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Introduction

1.1 Background

Energy harvesting wireless communication is one of the most recent advances in communications techniques. It refers to any communications systems that use devices powered by energy from either the ambient environment or a dedicated power transmitter in a cable-less or battery-free way. This new method of communications has two main benefits. First, conventional communications devices rely either on batteries or fixed mains connections for energy supply. However, all batteries have a limited lifetime, while mains connections are not flexible. Energy harvesting provides a promising solution to perpetual and flexible operations of communications devices. Specifically, wireless communication replaces the data cable with wireless interconnection, while energy harvesting aims to replace the power cable with harvested energy, the very last cable in wireless communications. Together, energy harvesting wireless communication provides unprecedented convenience for our daily life. Secondly, energy efficiency is a key issue in wireless communications systems. This is particularly important for conventional wireless devices that rely on batteries, such as sensor nodes or mobile phones. Due to this importance, many studies have been conducted to improve the energy efficiency of wireless communications, including green communications. In fact, most studies on modern communications systems are about their energy efficiency or spectral efficiency. For energy harvesting wireless communications, since the devices are powered by the ambient environment or power transmitter, this problem is less severe for the communication devices. Thus, the main benefits of energy harvesting are the increased convenience and the improved energy efficiency in communications.

These two benefits are achieved at certain costs and have generated several issues. In energy harvesting wireless communications, although the energy supply becomes wireless and endless to provide convenience and efficiency, respectively, the quality of the energy supply drops. For the energy harvested from the ambient environment, such as the sun or wind, there is great uncertainty in the energy availability. This is due to the unpredictable or uncontrollable changes in the ambient environment. For the energy harvested from the power transmitter, there is less uncertainty but to allow energy harvesting and information delivery at the same device, one has to either use two separate sets of equipment or share the same set of equipment. If energy harvesting and information delivery use separate equipment, the hardware cost increases. For example, two radio frequency (RF) fronts may be needed. If both share the same

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equipment, the coordination between energy harvesting and information delivery becomes complicated. The system throughput may also decrease.

These issues have significant impact on wireless system designs, as power and bandwidth are two precious resources for communications. Hence, most research works in energy harvesting wireless communications focus on these two issues. For example, when the energy supply is insufficient, the wireless node may not be able to transmit or receive data when it wants to. Also, when energy harvesting and information delivery are performed in the same frequency band using the same transceiver, the original time interval for data transmission may have to be divided into two parts for the best coordination between energy harvesting and information delivery. In the physical layer, these will affect signal transmission, signal detection, and signal estimation. In the upper layer, these will affect user scheduling, channel assignment, message control, and message routing. These issues will also change the ways in which many recently proposed wireless systems operate. Thus, the effect of energy harvesting and new designs based on energy harvesting will be investigated for both legacy systems and recently proposed systems in this book.

1.2 Relationship with Green Communications

Green communications is a concept proposed recently to tackle the energy efficiency problem of communications as well as to reduce the CO_2 footprint of communications devices. According to the report from the International Telecommunication Union, information and communications technologies account for 2% of all CO_2 emissions. Among them, mobile calls contribute 125 million tonnes of CO_2 emissions every year. These figures are steadily increasing due to the fact that more and more communications systems are being deployed. Thus, under the pressure from governments to achieve emission reduction targets by 2020 and 2050, telecommunications carriers will have to take action. Moreover, this action will eventually reduce their energy bills as well. For example, by shutting down or properly scheduling base stations in the evenings when the traffic is low, one of the methods proposed for green communications, the carriers can reduce their operational costs.

Energy harvesting can be one way of implementing green communications by powering wireless devices using environmentally friendly energy sources, such as solar power and wind power. This can replace or reduce the battery power and the mains power to save energy. However, energy harvesting does not necessarily save energy. For example,

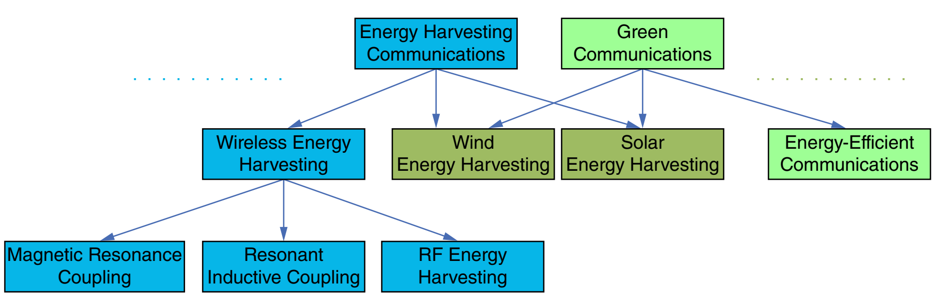

Figure 1.1 Relationship between energy harvesting communications and green communications.

in wireless energy harvesting using power transmitters, a large amount of energy will be wasted during the transmission loss in order to provide convenience at the remote node. Thus, energy harvesting communications and green communications are related to each other but do not belong to each other. Figure 1.1 shows the relationship between energy harvesting wireless communications and green communications.

1.3 Potential Applications

Energy harvesting wireless communication has a lot of interesting applications. One main application is wireless sensor networks (Sudevalayam and Kulkarni 2011). Many sensor nodes are designed for low-power and low-data-rate scenarios, which are very suitable for energy harvesting communications. These applications mainly use energy harvested from the ambient energy sources, such as the sun and the wind. Thus, they also fall into the category of green communications. In other applications, wireless energy harvesting from a dedicated wireless power transmitter can also be used, such as cellular communications (Huang and Lau 2014). Among these applications, the fifth-generation (5G) mobile communications system is a good use case.

1.3.1 Energy Harvesting for 5G

It is noted that 5G is actually a general backbone network that aims to support the Internet of Things, vehicular communications and other applications, in addition to cellular communications. In this sense, it is an enabling technology for wireless sensor networks too. In this section, we mainly focus on its cellular communications function.

For example, in Liu et al. (2015c), an integrated energy and spectrum harvesting mechanism for 5G networks has been proposed. Spectrum harvesting refers to cognitive radio operations for spectrum opportunities, while energy harvesting uses the ambient energy opportunities to support short-distance communications. A multi-tier network was considered and the effects of spectrum and energy harvesting on device-to-device (D2D) communications, Femtocell, Picocell and Macrocell operations have been discussed. It was shown that the aggregate network throughput of such a network can be greatly improved due to spectrum and energy harvesting.

In Hossain and Hasan (2015), a general overview on the 5G cellular network was given. Several key enabling technologies and research challenges have been discussed. Among them, the importance of using energy harvesting to improve the energy efficiency of 5G systems has been investigated. It was suggested that, for 5G services that do not have strict requirements on reliability or quality of service (QoS), ambient sources can be used for harvesting, similar to Liu et al. (2015a). However, for 5G services that require QoS, dedicated RF power transmitters can be used so that energy is always available when needed. A similar discussion is found in Buzzi et al. (2016) with more recent reviews.

In Ding et al. (2017b), energy harvesting was combined with non-orthogonal multiple access (NOMA) to improve energy efficiency and spectrum efficiency in 5G networks. In particular, the NOMA users could be powered by energy harvesting to relay the information in 5G networks. Similarly, in Khan et al. (2016), energy harvesting was combined with millimeter waves, another important 5G technique. In this case, 5G devices tried to harvest energy from the millimeter waves.

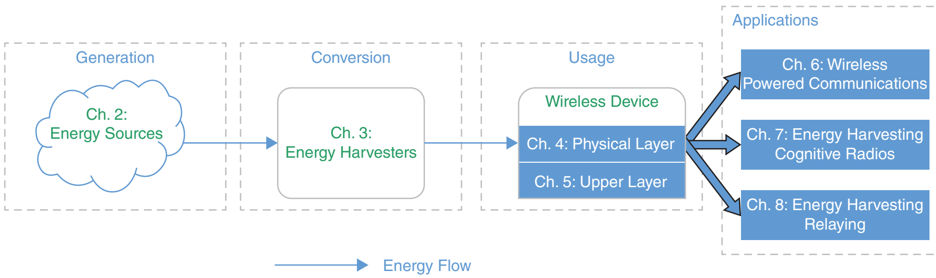

Figure 1.2 Organization of chapters in the book.

There are many other studies on the application of energy harvesting in 5G mobile communications. Since this is not the focus of the book, we have only given a very brief discussion here. Also, owing to the importance of energy harvesting, there is a huge investment in the integration of energy harvesting into existing systems around the world. Due to the enormous number of projects funded in this area, we do not discuss them here.

1.4 Outline of Chapters

In the following chapters, different aspects of energy harvesting wireless communications will be discussed. In Chapter 2, we will discuss different sources of energy that can be harvested and used for communications. Empirical and mathematical models will be examined. This deals with the energy source in energy harvesting wireless communications. In Chapter 3, we will study the relevant energy harvesters for different sources. Their principles and theories will be discussed. This deals with the energy conversion in energy harvesting wireless communications. In Chapter 4 and Chapter 5, the effect of energy harvesting and new techniques based on energy harvesting will be investigated for the physical layer and the upper layer at the wireless device, respectively. This deals with the energy usage in energy harvesting wireless communications. Finally, from Chapter 6 to Chapter 8, the application of energy harvesting in recently proposed systems, including wireless powered systems, cognitive radio systems and relaying systems, will be studied. These deal with the application of energy harvesting wireless communications. Figure 1.2 shows a diagram of how these chapters are organized, related, and what kind of problems they deal with.