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The Era of Wireless Information and Power Transfer

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1.1 Introduction

In recent decades, the rapid development of wireless communication technologies has triggered a massive growth in the number of wireless communication devices for various practical applications, including e-health, autonomous control, logistics and transportation, environmental monitoring, energy management, safety management, etc. It is expected that in the era of the Internet of Things (IoT), there will be 50 billion wireless communication devices connected together worldwide via the Internet with a connection density of 1 million devices per km^2 [1]. In particular, small wireless sensor modules will be unobtrusively and invisibly integrated into clothing, walls, and vehicles at locations which are inaccessible for wired/manual recharging. However, battery-powered wireless communication devices have limited energy storage capacity and their frequent replacement can be costly, cumbersome, or even impossible (e.g., biomedical implants), which creates a serious performance bottleneck for realizing reliable and ubiquitous wireless communication networks. A promising approach to prolong the lifetime of traditional wireless communication systems is to let the wireless communication devices harvest energy from the environment [2–4]. For example, solar, wind, and

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geothermal are the major renewable energy sources for generating electricity. Unfortunately, these conventional natural energy sources are usually climate and location dependent, which may be problematic for mobile devices. Also, the intermittent and uncontrollable nature of natural energy sources makes the use of energy harvesting in wireless communication systems, where providing a continuous and stable quality of service (QoS) is of paramount importance, challenging.

Wireless power transfer (WPT) offers a viable solution for facilitating efficient and sustainable communication networks serving energy-limited communication devices [5–8]. Specifically, in practical systems, wireless devices communicate with each other via electromagnetic (EM) waves in the radio frequency (RF) band. Indeed, RF signals carry both information and energy simultaneously. Thus, the RF energy of propagating signals radiated by transmitters can be recycled at receivers for prolonging the lifetime of networks and supporting the energy consumption required for information transmission. This technology eliminates the need for power cords and any physical contact for manual recharging. Moreover, the broadcast nature of wireless channels facilitates one-to-many wireless charging, which is crucial for wireless networks with large numbers of energy-limited devices. On the other hand, compared to natural renewable energy sources generating intermittent energy, RF-based energy harvesting enables a stable and controllable wireless energy supply for energy-limited communication receivers. More importantly, WPT technology enables simultaneous wireless information and power transfer (WIPT). It is expected that WIPT will serve as a building block for realizing self-sustained communication networks and as the key to unlock the potential of IoT networks. However, despite the conveniences introduced by WIPT technology, the integration of WIPT technology into communication networks also introduces many challenges. For instance, the WPT efficiency is usually low. In practice, wireless power has to be transferred via a carrier signal with a high carrier frequency such that antennas of reasonable size can be used for harvesting energy at handheld devices. However, the associated path loss severely attenuates the signal such that only a small amount of power can be harvested at the receiver. For example, for a communication distance of 10 m in free space, the attenuation of a wireless signal can be up to 50 dB for a carrier frequency of 915 MHz. Moreover, traditional communication networks were optimized for pure data communications. Therefore, it is expected that existing network protocols, resource allocation algorithms, and receiver structures will not be able to meet the unique challenges incurred by the nature of WPT. This book addresses these challenges and provides a comprehensive reference for various solutions for realizing efficient WIPT in practice. In the following sections, we will provide some background information on WPT and discuss exciting research directions. The specific details will then be covered in the subsequent chapters.

1.2 Background

The concept of WPT was first proposed by Nikola Tesla in 1899. The initial efforts on WPT focused on high-power-consumption applications. This raised serious public health concerns about strong electromagnetic radiation which prevented the further development of WPT in the late twentieth century. As a result, this area developed slowly until recent advances in silicon technology and multiple-antenna technology made WPT attractive once again. In fact, the use of WPT avoids the potentially high costs in planning, installing, displacing, and maintaining power cables in buildings and infrastructure. Hence, it is expected that innovative WPT networks are the key enabler of the IoT to connect all devices together via wireless powered sensors for the development of smart cities. The continued study of WPT in both industry and academia will produce frontier technologies by developing novel and cost-effective designs to enable breakthroughs in WPT in the information and communication technology industry sector. For example, it is estimated that the development of IoT for logistics and transportation has a total potential economic impact of 1.9 trillion per year in the next decade [9]. In order to seize the rising business opportunities, recently different companies, e.g., Samsung Electronics and Huawei Technologies, have begun to launch various research and study groups to facilitate the development and standardization of WPT for powering small wireless communication devices.

1.2.1 RF-Based Wireless Power Transfer

The existing WPT technologies can be categorized into three classes: inductive coupling, magnetic resonant coupling, and RF-based WPT. The first two technologies rely on near-field EM waves, which do not provide any mobility to energy-limited wireless communication devices due to the limited wireless charging distances (a few meters) and the required alignment of the EM-field with the energy harvesting circuits. In contrast, RF-based WIPT exploits the far-field properties of EM waves, which enable concurrent wireless charging and data communication over long distances (hundreds of meters). Moreover, RF energy is omnipresent and can be harvested from the signals in the environment transmitted by Wi-Fi access points, TV base station towers, cellular communication base stations, etc. Also, RF-based WIPT utilizes the RF spectrum and the radiation is regulated by the government to ensure safety. More importantly, RF signals can serve as a dual-purpose carriers for conveying both information and power simultaneously.

Nowadays, prototype RF-based energy harvesting circuits are able to harvest microwatts to milliwatts of power over the range of 10 m for a transmit power of 1 W (typical transmit power of a Wi-Fi router) and carrier frequencies of less than 1 GHz [10]. The harvested energy is sufficient to power not only wireless sensors (e.g., fire alarm sensors), but also digital clocks mounted on the wall, which reduces the inconvenience of battery replacement. Although WIPT is critical to the design and implementation of sustainable communication networks, existing system models and resource allocation algorithms have only been proposed and optimized for pure information transfer. In practice, network designers need to strike a balance in the non-trivial trade-off between information and power transfer, leading to significantly different resource allocation algorithms, system models, and interference management schemes, compared to conventional wireless data communications. The introduction of RF-based WIPT imposes new challenges for the design of communication networks since traditional techniques used for the design of data communications cannot solve the fundamental problems in WIPT networks. Hence, there is an emerging need for the development of novel design theories, hardware circuit architectures, and signal processing techniques to unlock the potential of WIPT networks.

1.2.2 Receiver Structure for WIPT

RF-based energy harvesting technology enables the possibility of simultaneous WIPT (SWIPT), wireless-powered communication (WPC), and wireless-powered backscatter communication (WPBC), e.g., [11–15]. Specifically, in SWIPT networks, cf. Figure 1.1a, a transmitter broadcasts an information-carrying signal to provide information and energy delivery service simultaneously. In wireless-powered communication networks (WPCNs), cf. Figure 1.1b, wireless-powered devices first harvest energy, either from a dedicated power station or from ambient RF signals, and then exploit the harvested energy to transmit information signals. In WPBC, cf. Figure 1.1c, energy is transferred in the downlink and information is transferred in the uplink, where backscatter modulation at a tag is used to reflect and modulate the incoming RF signal for communication with a reader (e.g., access point). Since no oscillators are needed at the tags to generate carrier signals, backscatter communications generally entail orders-of-magnitude lower power consumption than conventional radio communications.

In practice, existing RF-based energy harvesting circuits harvest the energy of the received signal directly in the RF domain. In fact, the energy harvesting process destroys the modulated information (e.g., phase-embedded information) in the signal. In addition, conventional information decoding is performed in the digital baseband and the frequency down-converted signals cannot be used for energy harvesting. In other words, information decoding and energy harvesting cannot be performed on the same received signal. As a result, various types of practical energy harvesting receivers have been proposed to enable SWIPT/WPCN. In particular, for SWIPT, the receiver should separate the energy harvesting and information decoding processes.

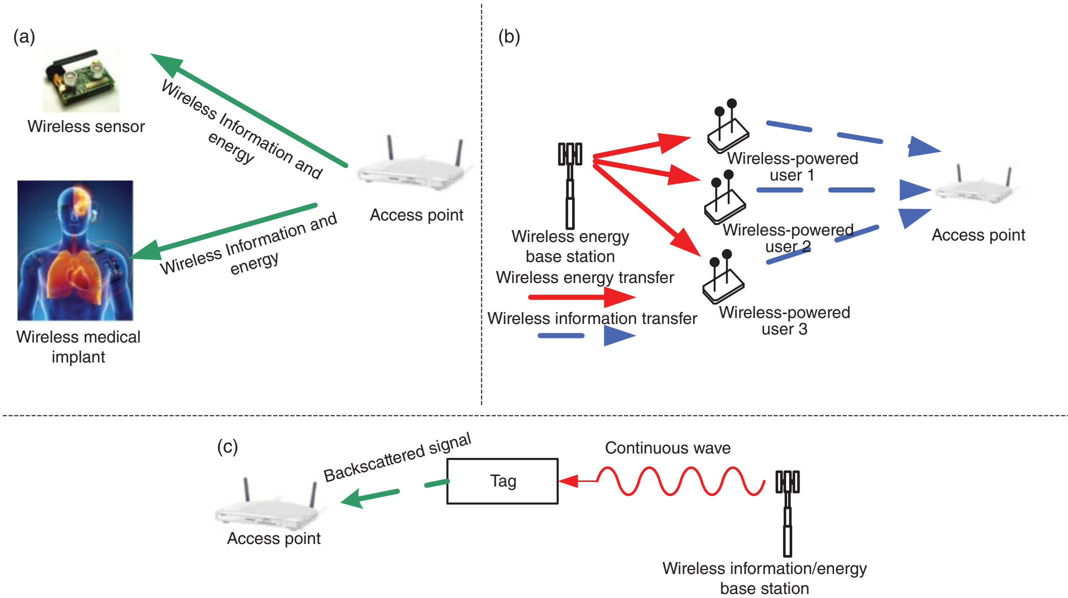

Figure 1.1 Three commonly adopted WIPT network architectures: (a) a SWIPT network, (b) a WPCN, and (c) a WPBC network.

A practical solution is to split the received RF power into two distinct parts, one for energy harvesting and the other one for information decoding. In the following, we discuss two receiver architectures commonly adopted in the literature to achieve this signal splitting.

Time Switching (TS) Receiver: For TS receivers, the transmission is divided into two orthogonal time slots, one for transferring wireless energy and the other one for conveying information, cf. Figure 1.2a. The receiver switches between the co-located energy harvesting circuit and information decoding circuit for harvesting energy and decoding information in successive time slots [16]. In practice, by taking into account the channel statistics and QoS requirements for power transfer, the time durations and the switching sequence for wireless information transfer and energy transfer can be optimized to achieve different system design objectives. Although the TS receiver structure allows for a simple transceiver hardware implementation, it requires accurate time synchronization and information/energy scheduling and the associated control signaling overhead can be demanding, especially in multi-user systems.

Power Splitting (PS) Receiver: A PS receiver splits the signal received at an antenna into two streams at different power levels using a PS unit, cf. Figure 1.2b. In particular, one stream is conveyed to the RF-based energy harvesting circuit for energy harvesting, and the other one is down-converted to baseband for information decoding [16]. Obviously, the PS process incurs a higher receiver complexity compared to the TS process. In addition, optimization of the ratio of the two power streams is generally needed to achieve a balance between the information decoding and energy harvesting performance. Furthermore, insertion loss, additional noise, and circuit related interference may be introduced by the PS process [17]. However, PS receivers enable the possibility of SWIPT, as the received signal can be concurrently exploited for both information decoding and energy harvesting. Therefore, the PS receiver is more suitable for applications with critical information/energy or delay constraints [5] than the TS receiver.

In this book we present the current research trends in system modeling, physical layer design, and resource allocation algorithm design to overcome the challenges in implementing WIPT networks, which is needed to bridge the gap between theory and practice. In the following, we first provide an overview of some of these exciting research problems which will then be discussed in detail in the subsequent chapters.

1.3 Energy Harvesting Model and Waveform Design

To enable RF-based energy harvesting at a wireless communication receiver, a rectenna is usually deployed for converting electromagnetic energy into direct current (DC) electricity. In practice, various rectifier technologies

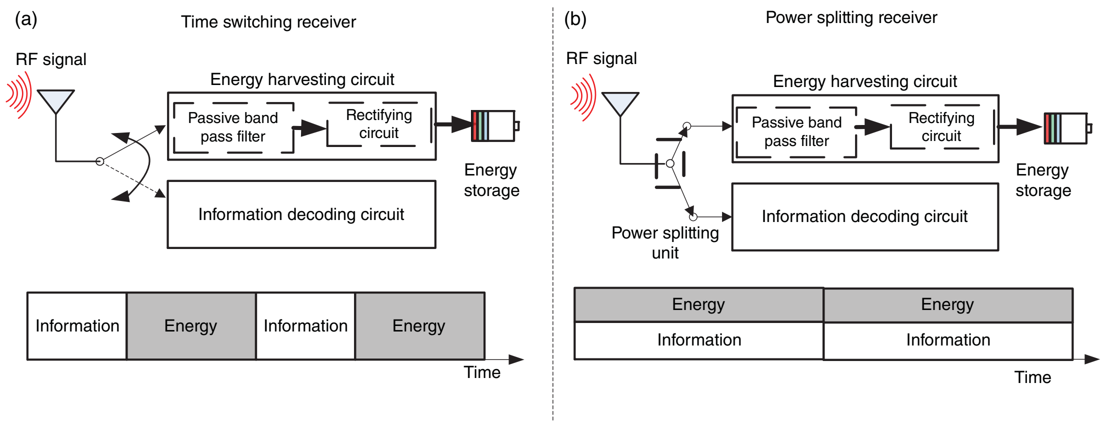

Figure 1.2 Block diagram of two receiver structures for WIPT: (a) time switching receiver and (b) power splitting receiver.

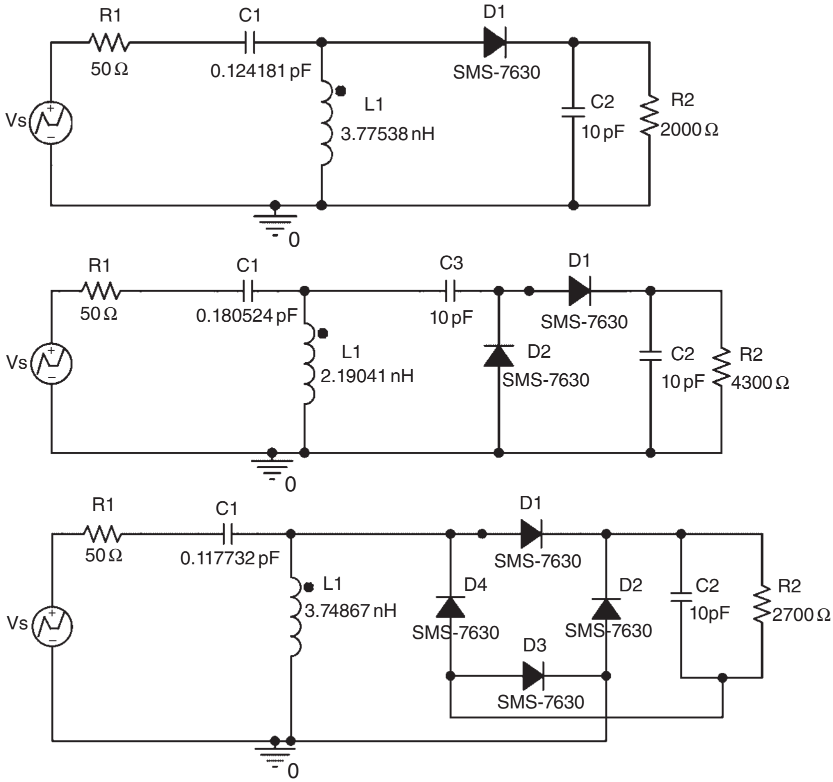

Figure 1.3 Examples of single series, voltage doubler, and diode bridge rectifiers designed for an average RF input power of −20 dBm at 5.18 GHz. v_s is the voltage source of the antenna [24]. R1 models the antenna impedance. C1 and L1 form the matching network. D1, D2, D3, and D4 refer to the Schottky diodes. C2 and R2 form the low-pass filter with R2 being the output load.

(including the popular Schottky diodes, complementary metal oxdide semiconductor (CMOS), backward tunnel diodes, etc.) and topologies (with single and multiple diode rectifiers) exist [18]. Examples of single series, voltage doubler, and diode bridge rectifiers consisting of one, two, and four Schottky diodes, respectively, are shown in Figure 1.3. In general, an accurate energy harvesting model can be obtained by deriving mathematical equations to describe the input–output characteristic of an energy harvesting circuit based on its schematic, e.g., Figure 1.3. However, this usually leads to complicated expressions which are intractable for performance analysis and resource allocation algorithm design. As a result, a linear model is often assumed for characterizing the harvested power after the rectifying circuit. In particular, a constant energy harvesting efficiency is assumed to model the capability of the RF-to-DC conversion circuit, e.g., [19, 20]. In other words, with this model, the power conversion efficiency is independent of the input power level of the energy harvesting circuit. Although the linear model is tractable, it has been verified by experimental data that RF-based energy harvesting circuits usually result in nonlinear end-to-end wireless power transfer [21]. More importantly, employing the linear energy harvesting model for resource allocation algorithm design may lead to unsatisfactory suboptimal performance, e.g., [18, 22, 23].

On the other hand, the performance of wireless energy harvesting is directly related to waveform design. For example, experiments have shown that signals with high peak-to-average power ratio (PAPR), such as multisine and chaotic signals, tend to yield higher DC powers for a given average incident RF power compared to constant envelope signals [25, 26]. This is because compared to a constant-envelope signal, for instance, a pulsed high-PAPR signal having the same average power charges the capacitor used in the rectifier to a higher peak amplitude, leading to a higher output DC voltage during the discharge time of the capacitor. On the other hand, for information transfer, Gaussian signals are optimal while constant-envelope signals are desirable from an implementation point of view. Hence, from a waveform design perspective, there is a non-trivial tradeoff between the performance of wireless information transfer and wireless power transfer. Further details on nonlinear energy harvesting models and waveform design can be found in Chapters 1, 3, and 11.

1.4 Efficiency and Interference Management in WIPT Systems

Different from conventional wireless communication systems, where data rate and energy efficiency are the most important system performance metrics [4, 27, 28], in WIPT systems, the wireless energy transfer efficiency and fairness in resource allocation are equally important QoS metrics. Thus, the design of resource allocation algorithms should take into account the emerging need for energy transfer efficiency. In fact, the introduction of the energy harvesting capability to energy-limited receivers introduces a paradigm shift for system design. For instance, in conventional communication networks, co-channel interference is regarded as one of the major factors that limits the system performance, especially in multi-user systems. Hence, most interference management techniques designed for pure information communication systems aim to suppress or avoid interference via sophisticated resource allocation. However, in WIPT 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 overall system performance, especially when the receivers do not have enough energy to support their normal operations, since in this case keeping the receivers “alive” via energy harvesting is more important than information decoding. Moreover, by exploiting the extra degrees of freedom offered by multiple antennas, constructive interference can be created, which improves the performance of both information and energy transfer. Hence, there is a non-trivial tradeoff between interference, total harvested power, and energy consumption in WIPT networks. Resource allocation fairness issues in WIPT networks is covered in Chapter 7. A thorough study of the spectral and energy efficiency of WIPT networks is provided in Chapter 13, while the use of multiple antennas for improving the spectral efficiency of WIPT networks is investigated in Chapter 5. In addition, a detailed study on creating constructive interference for improving the performance of WIPT networks is presented in Chapter 10.

1.5 Security in SWIPT Systems

In SWIPT systems, one can increase the energy of the information-carrying signal to facilitate energy harvesting at energy-limited receivers. However, this method will also increase the susceptibility to eavesdropping due to the broadcast nature of wireless channels. Moreover, the escalating number of wireless energy harvesting devices also poses a security threat in future wireless communication networks due to the enormous amount of data transmitted over wireless channels [29–34]. Nowadays, cryptographic encryption algorithms operating in the application layer are adopted to ensure wireless communication security. Unfortunately, these traditional security methods may not be applicable in future wireless networks with large numbers of transceivers, since encryption algorithms usually require secure secret key distribution and centralized secrete key management via an authenticated third party. As an alternative or a complementary technology to the existing encryption algorithms, physical layer (PHY) security has been proposed for guaranteeing secure communication. The principle of PHY layer security is to exploit the unique characteristics of wireless channels, such as fading, noise, and interference, to protect the communication between legitimate devices from eavesdropping. In particular, it has been shown that in a wire-tap channel, a source and a destination can exchange perfectly secure information if the source–destination channel has better conditions compared to the source–eavesdropper channel [35]. Hence, multiple-antenna technology has been proposed to ensure secure communication, e.g., [36–40]. Specifically, by exploiting the extra spatial degrees of freedom offered by multiple antennas, an artificial noise/interference signal can be injected into the communication channel deliberately to impair the received signals at the potential eavesdroppers. Thereby, communication secrecy can be guaranteed at the expense of allocating a large portion of the transmit power to artificial noise generation. On the other hand, the transmitted artificial noise can be harvested by the receivers and the recycled energy can be used to extend the lifetime of energy-constrained portable devices. The dual use of artificial noise for securing communication and facilitating energy harvesting is an important and unique property of secure SWIPT systems. This issue is discussed in detail in Chapter 11.

1.6 Cooperative WIPT Systems

Cooperative techniques for improving the performance of communication systems have drawn significant interest over the past decade. The basic idea of cooperative communication is that multiple single-antenna terminals of a multi-user system share their antennas to form a virtual multiple-input multiple-output (MIMO) communication system. Roughly speaking, there are three types of cooperation, namely, user cooperation, base station cooperation (distributed antennas), and relaying. In particular, cooperative relaying offers a low-cost implementation for achieving coverage extensions, diversity gains, and throughput gains. Nevertheless, in practical systems, relays may be equipped with limited energy supply and there is no strong incentive for the relays to cooperate. In contrast, with WIPT technology, operators can not only share the spectrum with users, but also energy and time. For instance, base stations run by the operators can broadcast wireless energy to charge up energy-limited cooperative devices as a token for future cooperation. This approach creates more incentives for both parties to cooperate and therefore improves the systems' overall spectrum efficiency without requiring external energy sources, e.g., [15, 41]. On the other hand, the distributed antenna system architecture of cooperative networks can be used to reduce the distance between transmitters and receivers. Furthermore, it inherently provides spatial diversity for combating path loss and shadowing, which can be exploited to facilitate efficient WIPT, e.g., [32]. Hence, cooperative techniques can be seamlessly integrated with WIPT for realizing sustainable communication networks. In Chapter 15, a macroscopic approach for characterizing the performance of large-scale wireless networks is discussed. In Chapter 12, the performance of a typical three-node cooperative WPCN is analyzed and evaluated.

1.7 WIPT for 5G Applications

The fifth-generation (5G) wireless networks will be a revolutionary design compared to existing communication systems. It is anticipated that 5G networks will connect at least 100 billion devices worldwide with approximately

Table 1.1 Requirements for 5G wireless communication systems [42]

Figure of merit	5G requirement	Comparison with 4G
Peak data rate	10 Gb/s	100 times higher
Guaranteed data rate	50 Mb/s	–
Mobile data volume	10 Tb/s/km^2	1000 times higher
End-to-end latency	Less than 1 ms	25 times lower
Number of devices	1 M/km^2	1000 times higher
Total number of human-oriented terminals	$\geq$ 20 billion	–
Total number of IoT terminals	$\geq$ 1 trillion	–
Reliability	99.999 %	99.99%
Energy consumption	–	90% less
Mobility	500 km/h	–

7.6 billion mobile subscribers due to the tremendous popularity of smartphones, laptops, sensors, etc., and provide an individual user experience of up to 10 Gb/s. Some of the requirements for 5G wireless networks are listed in Table 1.1. In order to fulfill the requirements of 5G communication networks, various disruptive techniques, such as non-orthogonal multiple access (NOMA), millimetre wave (mmWave) communications, and mobile-edge computing, have been proposed in the literature. On top of this, advanced signal processing algorithms have been developed to improve the energy efficiency of communication systems. Nevertheless, despite the potential system throughput improvements and the reductions in consumed energy brought by these techniques, energy-limited communication devices with short life span still create a system performance bottleneck. Therefore, combing WIPT technology with 5G-enabling techniques has become an emerging research topic. In Chapters 6, 8, and 14, the application of WIPT in systems employing NOMA, mmWave, and mobile-edge computing is studied in detail.

1.8 Conclusion

This book is aimed at graduate students, researchers, and engineers in the field who are interested in WIPT communication networks and their applications. In particular, the first few chapters provide an introduction to WIPT and some basic hardware designs enabling WIPT. The middle part of the book is at a more advanced level and provides a further understanding and knowledge of WIPT systems. In the last part, we will study the fundamental problems in WIPT networks, including communication security in WIPT systems, energy transfer efficiency, and interference management in WIPT systems. In addition, various practical applications of WIPT and corresponding case studies are included in the last part of the book, which is aimed at practitioners.

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