# Design Principles for Simultaneous Wireless Information and Power Transmission Systems

Wensheng Zhang*, Cheng-Xiang Wang†, Xiaotian Zhou*, Xiaofeng Tao‡
*School of Information Science and Engineering, Shandong University, Jinan, 250100, China
† Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, EH14 4AS, UK
‡ Wireless Technology Innovation Institute, Beijing University of Posts and Telecommunications, Beijing, 100876, China
Emails: zhangwsh@sdu.edu.cn, cheng-xiang.wang@hw.ac.uk, xtzhou@sdu.edu.cn, taoxf@bupt.edu.cn

***Abstract*—By integrating conventional wireless power transfer (WPT) and wireless information transfer (WIT) into one efficient and creative transmission system, the simultaneous wireless information and power transfer (SWIPT) system has been considered as one promising paradigm for energy harvesting. To make the concept of SWIPT feasible and fully explore its underlying benefits, the practical system design is needed. In this paper, a potential SWIPT architecture with threshold-based switch (TBS) and signal mapping (SM) is proposed. The fundamental design principles, as well as several challenges are addressed based on the proposed architecture, which may provide the theoretical benchmark for the feasible system design in the future.**

## I. Introduction

Recently, energy harvesting (EH), as a promising solution to prolong the life-time of energy-constrained autonomous devices, has attracted substantial research attention from academics and industry alike. The EH technology can efficiently collect ambient energy (e.g., light, heat, vibration, and electromagnetic radiation), and store it to the devices of wireless body area network (WBAN) or wireless sensor network (WSN).

As one of the most efficient EH schemes, wireless power transfer (WPT) was initially introduced and demonstrated by Nikola Tesla a century ago with his famous Warden Clyffe Tower in Shoreham, New York [1]. WPT is very useful in the special senario where the power line cannot be connected and the battery is inconvenient or even impossible to be replaced. Based on different power transfer distances, there are two kinds of WPTs: far-field WPT (electromagnetic (EM) radiation) and near-filed WPT (inductive coupling and magnetic resonate coupling) [2]. The former can be implemented by scavenging the energy of RF signals transmitted by base station (BS) and hence draws lots of attentions from the wireless areas.

On the other hand, wireless information transfer (WIT), which is also known as wireless communications nowadays, has been developed independently from WPT and solely for the information transmission through electromagnetic radiation. Due to the separation of WPT and WIT, the electrical engineering was divided into two subfields: electric power engineering and communication engineering [3]. However, as WPT and WIT share the same transfer medium, i.e., electromagnetic radiation, people argued that energy and information could be transmitted simultaneously for efficiency. Inspired by the idea, a promising scheme named simultaneous wireless information and power transfer (SWIPT) was initially proposed in [3], [4] and precisely described in [5].

The potential benefits of SWIPT come from the integration of various functions of WPT and WIT, and can be summarized as follows:

1) Both energy and information can be delivered to a remote device by the same modulated signal and the system energy efficiency (EE) and spectrum efficiency (SE) can be improved as the same spectrum is used for dual purposes [6].
2) The components (e.g., antenna or antenna array) in the transmitter and receiver can be shared by WPT and WIT. Hence, the total system cost can be reduced.
3) The new techniques can provide potential solutions to some special wireless systems without power supply, such as implanted medical devices and remote environment monitors.

Despite the numerous benefits of SWIPT, to make such a concept feasible we also face the corresponding challenges listed as follows:

1) SWIPT architecture should be redesigned according to different requirements of WPT and WIT.
2) Different transmission mechanisms of WPT and WIT impose varying technical constraints on the hardware realization and therefore, the hard components should be redesigned delicately.
3) Last but not least, the security issues of SWIPT should be considered due to potential eavesdropper problems, especially when the energy receiver and the information receiver are separated.

Although EH has been developed several years, the research on SWIPT is still in an early stage, leaving many research and deployment issues to be dealt with. This paper focuses on the practical design issues of SWIPT and aims at providing an efficient SWIPT architecture. A potential and practical SWIPT architecture is presented in Section II. Some critical design principles including key tradeoffs and optimization issues are provided in Section III. Future research opportunities and challenges are then highlighted in Section IV. Finally, we conclude the paper in Section V.

978-1-5090-0243-6/15/$31.00 ©2015 IEEE

## II. SWIPT Architecture

As shown in Fig. 1, a single-input single-output (SISO) system consisting of a transmitter $T_x$ and a receiver $R_x$ is considered. The transmitter with a constant power supply transmits the signal $y(t)$ containing a mount of energy and coded information to the receiver over a flat-fading channel. The receiver $R_x$ decodes the information with the WIT system and harvests the energy with the WPT system from the received signal $x(t)$, which can be expressed as

$$x(t) = h\sqrt{P}y(t) + n(t) \tag{1}$$

where $h$, $P$, and $n(t)$ denote the channel gain, the transmit power, and the noise, respectively, it is assumed that $n(t) \sim CN(0, \sigma^2)$.

### A. Threshold-based switch

Not all modulated RF signals can simultaneously transmit information and energy since effective isotropic radiated power (EIRP) is regulated by FCC ($\leq$ 36 dBm) [7] and the current EH techniques are not able to harvest RF signal with ultra lower power (ULP) (say, $\leq -60$ dBm ). Considering the constraints, a TBS for the proposed SWIPT can be described as

$$x(t) \rightarrow \begin{cases} \Rightarrow \text{WPT}, & E > \Gamma_2 \\ \Rightarrow \text{SM}, & \Gamma_2 \leq E \leq \Gamma_2 \\ \Rightarrow \text{WIT}, & E < \Gamma_1 \end{cases} \tag{2}$$

where $E$, $\Gamma_1$, and $\Gamma_2$ denote the signal energy, lower energy threshold, and upper energy threshold, respectively. The signal energy can be calculated as

$$E = |x(t)|^2. \tag{3}$$

With the TBS, the received signal $x(t)$ is able to be delivered to the corresponding modules based on its energy.

The lower energy threshold $\Gamma_1$ is determined by a so-called power-floor for current EH techniques, below which it is hard for WPT to harvest such low power. Moreover, it is reasonable to assume that WIT cannot correctly decode the information from the transmitted energy RF signal with transmit power larger than a upper threshold $\Gamma_2$.

### B. Signal mapping

A dynamic power splitting (DPS) scheme including time splitting (TS), static power splitting (SPS), and on-off power splitting (OPS) have been proposed in [8]. In the case of TS, the received signal $x(t)$ is divided into two parts based on a time division (TD) basis. For the SPS approach, a single symbol is split into two parts according to a given energy ratio: part of energy is scavenged by WPT and the left is for the decoding of WIT. The OPS scheme combines the TS scheme and SPS scheme.

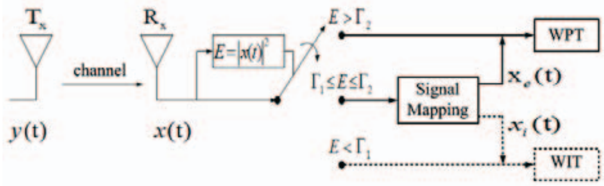


Fig. 1. The proposed SWIPT architecture.

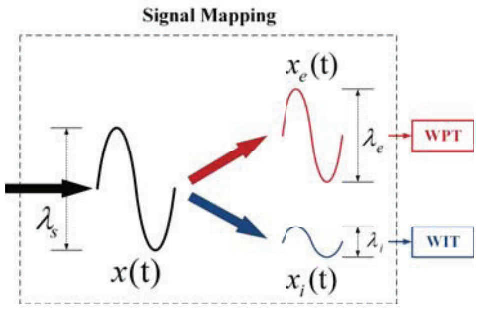


Fig. 2. The signal mapping splits the received signal $x(t)$ into information signal $x_i(t)$ and the energy signal $x_e(t)$.

Different from the above schemes, a novel splitting scheme is proposed in this paper. As shown in Fig. 2, the received signal $x(t)$ is divided into two parts: information signal $x_i(t)$ and energy signal $x_e(t)$ utilizing a signal mapping scheme. The information signal $x_i(t)$ is mapped from the received signal $x(t)$ and the left energy of $x(t)$ is delivered by the energy signal $x_e(t)$. A threshold scheme can be utilized to determine the minimum energy of the information signal $x_i(t)$ and the threshold $\lambda_i$ is determined by the minimum system data-rate, i.e., when the energy of the received signal $x(t)$ is located in the range of $\Gamma_1$ and $\Gamma_2$, the information signal $x_i(t)$ is mapped from the received signal $x(t)$ with the energy of $\lambda_i$ and the left energy is still carried by the energy signal $x_e(t)$. The threshold $\lambda_i$ can be simply formulated as

$$\lambda_i \propto 2^{R_m} - 1 \tag{4}$$

where $R_m$ denotes the minimum system datarate.

### C. WPT and WIT

The typical structures of WPT and WIT are shown in Fig. 3. For WPT, the incident power contained in the RF signal is rectified and the ultra low power (ULP) is stored in a battery or super capacitor. To efficiently harvest the energy with very low incident power, the impedance matching and booster circuits should be delicately designed. The sensitivity of the whole circuit is mainly determined by the rectifier performance. For WIT, the conventional information receiver can be used to decode the received information. However, in order to improve system energy efficiency (EE) and intelligently cooperate with WPT, a software defined dadio (SDR) -based WIT can be used. In the proposed WIT, the flexible RF is used to deal with the RF signals and the software supported by the processor is included to decode the received information. More specially, the computational capability of the processor enables the feasible signal mapping and other operations of the whole system.

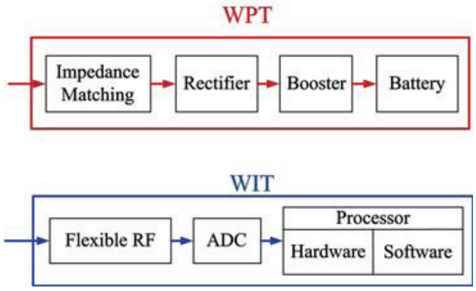


Fig. 3. The structures of WPT and WIT.

## III. SWIPT Design principles

### A. Key tradeoffs

In order to design an energy-efficient, spectral-efficient, high-sensitive, and high-flexible SWIPT, some critical design principles should be followed. The tradeoffs between EE and SE for a SWIPT system and conversion efficiency (CE) and incident power (IP) for WPT should be considered.

The CE is defined as the ratio of the scavenged energy to the transmitted energy. Considering the current EH techniques, there is a relation between CE and IP for a specific WPT circuit. The CE is jointly determined by the main components in WPT including rectenna, rectifier, booster circuit, and battery and so on. Among the main factors, the received IP is the most critical issue, which is determined by the rectifier sensitivity.

The CE-IP tradeoff for a wideband DTV signal $(500-600$ MHz) harvesting system is shown in Fig. 4 [9], in which the optimal frequency[1] and load resistance are $550$ MHz and $2$ KOhms, respectively. From this figure, we can find that CE increases with the improvement of IP. Moreover, different center frequency and circuit load generate different CE with the same IP. It is verified in this Fig., CE is jointly determined by IP, center frequency, and load circuit.

As for WIT, the tradeoff between system throughput and energy function should also be considered [3].

### B. Incident power floor and ULP management

For the received RF signal $x(t)$, there is a power floor (PF) $P_f$, below which it is not suitable for WPT to harvest the carried energy. The PF is jointly determined by the minimum IP, battery charging limit, and conversion efficiency requirement. Specifically, the rectifier output voltage, the Schottky diode threshold voltage, and the quality factor of the matching circuit are the most important factors [10]. For a battery or

[1]For a wideband signal, there is an optimal center frequency to transmit power most efficiently.

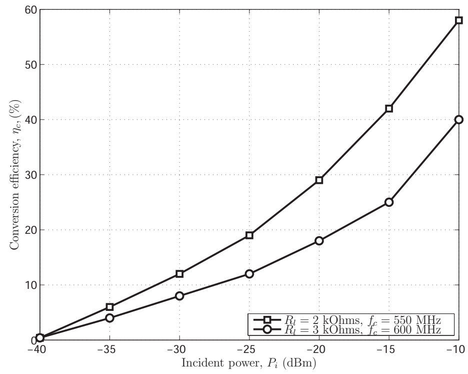


Fig. 4. The CE-IP relation in a DTV signal harvesting system. A load circuit is used to evaluate the system performance in the proposed system [9].

super capacitor, it is impractical to be charged with a very low voltage or ULP. Recall the case in Fig. 4, if IP is quite low (say, $-40$ dBm), the corresponding CE is also very low (less than $0.5\%$), leading to worthless harvest operation. Therefore, the IP should be large enough to satisfy the minimum CE requirement. To overcome such limit, in the proposed SWIPT architecture in Fig. 1, we set the lower threshold $\Gamma_1$ of TBS, which is determined by PF and below it the received signal $x(t)$ cannot be harvested. With such threshold, WPT is not required to deal with the transmitted signal with ULP and such signal is delivered to WIT by the TBS. Therefore, SWIPT with TBS can reduce WPT cost due to low sensitivity requirements.

Another scenario is how to manage efficiently the harvested ULP, which is usually very low $(\mu W)$. The techniques of trickle power charging are required for power store devices such as super capacitor, thin film battery, and flexible paper battery, and so on. Based on the specific voltage and current requirements of the store devices, the booster circuit should be delicately designed. However, it is a time-consuming operation to trickle charge a battery with the harvested ULP, leading to a low energy conversion efficiency.

### C. Radiation pattern

Different from conventional EH systems and wireless communication systems, the radiation patterns of SWIPT such as omni-directional radiation, beamforming [5], [11], power tone [6], and relay [12] should be considered.

Using the omni-directional radiation is the conventional way to transmit power and information by modulated signal for SWIPT. As for the antenna, it should be wideband, horizontally polarized, and omni-directional. Based on the Friis transmission equation, the omni-directional radiation scheme maximizes connectivity for mobile applications but minimizes energy conversion efficiency for energy devices. For the MIMO SWIPT system, beamforming is an efficient approach to improve energy efficiency of WPT as well as the system throughput of WIT when the channel state information (CSI) is known at the transmitter [5], [11]. However, practically it is tough to precisely estimate the CSI for a time-varying channel. Power tone is another technique to transmit energy in the down-link from BS to ME [6]. However, the power tone cannot be modulated and the information has to be transmitted with other modulation scheme, such as OFDMA. In this case, WPT and WIT are actually separated and the energy and information cannot be simultaneously transmitted.

The idea of employing the relay scheme in SWIPT has been proposed in [12] to forward information to remote devices. The relay harvests energy from the modulated signals transmitted by BS and exploits such energy to forward the information, hence prolonging the lifetime of power constrained relay. Time switching-based relaying (TSR) and power splitting-based relaying (PSR) protocols for EH relay systems have been proposed in [12]. Based on the fact that WIT and WPT have very different energy sensitivities (e.g., $-60$ dBm for information receiver versus $-10$ dBm for energy receiver [8]), the relay is required to deliver the energy to a remote EH device.

In this paper, we simply illustrate a new relay scheme to relay both information and energy to a remote wireless EH device. As shown in Fig. 5, the proposed relay including a $C$-capacity battery receives the information and energy from BS and forward them to the remote device (RD), the information links and energy links are indicated by solid and dash lines, respectively. Only when the battery energy is larger than a given $\gamma$, the relay is able to deliver its energy to its counterpart. The energy threshold is determined by the minimum energy required by information relay under an assumption that the information relay takes higher priority. The amplify-and-forward (AF) and decode-and-forward (DF) schemes can be employed to relay information signal. As for the energy, store-and-forward (SF) and receive-and-forward (RF) can be exploited. The AF scheme for information relay and the SF scheme for energy relay are utilized in our scheme. However, we should note that the proposed relay scheme can only be beneficial in the case that the energy conversion efficiency is insignificant due to large energy loss during the relay operations (transmission and conversion). More specially, the tradeoffs between the energy transmission and the conversion turn to be critical.

### D. Spectral-Energy efficiency in Intelligent SWIPT

The EE and SE of the proposed SWIPT can be jointly evaluated by system consumed energy $E_c$, system throughput $R$, and system bandwidth $B$. Let $\eta_e$ and $\eta_s$ denote the EE and SE, respectively, which can be defined as

$$\eta_e = \frac{R}{E_c} \tag{5}$$

$$\eta_s = \frac{R}{B}. \tag{6}$$

As for EH system, we define a new performance metric, namely spectral-energy efficiency (SEE), to evaluate the ability of energy harvesting for a certain amount of spectrum. Let $\eta_{se}$ denote SEE, which is formulated as

$$\eta_{se} = \frac{E_e}{B}, \tag{7}$$

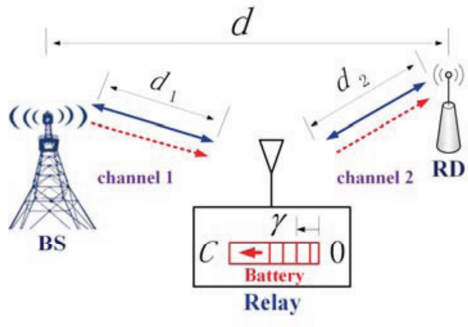


Fig. 5. Information and energy relay system.

where $E_e$ denotes the harvested energy. Therefore, to design an efficient SWIPT, the efficiency parameters including EE, SE, and SEE should be considered. In SWIPT, a flexible and intelligent WPT is required to deal with the wideband signal with low incident power, long trickle charging time, finite battery capacity and so on. Moreover, an SDR-based WIT can be exploited in the proposed SWIPT and the processor of WIT can be reused by other units in SWIPT, such as SM, TBS, and threshold-based battery.

### E. Optimization issues

SWIPT is proposed to efficiently harvest energy and decode information from the modulated signal $x(t)$, which is transmitted from the BS to the receiver over a fading channel. The modules of TBS and SM are jointly used to separate energy signal $x_e(t)$ and information signal $x_i(t)$ based on the given thresholds $\Gamma_1$ and $\Gamma_2$. The splitting algorithms and the corresponding thresholds can be determined by some optimization rules based on system requirements, such as EE, SE, CE, and ESE.

There are two kinds of optimizations: hardware optimization and software optimization. For far-field SWIPT, WPT has to harvest energy from the modulated signal with very low power density due to path attenuation. The number of rectifier stages can be optimized to improve the minimum incident power threshold [2]. The high-$Q$ resonator and corresponding matching circuit should also be considered in order to improve the power conversion efficiency at a low incident power [2]. The power management is another critical issue in an intelligent SWIPT, in which the operations of rectify, store, and utilization should be dealt with in an intelligent and energy-saving way. A micro-controller unit (MCU) -based ULP management system has been discussed in [13], in which online power state efficiency optimization and maximum power point tracking scheme are proposed to improve conversion efficiency. Online and offline adaptive optimization algorithms are used to adjust the corresponding circuit parameters to achieve high conversion efficiency at different power levels. Note that, the processor of the SDR-based WIT in the proposed SWIPT can be used as the MCU.

An optimal splitting rule is proposed to achieve different tradeoffs between the maximum capacity for WIT and the maximum harvested energy for WPT is proposed in [8], in which a rate-energy region scheme is used to evaluate the proposed optimization algorithm. Different from conventional wireless communication systems, SWIPT receiver has many specific limits, such as, the circuit power consumption, the amount of harvested power, the minimum required system data rate, and the QoS requirements and so on. A non-convex optimization issue has been discussed to deal with above limits in SWIPT system [14]. In particular, there are two kinds of optimization operations based on required information: off-line optimization with known energy and information transmission parameters, on-line optimization with unknown transmission scenarios. For SWIPT system shown in Fig.1, the off-line optimization scheme can be used to determine the optimal thresholds for the switch and SM.

## IV. Future research challenges

The final goal of an intelligent SWIPT system is to transmit energy and information to a remote device located in a special circumstance, where the energy or information cannot be delivered conveniently. On the other hand, the system requirements for EE, SE, CE, and ESE should be satisfied. Based on the basic purpose of SWIPT, several potential research challenges can be summarized as follows:

- Intelligent rectenna design. The EH rectenna should be wideband, horizontally polarized, and omni-directional and it can harvest very low incident power (e.g., $-40$dBm). SWIPT antenna much be able to receive the modulated signal with uncertainties and large variations.
- ULP management in SWIPT. The ULP is harvested by WPT and stored in the battery. The matching circuit and booster circuit should be designed delicately to charge the battery with trickle current. An optimal ULP utilization scheme should be designed to exploit the energy efficiently.
- Intelligent energy and signal splitter design. Dynamic power splitting (DPS) scheme including time switching (TS), static power splitting (SPS), and on-off splitting has been proposed in [8], which is based on an assumption that all received signal can be separated by the splitter. Based on different splitting ratios, a hybrid splitting scheme has been proposed in [14]. This paper also proposes a two-stage splitting scheme which combines the power-based switch and the signal mapping. In the first stage, the switch delivers the received signal based on its energy to one of WIT, WPT, and the SM. In the second stage, the MP separates the signal based on a minimum energy requirement of WIT and the left energy is delivered to WPT.
- SDR-based WIT design. A SDR-based WIT architecture is also indicated in this paper to improve EE by reducing energy consumption and reduce system cost by component reuse. The processor in WIT can also provide the computation capacity to other units, such as the switch, WPT, and the power management unit. On the other hand, several WPT components such as the matching, rectifier, and booster circuits can also be implemented in an intelligent way.

## V. Conclusions

This paper has discussed several critical principles in the design of an intelligent SWIPT by providing an overview of the current research of EH. A potential SWIPT architecture with threshold-based switch, SM, and SDR-based WIT has been proposed. Some key tradeoffs (EE vs. SE and CE vs. IP) and optimization issues have also been discussed. Specially, some potential future research challenges are also presented.

## Acknowledgements

The authors acknowledge the support from the National Natural Science Foundation of China (Grant No. 61371110, 61401254), the 863 project in 5G wireless networking, Ministry of Science and Technology (Grant No. SS2014AA01A701), China Postdoctoral Science Foundation (Grant No. 2012M521334, 2013T60669 and 2014M551906), the Outstanding Young Scientist Research Award Foundation of Shandong Province (Grant No. BS2013DX004), the EU FP7 QUICK project (Grant No. PIRSES-GA-2013-612652), the EU H2020 5G Wireless project under Grant 641985.

## References

[1] W. Lumpkins, “Nikola Tesla’s dream realized: wireless power energy harvesting,” *IEEE Consum. Electron. Mag.*, vol. 3, no. 1, pp. 39–42, Jan. 2014.

[2] T. Le, K. Mayaram, and T. Fiez, “Efficient far-field radio frequency energy harvesting for passively powered sensor networks,” *IEEE J. Solid-State Circuits*, vol. 43, no. 5, pp. 1287–1302, May 2008.

[3] L. Varshney, “Transporting information and energy simultaneously,” in *Proc. IEEE ISIT*, Jul. 2008, pp. 1612–1616.

[4] P. Grover and A. Sahai, “Shannon meets tesla: Wireless information and power transfer,” in *Proc. IEEE ISIT*, Jun. 2010, pp. 2363–2367.

[5] R. Zhang and C. K. Ho, “MIMO broadcasting for simultaneous wireless information and power transfer,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[6] K. Huang and E. Larsson, “Simultaneous information and power transfer for broadband wireless systems,” *IEEE Trans. Signal Processing*, vol. 61, no. 23, pp. 5972–5986, Dec. 2013.

[7] FCC Codes of Regulation, part 15. [Online]. Available: http://www.access.gpo.gov/nara/cfr/waisidx_03/47cfr15_03.htm

[8] X. Zhou, R. Zhang, and C. K. Ho, “Wireless information and power transfer: architecture design and rate-energy tradeoff,” *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4754–4767, Nov. 2013.

[9] C. Mikeka, H. Arai, A. Georgiadis, and A. Collado, “DTV band micropower RF energy-harvesting circuit architecture and performance analysis,” in *Proc. IEEE RFID-TA*, Sept. 2011, pp. 561–567.

[10] A. Shameli, A. Safarian, A. Rofougaran, M. Rofougaran, and F. De Flaviis, “Power harvester design for passive UHF RFID tag using a voltage boosting technique,” *IEEE T. Microw. Theory*, vol. 55, no. 6, pp. 1089–1097, Jun. 2007.

[11] Z. Xiang and M. Tao, “Robust beamforming for wireless information and power transmission,” *IEEE Wireless Commun. Lett.*, vol. 1, no. 4, pp. 372–375, Aug. 2012.

[12] A. Nasir, X. Zhou, S. Durrani, and R. Kennedy, “Relaying protocols for wireless energy harvesting and information processing,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3622–3636, Jul. 2013.

[13] A. Dolgov, R. Zane, and Z. Popovic, “Power management system for online low power RF energy harvesting optimization,” *IEEE Trans. Circuits Syst.*, vol. 57, no. 7, pp. 1802–1811, Jul. 2010.

[14] 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, pp. 6352–6370, Dec. 2013.