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Introduction

Energy harvesting (EH) is expected to have abundant applications in future wireless communication systems to power transceivers by utilizing environmental energy such as solar, thermal, wind, and kinetic energy. It becomes a promising technology that enables sensor networks, cellular networks, and wireless communications in wide rural areas.

Since renewable energy is generally clean and cheap, EH offers various benefits compared with conventional energy supplies such as batteries and fossil-fuel-based generators. For example, in cellular networks, solar panels and wind farms have been deployed to power base stations, thus lowering the expenses of energy bills, reducing the level of carbon dioxide emissions, and improving the flexibility of deployment. Besides, in wireless sensor networks, EH has been considered as a good substitute for the traditional battery, which in principle prolongs the network operation time to almost infinity. In short, EH in turn leads to a promising future for wireless networks: green and self-sustainable.

1.1 Energy Harvesting Models and Constraints

Despite many advantages, the use of EH also imposes new challenges on the design of wireless communication. Obviously, the harvested energy from solar, thermal, wind, and kinetic energy sources is not stable and might change randomly over time. Therefore, besides the randomness of the channel fading, there is another dimension of stochastic resource to be dealt with, and it brings new constraints in the optimization of EH wireless communication systems.

Wireless communication channels often fluctuate more substantially and dynamically than practical EH rates (e.g. the channel changes on the order of milliseconds, while the EH rate changes on the order of seconds or minutes), while channel fading is the main challenge faced in the design of reliable wireless communications. To illustrate this issue, we adopt a point-to-point wireless communication system, which consists of one transmitter powered by an energy harvester and one receiver with a reliable power supply, to show the phenomenon of the multi-time-scale channel/EH rate variations. In practice, the coherence time of EH processes is often much larger than that of wireless channels, as previously mentioned. Therefore, a block-based quasi-static EH model is practically valid, where the EH rate remains constant within each EH coherent block and may change from one block to another, and at the same time each EH block spans over many communication channel coherent blocks, as shown in Figure 1.1. For the

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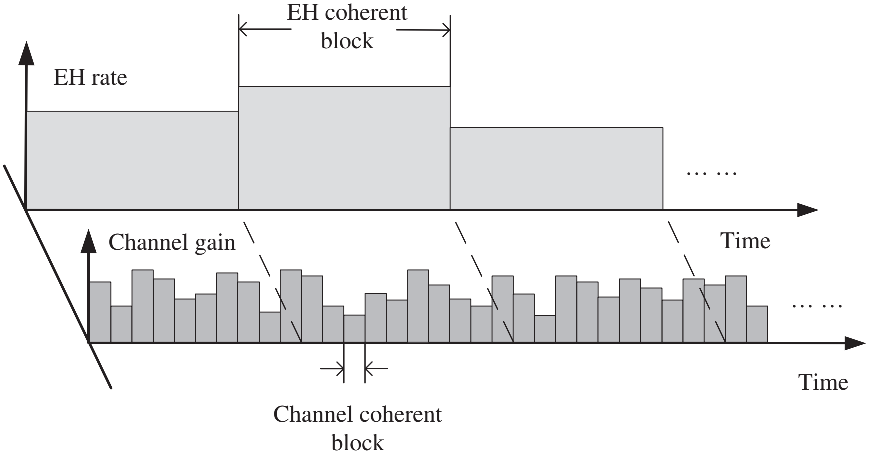

Figure 1.1 Time variations in EH process versus wireless channel.

purpose of exposition, we consider wireless data transmissions over a finite horizon of $M \leq 1$ EH blocks. Each EH block is further divided into $N \leq 1$ communication blocks each of one unit time and a constant channel gain.

Moreover, the random and intermittent characteristics of renewable energy impose a new type of EH constraint: the available energy at an EH communication node up to any time is bounded by its accumulatively harvested energy at that time. This is in contrast to conventional communication systems with stable energy sources, in which the available energy at any time is either unbounded or only limited by the remaining energy in the storage device (e.g. battery).

Mathematically, let $E_m \geq 0$ denote the EH rate in the mth EH block and $h_{n,m} \geq 0$ the channel power gain of the (n, m)th communication block (i.e. the nth communication block of the mth EH block) with $n = 1, \dots, N, m = 1, \dots, M$. Furthermore, we use $P_{n,m} \geq 0$ to denote the power consumption at the transmitter in the (n, m)th communication block. Unless otherwise stated, we consider that $P_{n,m}$ represents the transmit power at the transmitter and ignore the power consumption by circuit, signal processing, etc. Assuming an ideal energy storage device (i.e. with infinite capacity and no energy leakage) employed at the transmitter, we have the *EH constraints* on the scheduled power consumptions $\{P_{n,m}\}$; that is, the energy accumulatively consumed up to any communication block (n, m), i.e. $\sum_{j=1}^{m-1}\left(\sum_{i=1}^{N} P_{i,j}\right) + \sum_{i=1}^{n} P_{i,m}$, should be no larger than the energy accumulatively harvested by then, i.e. $N\sum_{j=1}^{m-1} E_j + nE_m$. In other words, we have the EH constraints as

$$\sum_{j=1}^{m-1}\sum_{i=1}^{N} P_{i,j} + \sum_{i=1}^{n} P_{i,m} \leq N\sum_{j=1}^{m-1} E_j + nE_m, \quad n = 1, \dots, N, m = 1, \dots, M. \tag{1.1}$$

Due to both the new EH constraints and the multi-time-scale channel/EH rate variations, it is a challenging problem to jointly optimize the communication scheduling and energy management in EH-based wireless communications.

Finally, the availabilities of the channel state information (CSI) $\{h(n, m)\}$ and the energy state information (ESI) $\{E(m)\}$ at the transmitter, respectively, can significantly affect the performance of EH communication systems. Among all different assumptions about the channel state information at the transmitter (CSIT) and energy state information at the transmitter (ESIT), there are four cases of primary interest in this book, listed below:

(1) *Case 1*: Noncausal CSIT and ESIT. At the beginning of the transmission, the transmitter perfectly knows the past, current, and future CSI and ESI. This case approximates the practical scenario when the transmitter can accurately predict the future CSI (e.g. slowly varying channels in low-mobility applications) and the future ESI (e.g. based on historical data in a periodically varying energy environment). The optimal solution in this case provides a performance upper bound for all other CSIT/ESIT availability cases.
(2) *Case 2*: Causal CSIT and ESIT. At the beginning of each EH/communication block, the transmitter knows the past and current CSI/ESI, as well as the statistical information (e.g. distributions) of future CSI/ESI. In general, the solution of this case achieves the lowest utility among the first three cases considered herein.
(3) *Case 3*: Causal CSIT and noncausal ESIT. This is a hybrid model based on cases 1 and 2, in which all ESI is perfectly known at the beginning of the transmission while only the past and current CSI is known.
(4) *Case 4*: No CSIT and noncausal/causal ESIT. During the transmission, the transmitter does not have any CSI and only has statistical information on the CSI. The noncausal or causal ESIT is defined as that in Case 1 or 2 above. Note that in all the above cases, we assume that at each communication block, the receiver perfectly knows the CSI in that block.

1.2 Structure of the Book

Based on the previous section, it is observed that EH brings a new dimension to the wireless communication problems, in the form of intermittency and randomness of the available energy, as well as the possibility of the energy cooperations among the transmission nodes in wireless networks. In this book, we summarize the progresses taken in the past few years in this new research field. This book is divided into three parts:

(1) In part I, we focus on the optimal transmission design for EH wireless communication systems. In particular, Chapter 2 addresses the optimal power allocation problems for the point-to-point EH channels to maximize the system throughput or minimize the average outage probability and also considers the effects of imperfect circuits and limited battery storage. Chapter 3 examines the power allocation for various multi-node wireless channels powered by energy harvesters, including the multiple-access channels (MACs), relay channels, and large relay networks. Chapter 4 studies the cross-layer design for EH communications, considering some upper layer issues such as transmission delay and traffic variations over time.
(2) In part II, we focus on the design and optimization of some EH networks. Chapter 5 considers the *ad hoc* networks, where there is no central control of the whole network, and studies the opportunistic access control schemes and the corresponding throughput scaling behavior. Chapter 6 considers a standard cellular network with multiple base stations powered by energy harvesters and studies the energy and

communication cooperations among them. Chapter 7 considers several new issues in the next-generation cellular networks and studies EH-based hyper-cellular networks with control and traffic separation and proactive content caching and push for better utilization of the renewable energy on small-cell base stations.

(3) Part III includes three appendices about the basic tools widely used in this book.