information and power transfer in the transceiver and the energy harvester.

5. SWIPT - Cooperative Non-orthogonal Multiple Access (NOMA)

In the NOMA concept, the key is to maintain significant differences in power levels of the signals. Therefore, it is possible to separate the high level signals and cancel them out to retain a low level

signal in the receiver. Hence, NOMA exploits the path loss differences in the groups of users, though it requires extra processing power in the receiver. Considering a downlink scheme, having two user groups, the first group of users are having better channel conditions, which are close to a base station (near-users) and the second group of users (far-users) is comparatively far away from the base station and has poor channel conditions. Applying cooperative transmission to NOMA can possibly improve the reliability of remote-users. According to the proposed method in [9], neighboring-users are used as relays in the network to improve remote-user channel conditions. The advantage in this approach is that the consecutive interference cancellation is used by the neighboring-users and, consequently, the neighboring-users know the information of the remote-users. In [10], the use of SWIPT assisted NOMA is considered, where SWIPT was applied to the neighboring-users, to improve reliability of the remote-users, without draining the battery life of neighboring-users. Thus, cooperative NOMA and SWIPT communication concepts are integrated together and have proposed a new protocol called a cooperative SWIPT NOMA protocol [10]. It was reported that, $\frac{\ln SNR}{SNR^2}$ is the rate of outage probability of remote-users while $\frac{1}{SNR^2}$ is for conventional cooperative networks (here, SNR indicates the signal of noise power). As a result of this integration (SWIPT and NOMA), by carefully selecting network parameters, such transmission rate or power splitting coefficient can lead to an acceptable system performance using harvested energy to power the relay transmission even without the users exploiting their own device batteries.

6. Future Work

Here, we briefly summarized a few of the future research challenges in SWIPT, which will be an enabler technology in the next generation communication systems. Efficient wireless charging, channels, power and time adaptation strategies will need to be analyzed further in energy harvesting communications. An efficient multi-user scheduling mechanism is needed for SWIPT assisted wireless networks, which consider the amount of harvested energy or energy requirements to avoid energy outages and energy overflows in receiving signals. Due to the broadcast nature of wireless networks, a security framework would be required for both communication and energy in a transmitted signal, which introduces a new QoS concern arisen in SWIPT-enabled wireless networks. Different ways of combining advance resource allocation and antenna technologies are needed to further minimize the path loss in wireless communication to improve efficiency of SWIPT. Also, investigating spectrum- and energy-efficient resource allocation to optimize the system performance in 4G and 5G communication systems is also challenging. The throughput and fairness optimization in SWIPT assisted NOMA resource allocation forms an interesting future research direction. Moreover, interference management and the effect of the mobility of each device in the network should be investigated further. In general, a huge number of IoT devices are to be fabricated to become cost effective. Additionally, these devices will most probably be battery operated and situated in a distant area where charging is impossible for various reasons. On the other hand, the IoT devices are likely to be contracted in size and become non-replaceable. This indicates that cost, energy, network lifetime, and space efficiency will be the serious obstacles of the upcoming IoT devices. Hence, various signal processing tools from wireless sensor networks (WSN) and radar applications can be adopted for IoT grounded Machine Type Communications applications [11].

7. Conclusion

In the paper, we have provided an overview of integration of SWIPT with wireless communication setups. Different techniques, time switching, power splitting, antenna switching, and spatial switching can be used to practically achieve SWIPT in domains of time, power, antenna, and space. Moreover, SWIPT helps improve self-sustainability of networks by harvesting energy from the received signal to free devices from the constraint of limited battery power. The biggest challenge in the next generation wireless communication will be the attempts to combine all the enabling technologies and to make them work together.

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