1 Introduction

Over the past decade, there has been a significant advance in the design of wireless networks, ranging from physical-layer algorithm development, medium-access control (MAC) layer protocol design, to network- and system-level optimization. Many wireless standards have been proposed to suit the demands of various applications. Over time, researchers have come to the realization that, for wireless networks, because of fading channels, user mobility, energy/power resources, and many other factors, one cannot optimize wireless communication systems as has been traditionally done in wired networks, in which one can simply focus on and optimize each networking layer without paying much attention to the effects of other layers. For wireless networks, cross-layer optimization is a central issue to ensure overall system performance. Yet resource allocation is one of the most important issues for cross-layer optimization of wireless networks.

For instance, across different layers, one cannot design physical-layer coding, modulation, or equalization algorithms by assuming that the MAC layer issues are completely perfect, and vice versa. There are also user diversities—different users at different times and locations may suffer different channel conditions, and therefore may have different demands and capability. Fixing and allocating bandwidths and resources without considering such user diversity can simply waste system resources, and thus performances. In addition, in wireless networks there are space, time, and frequency diversities as well. Taking advantage of those diversities can significantly improve communication performance. All those factors contribute to the need of careful consideration of resource allocations.

We have witnessed the advance of resource allocation in recent years with tremendous progress. As one can imagine, because of the number of degrees of freedom and many different parameters, resource allocation is a broad issue covering a wide range of problems. Therefore, the optimization tools employed also vary a lot. Besides the commonly used convex optimization in communication system design, many resource allocation problems are nonlinear and nonconvex in nature. When it comes to channel allocation and scheduling, sometimes the problems become integer, combinatorial, or both. If one takes into account time-varying conditions, then the problem evolves into one of dynamic optimization. When cooperation among distributed and autonomous users is considered, game theory can be employed to find the optimal strategy and solution. It is fair to say that there is no single optimization tool available to solve all resource-allocation problems at once.

What makes resource allocation more challenging is that, in fact, when it comes to the applications, different wireless networks aim at different service goals, and therefore have different design specifications. One network can be severely energy sensitive and power constrained, whereas the other can be bandwidth limited or throughput hungry. In some situations, a network may have a high degree of mobility with opportunistic access, whereas in other cases a network has an ultrawide bandwidth to share with others but little mobility.

As such, different networks face different resource-allocation problems, different characteristics of problems employ different optimization techniques, and joint considerations of different layers encounter different constrained optimization issues.

This book aims at providing a comprehensive view to answer the preceding challenges in the hope of allowing readers to be able to practice and optimize the allocation of scant wireless resources over assorted wireless network scenarios. Given the nature of the topic, this book is interdisciplinary in that it contains concepts in signal processing, economics, decision theory, optimization, information theory, communications, and networking to address the issues in question. In addition, we try to provide innovative insight into the vertical integration of wireless networks through the consideration of cross-layer optimization.

The goals of this book are for readers to have a basic understanding of wireless resource-allocation problems, to be equipped with an adequate optimization background to conduct research on or design wireless networks, and to be well informed of state-of-the-art research developments. To achieve these goals, this book contains three parts:

- Part I: Basic Principles
  We will study the basic principles of resource allocation for multiple users to share the limited resources in wireless networks under different practical constraints. In addition to the explanation of the basic principles, we will also illustrate the limitations and trade-offs of different approaches.
- Part II: Optimization Techniques
  We will consider various optimization techniques that can be applied to wireless resource-allocation problems. These techniques will be categorized and then compared for their advantages and disadvantages. Some applications for different network scenarios are given as examples.
- Part III: Advanced Topics
  Through the use of some state-of-the-art design examples of different wireless networks, we will illustrate the wide varieties of topics and their potential future design directions. By considering the technical challenges of a variety of networks, we will show how to employ different techniques for different scenarios such as cellular networks, wireless local-area networks, ad hoc/sensor networks, ultrawide-band networks, and collaborative communication networks.

In Part I, the chapters that cover the basics of resource allocation are as follows:

2. Wireless Networks: An Introduction
   In this chapter, we first consider different wireless channel models such as large-scale propagation-loss models and small-scale propagation-loss models. Then, according to

the decreasing order of the coverage areas, we discuss four types of wireless networks: cellular networks, WiMax networks, WiFi networks, and wireless personal-area networks. In the wireless ad hoc networks without a network infrastructure, autonomous users should be able to establish the basic network functions in a distributed way. Wireless sensor networks can detect the events and transmit the information to the data-gathering point with a low consumption of energy. Finally, to cope with the limited spectrum, a cognitive radio can detect the spectrum hole and utilize the unused spectrum.

3. Power Control
   Power control is an effective resource-allocation method to combat fading channel and cochannel interference. The transmitted power is adjusted according to the channel condition so as to maintain the received signal quality. Power control is not a single user's problem, because a user's transmit power causes other users' interferences. We describe the basics of power control first. Then we classify the power-control schemes and discuss the centralized, distributed, and statistical schemes in details. Finally, code-division multiple-access power control is highlighted.
4. Rate Adaptation
   Rate adaptation is one of the most important resource-allocation issues, because the system can adapt the users' rates so that the limited radio resources can be efficiently utilized. In this chapter, we give an overview of the rate-adaptation system. Rate controls over different layers are discussed, such as source rate control, rate control for network/MAC layers, channel-coding rate control, and joint source–channel coding.
5. Multiple Access and Spectrum Access
   The multiple-access scheme is a general strategy to allocate limited resources, such as bandwidth and time, to guarantee the basic quality of services, improve the system performances, and reduce the cost for the network infrastructures. In this chapter, we first study some fixed multiple-access methods such as frequency-division, time-division and code-division multiple access. Then scheduling and random-access protocols are investigated. A third-generation multiple-access system is given as an example. Although multiple access considers the problem of allocating limited radio resources to multiple users, spectrum access decides whether an individual user can access a certain spectrum. We study channel allocation and opportunity spectrum access. Finally, handoff and admission control are illustrated.

In Part II, the chapters cover optimization techniques commonly used in resource allocation:

6. Optimization Formulation and Analysis
   In this chapter, we discuss how to formulate the wireless networking problem as a resource-allocation optimization issue. Specifically, we study what the resources are, what the parameters are, what the practical constraints are, and what the optimized performances across the different layers are. In addition, we address how to perform resource allocation in multiuser scenarios. The trade-offs between the different optimization goals and different users' interests are also investigated. The goal is to provide readers with a new perspective from the optimization point of view for wireless networking and resource-allocation problems.

7. Mathematical Programming
   If the optimization problem is to find the best objective function within a constrained feasible region, such a formulation is sometimes called a mathematical program. Many real-world and theoretical problems can be modeled within this general framework. In this chapter, we discuss the four major subfields of mathematical programming: linear programming, convex programming, nonlinear programming, and dynamic programming. Finally, a wireless resource-allocation example using programming is illustrated.
8. Integer/Combinatorial Optimization
   Discrete optimization is the problem in which the decision variables assume discrete values from a specified set. Combinatorial optimization problems, on the other hand, are problems of choosing the best combination out of all possible combinations. Most combinatorial problems can be formulated as integer programs. In wireless resource allocation, many variables have only integer values, such as the modulation rate, and other variables, such as channel allocation, have a combinatorial nature. Integer optimization is the process of finding one or more best (optimal) solutions in a well-defined discrete problem space. The major difficulty with these problems is that we do not have any optimality conditions to check whether a given (feasible) solution is optimal. We list several possible solutions such as relaxation and decomposition, enumeration, and cutting planes. Finally, a resource-allocation example is formulated and solved as a Knapsack problem.
9. Game Theory
   Game theory is a branch of applied mathematics that uses models to study interactions with formalized incentive structures ("games"). It studies the mathematical models of conflict and cooperation among intelligent and rational decision makers. "Rational" means that each individual's decision-making behavior is consistent with the maximization of subjective expected utility. "Intelligent" means that each individual understands everything about the structure of the situation, including the fact that others are intelligent, rational decision makers. In this chapter, we discuss four different types of games, namely, the noncooperative game, repeated game, cooperative game, and auction theory. The basic concepts are listed, and simple examples are illustrated. The goal is to let the readers understand the basic problems and basic approaches. As a result, we hope the readers can formulate the problems and find solutions in their research areas.

In Part III, we consider some network-aware advanced topics to illustrate the versatility of resource allocation:

10. Resource Allocation with Antenna-Array Processing
    For spatial diversity, transceivers employ antenna arrays and adjust their beam patterns such that they have good channel gain toward the desired directions, while the aggregate interference power is minimized at their output. Antenna-array processing techniques such as beamforming can be applied to receive and transmit multiple signals that are separated in space. Hence, multiple cochannel users can be supported in each cell to increase the capacity by exploring the spatial diversity. We

investigate two examples. First, joint power control, beamforming, and base-station assignment are studied. Second, if the channel information is not available, blind beamforming can be employed to control multiple users' power and beam pattern to achieve the desired link qualities.

11. Dynamic Resource Allocation
A general strategy to combat detrimental effects, such as fading, is the dynamic allocation of resources such as transmitted power, modulation rates, channel assignment, and scheduling based on the channel conditions. Several design challenges need to be overcome: To optimize radio resource utilization, an important trade-off exists between system performances and fairness among users. To satisfy the growing demands for heterogeneous applications of wireless networks, it is critical to deliver flexible, variable-rate services with high spectral efficiencies to provide a different quality of service. Finally, if the dynamics of channels is known, each user can calculate the optimal dynamic strategies to maximize the long-term benefits.
12. Game-Theoretic Approaches for Resource Allocation
Some wireless networks, such as ad hoc networks, consist of a collection of radio transceivers without requiring centralized administration or a prearranged fixed network infrastructure. As a result, ensuring cooperation among selfish users becomes an important issue for designing wireless networks. Game theory is an effective method for analyzing and designing the distributed resource allocation. In this chapter, for noncooperative game theory, we study three examples for power control, multicell orthogonal frequency-division multiple-access channel allocation, and source–relay resource allocation for cooperative communications. For repeated game theory, we study a punishment-based approach for rate control and a self-learning-based approach for packet forwarding. Finally, for cooperative game theory, we use a negotiation-based approach for single-cell orthogonal frequency-division multiple-access resource allocation and opportunistic spectrum access for a cognitive radio.
13. Resource Allocation for Cooperative Networks
Cooperative communications have gained attention as an emerging transmit strategy for future wireless networks. Cooperative communications efficiently take advantage of the broadcasting nature of wireless networks. The basic idea is that users or nodes in a wireless network share their information and transmit cooperatively as a virtual antenna array, thus providing diversity that can significantly improve system performance. In this chapter, we investigate the impact of cooperative communications on the design of different layers.
14. Ad Hoc/Sensor/Personal-Area Networks
Over the past few decades, the increasing demands from military, national security, and commercial customers have been driving the large-scale deployment of ad hoc networks, sensor networks, and personal-area networks, which have no sophisticated infrastructures such as base stations. In these scenarios, the mobile users have to set up the network functionality on their own. For ad hoc networks, we investigate the connectivity problem. For sensor networks, we study how to prolong the lifetime.

Finally, for personal-area networks, we employ resource allocation to extend the coverage area.

15. Resource Allocation for Wireless Multimedia
    With the advancement of multimedia compression technology and wide deployment of wireless networks, there is an increasing demand especially for wireless multimedia communication services. To overcome many potential design challenges, dynamic resource allocation is a general strategy used to improve the overall system performance and ensure individual quality of service. Specifically, in this chapter, we consider two aspects of design issues: *cross-layer optimization* and *multiuser diversity*. We study how to optimally transmit multiuser multimedia streams, encoded by current and future multimedia codecs, over resource-limited wireless networks such as third-generation cellular systems, wireless local-area networks, fourth-generation cellular systems, and future wireless local-area networks and wireless metropolitan-area networks.

Part I

Basics Principles

Cambridge University Press
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Zhu Han and K. J. Ray Liu
Excerpt
More information

2 Wireless Networks: An Introduction

2.1 Introduction

"Wireless network" refers to a telecommunications network whose interconnections between nodes is implemented without the use of wires. Wireless networks have seen unprecedent growth during the past few decades and will continuously evolve in the future. Seamless mobility and coverage ensure that various types of wireless connections can be made anytime, anywhere. In this chapter, we introduce some basic types of wireless networks and give the readers some preliminary backgrounds for the current state-of-the-art development.

Wireless networks use electromagnetic waves, such as radio waves, for carrying information. Therefore the performance is greatly influenced by randomly fluctuating wireless channels. To understand the channels, in Section 2.2, we will study the existing wireless channel models used for different network scenarios.

There are many existing wireless standards. We consider them according to the order of coverage area, and start with cellular wireless networks. The third-generation (3G) wireless cellular network standards have been enhanced to offer significantly increased performance for data and broadcast services through the introduction of high-speed downlink packet access, enhanced uplink, and multimedia broadcast multicast services. In Section 2.3, we provide an overview of the key elements and technologies. Specifically, we discuss WCDMA, CDMA2000, TD/S CDMA, and 4G and beyond.

WiMax, based on the IEEE 802.16 standard for a wireless metropolitan-area network (WMAN), is expected to enable true broadband speeds over wireless networks at a cost that enables mass-market adoption. WiMAX has the ability to deliver true broadband speeds and help make the vision of pervasive connectivity a reality. We discuss some techniques and the standard in Section 2.4.

A wireless local-area network (WLAN) is a network in which a mobile user can connect to a local-area network (LAN) through a wireless connection. The IEEE 802.11 group of standards specifies the technologies for a WLAN. Based on IEEE 802.11, WiFi is a brand originally licensed by the WiFi Alliance to describe WLAN technology. WiFi provides a low-cost and relatively simple way to gain high-speed access to the Internet. In Section 2.5, we study some specifications in IEEE 802.11 standards.

A wireless personal-area network (WPAN) is a personal-area network (PAN) for wireless interconnecting devices centered around an individual person's workspace. Typically, a WPAN uses a certain technology that permits communication within about

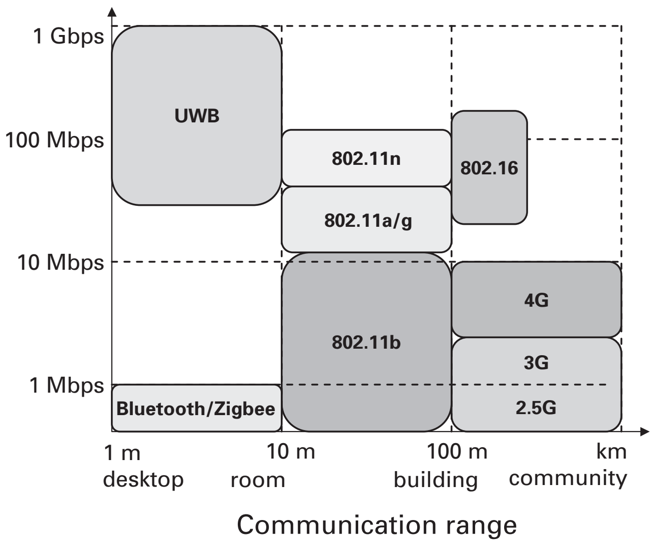

Figure 2.1 Standards comparison.

10 m; in other words, a very short range. IEEE 802.15 standards specify some technologies used in Bluetooth, Zigbee, and Ultra Wide Band. We investigate these technologies in Section 2.6.

We list different standards in Figure 2.1 for different communication rates and different communication ranges. Those standards will fit different needs of various applications, and we also discuss the techniques that can utilize multiple standards in different situations, so that a connection can be made anytime and anywhere.

Finally, in the last three sections in this chapter, we discuss some wireless networks without standards. Specifically, we study wireless ad hoc networks, wireless sensor networks, and cognitive radios, respectively. The motivations for deploying such networks, the design challenges to maintain basic functionality, and recent developments in real implementation are explained in detail.

2.2 Wireless Channel Models

Unlike the wired channels that are stationary and predictable, wireless channels are extremely random and hard to analyze. Models of wireless channels are one of the most difficult challenges for wireless network design. Wireless channel models can be classified as large-scale propagation models and small-scale propagation models, relative to the wavelength.

Large-scale models predict behavior averaged over distances much greater than the wavelength. The models are usually functions of distance and significant environmental features, and roughly frequency independent. The large-scale models are useful for modeling the range of a radio system and rough capacity planning. Some theoretical models (the first four) and experimental models (the rest) are listed as follows:

- Free-Space Model
  Path loss is a measure of attenuation based on only the distance from the transmitter to the receiver. The free-space model is valid only in the far field and only if there is no interference and obstruction. The received power $P_r(d)$ of the free-space model as a function of distance d can be written as

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{2.1}$$

  where P_t is the transmit power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the wavelength, and L is the system-loss factor not related to propagation. Path-loss models typically define a "close-in" point d_0 and reference other points from the point. The received power in decibel form can be written as

$$P_d(d) \text{ dBm} = 10 \log \left[\frac{P_r(d_0)}{0.001\text{W}}\right] + 20 \log \left(\frac{d_0}{d}\right). \tag{2.2}$$

- Reflection Model
  Reflection is the change in direction of a wave front at an interface between two dissimilar media so that the wave front returns into the medium from which it originated. A radio propagation wave impinges on an object that is large compared with the wavelength, e.g., the surface of the Earth, buildings, and walls.

  A two-ray model is one of the most important reflection models for wireless channels. An example of reflection and the two-ray model is shown in Figure 2.2. The two-ray model considers a model in which the receiving antenna sees a direct-path signal as well as a signal reflected off the ground. Specular reflection, much like light off of a mirror, is assumed, and, to a very close approximation, the specular reflection arrives with strength equal to that of the direct-path signal. The reflected signal shows up with a delay relative to the direct-path signal and, as a consequence, may add constructively (in phase) or destructively (out of phase). The received power of the two-ray model can be written as

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}, \tag{2.3}$$

  where h_t and h_r are the transmitter height and receiver height, respectively.

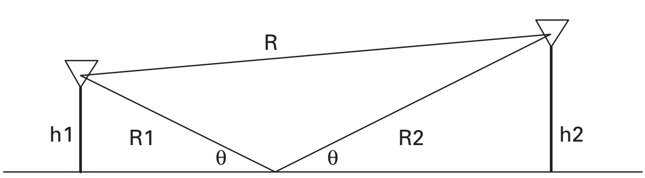

Figure 2.2 Reflection and two-ray model.