Cooperative Communications and Networking

Presenting the fundamental principles of cooperative communications and networking, this book treats the concepts of space, time, frequency diversity, and MIMO, with a holistic approach to principal topics where significant improvements can be obtained.

Beginning with background and MIMO systems, Part I includes a review of basic principles of wireless communications, space–time diversity and coding, and broadband space–time–frequency diversity and coding. Part II then goes on to present topics on physical layer cooperative communications, such as relay channels and protocols, performance bounds, optimum power control, multi-node cooperation, distributed space–time and space–frequency coding, relay selection, differential cooperative transmission, and energy efficiency. Finally, Part III focuses on cooperative networking including cooperative and content–aware multiple access, distributed routing, source–channel coding, source–channel diversity, coverage expansion, broadband cooperative communications, and network lifetime maximization.

With end-of-chapter review questions included, this text will appeal to graduate students of electrical engineering and is an ideal textbook for advanced courses on wireless communications. It will also be of great interest to practitioners in the wireless communications industry.

Presentation slides for each chapter and instructor-only solutions are available at www.cambridge.org/9780521895132

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To my parents Dr. Chau-Han Liu and Tama Liu – KJRL
To my parents Dr. Kamel and Faten and my wife Dina – AKS
To my wife Ming Yu and my son David – WS
To my wife Mariela and my daughters Victoria and Emma – AK

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Preface

Wireless communications technologies have seen a remarkably fast evolution in the past two decades. Each new generation of wireless devices has brought notable improvements in terms of communication reliability, data rates, device sizes, battery life, and network connectivity. In addition, the increase homogenization of traffic transports using Internet Protocols is translating into network topologies that are less and less centralized. In recent years, ad-hoc and sensor networks have emerged with many new applications, where a source has to rely on the assistance from other nodes to forward or relay information to a desired destination.

Such a need of cooperation among nodes or users has inspired new thinking and ideas for the design of communications and networking systems by asking whether cooperation can be used to improve system performance. Certainly it means we have to answer what and how performance can be improved by cooperative communications and networking. As a result, a new communication paradigm arose, which had an impact far beyond its original applications to ad-hoc and sensor networks.

First of all, why are cooperative communications in wireless networks possible? Note that the wireless channel is broadcast by nature. Even directional transmission is in fact a kind of broadcast with fewer recipients limited to a certain region. This implies that many nodes or users can "hear" and receive transmissions from a source and can help relay information if needed. The broadcast nature, long considered as a significant waste of energy causing interference to others, is now regarded as a potential resource for possible assistance. For instance, it is well known that the wireless channel is quite bursty, i.e., when a channel is in a severe fading state, it is likely to stay in the state for a while. Therefore, when a source cannot reach its destination due to severe fading, it will not be of much help to keep trying by leveraging repeating-transmission protocols such as ARQ. If a third party that receives the information from the source could help via a channel that is independent from the source–destination link, the chances for a successful transmission would be better, thus improving the overall performance.

Then how to develop cooperative schemes to improve performance? The key lies in the recent advances in MIMO (multiple-input multiple-output) communication technologies. In the soon-to-be-deployed fourth-generation (4G) wireless networks, very high data rates can only be expected for full-rank MIMO users. More specifically, full-rank MIMO users must be equipped multiple transceiver antennas. In practice, most users either do not have multiple antennas installed on small-size devices, or the propagation environment cannot support MIMO requirements. To overcome the limitations of achieving MIMO gains in future wireless networks, one must think of new techniques beyond traditional point-to-point communications.

A wireless network system is traditionally viewed as a set of nodes trying to communicate with each other. However, from another point of view, because of the broadcast nature of wireless channels, one may think of those nodes as a set of antennas distributed in the wireless system. Adopting this point of view, nodes in the network may cooperate together for distributed transmission and processing of information. A cooperating node can act as a relay node for a source node. As such, cooperative communications can generate independent MIMO-like channel links between a source and a destination via the introduction of relay channels.

Indeed, cooperative communications can be thought of as a generalized MIMO concept with different reliabilities in antenna array elements. It is a new paradigm that draws from the ideas of using the broadcast nature of the wireless channels to make communicating nodes help each other, of implementing the communication process in a distribution fashion, and of gaining the same advantages as those found in MIMO systems. Such a new viewpoint has brought various new communication techniques that improve communication capacity, speed, and performance; reduce battery consumption and extend network lifetime; increase the throughput and stability region for multiple access schemes; expand the transmission coverage area; and provide cooperation tradeoff beyond source–channel coding for multimedia communications.

The main goals of this textbook are to introduce the concepts of space, time, frequency diversity, and MIMO techniques that form the foundation of cooperative communications, to present the basic principles of cooperative communications and networking, and to cover a broad range of fundamental topics where significant improvements can be obtained by use of cooperative communications. The book includes three main parts:

- **Part I: Background and MIMO systems** In this part, the focus is on building the foundation of MIMO concepts that will be used extensively in cooperative communications and networking. Chapter 1 reviews of fundamental material on wireless communications to be used in the rest of the book. Chapter 2 introduces the concept of space–time diversity and the development of space–time coding, including cyclic codes, orthogonal codes, unitary codes, and diagonal codes. The last chapter in this part, Chapter 3, concerns the maximum achievable space–time–frequency diversity available in broadband wireless communications and the design of broadband space–frequency and space–time–frequency codes.
- **Part II: Cooperative communications** This part considers mostly the physical layer issues of cooperative communications to illustrate the differences and improvements under the cooperative paradigm. Chapter 4 introduces the concepts of relay channels and various relay protocols and schemes. A hierarchical scheme that can achieve linear capacity scaling is also considered to give the fundamental reason

for the adoption of cooperation. Chapter 5 studies the basic issues of cooperation in the physical layer with a single relay, including symbol error rate analysis for decode-and-forward and amply-and-forward protocols, performance upper bounds, and optimum power control. Chapter 6 analyses multi-node scenarios. Chapter 7 presents distributed space–time and space–frequency coding, a concept similar to the conventional space–time and space–frequency coding but different in that it is now in a distributed setting where assumptions and conditions vary significantly. Chapter 8 concerns the issue of minimizing the inherent bandwidth loss of cooperative communications by considering when to cooperate and whom to cooperate with. The main issue is on devising a scheme for relay selection and maximizing the code rate for cooperative communications while maintaining significant performance improvement. Chapter 9 develops differential schemes for cooperative communications to reduce transceiver complexity. Finally, Chapter 10 studies the issues of energy efficiency in cooperative communications by taking into account the practical transmission, processing, and receiving power consumption and illustrates the tradeoff between the gains in the transmit power and the losses due to the receive and processing powers when applying cooperation.

- **Part III: Cooperative networking** This part presents impacts of cooperative communications beyond physical layer, including MAC, networking, and application layers. Chapter 11 considers the effect of cooperation on the capacity and stability region improvement for multiple access. Chapter 12 studies how special properties in speech content can be leveraged to efficiently assign resources for cooperation and further improve the network performance. Chapter 13 discusses cooperative routing with cooperation as an option. Chapter 14 develops the concept of source–channel–cooperation to consider the tradeoff of source coding, channel coding, and diversity for multimedia content. Chapter 15 focuses on studying how source coding diversity and channel coding diversity interact with cooperative diversity, and the system behavior is characterized and compared in terms of the asymptotic performance of the distortion exponent. Chapter 16 presents the coverage area expansion with the help of cooperation. Chapter 17 considers the various effects of cooperation on OFDM broadband wireless communications. Finally, Chapter 18 discusses network lifetime maximization via the leverage of cooperation.

This textbook primarily targets courses in the general field of cooperative communications and networking where readers have a basic background in digital communications and wireless networking. An instructor could select Chapters 1, 2, 4, 5, 6, 7.1, 8, 10, 11, 13, 14, and 16 to form the core of the material, making use of the other chapters depending on the focus of the course.

It can also be used for courses on wireless communications that partially cover the basic concepts of MIMO and/or cooperative communications which can be considered as generalized MIMO scenarios. A possible syllabus may include selective chapters from Parts I and II. If it is a course on wireless networking, then material can be drawn from Chapter 4 and the chapters in Part III.

This book comes with presentation slides for each chapter to aid instructors with the preparation of classes. A solution manual is also available to instructors upon request. Both can be obtained from the publisher via the proper channels.

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