Cooperative Cellular Wireless Networks

A self-contained guide to the state-of-the-art in cooperative communications and networking techniques for next-generation cellular wireless systems, this comprehensive book provides a succinct understanding of the theory, fundamentals, and techniques involved in achieving efficient cooperative wireless communications in cellular wireless networks.

It consolidates the essential information, addressing both theoretical and practical aspects of cooperative communications and networking in the context of cellular design. This one-stop resource covers the basics of cooperative communications techniques for cellular systems, advanced transceiver design, relay-based cellular networks, and game-theoretic and micro-economic models for protocol design in cooperative cellular wireless networks. Details of ongoing standardization activities are also included.

With contributions from experts in the field divided into five distinct sections, this easy-to-follow book delivers the background needed to develop and implement cooperative mechanisms for cellular wireless networks.

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"Edited by three of the most prominent experts in the field of cooperative communications, this is the defining book on this topic. It is a must have for any practicing researcher/engineer in this field."

Vahid Tarokh, Harvard University

"Cooperative communications has been one of the most active areas of research in the communications field over the past decade. This research effort has now produced a significant body of work in the area, and this book is a valuable resource for students or practitioners wanting to enter the field, or simply to understand the scope and implications of the research."

H. Vincent Poor, Princeton University

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For our families

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Preface

Cooperative communications and networking represent a new paradigm which uses both transmission and distributed processing to significantly increase the capacity in wireless communication networks. Current wireless networks face challenges in fulfilling users' ever-increasing expectations and needs. This is mainly due to the following reasons: lack of available radio spectrum, the unreliable wireless radio link, and the limited battery capacity of wireless devices. The evolving cooperative wireless networking paradigm can tackle these challenges. The basic idea of cooperative wireless networking is that wireless devices work together to achieve their individual goals or one common goal following a common strategy. Wireless devices share their resources (i.e., radio link, antenna, etc.) during cooperation using short-range communications. The advantages of cooperation are as follows: first, the communications capability, reliability, coverage, and quality-of-service (QoS) of wireless devices can be enhanced by cooperation; second, the cost of information exchange (i.e., transmission power, transmission time, spectrum, etc.) can be reduced. Cooperative communication and networking will be a key component in next generation wireless networks. In this book we particularly focus on cooperative transmission techniques in cellular wireless networks.

Although cellular wireless systems are regarded as a highly successful technology, their potential in throughput and network coverage has not been fully realized. Cooperative communication is a key technique to harness the potential throughput and coverage gains in these networks. Cooperation is possible among mobile stations (MSs) inside a cell as well as among base stations (BSs). In addition, specialized relay stations (RSs) can be installed in the network to facilitate cooperative communications. In addition to improving throughput and coverage, cooperative communication can improve the energy saving performance at the mobile devices, increase reliability in transmission, and decrease the overall interference in the network. However, successful deployment and operation of a cooperative cellular wireless network hinges on the development of advanced radio transmission and resource management techniques and optimization of these techniques considering the different network parameters. This has spurred a vibrant flurry of research on different aspects of cooperative communication during the last few years.

With BS cooperation, neighboring cells can exchange information aiming at mitigating intercell interference by coordinating the multicell transmission to a mobile or reception from a mobile. In a relay-based cooperative cellular wireless network, an MS may communicate with a BS via potential relays, and similarly, a BS can send data to distant nodes through relays. The potential relays could be either preinstalled fixed RSs or relay-capable MSs. The RSs are much cheaper than conventional BSs because they have far fewer functionalities compared to BSs. If the relay is positioned suitably, it is possible to increase the data rate (especially at the cell boundaries) and the reliability of the system. Similar to multiantenna transceivers, relays provide diversity by creating multiple replicas of the signal of interest. By properly coordinating different spatially distributed nodes in the system, a virtual antenna array can be synthesized that emulates the operation of a multiantenna transceiver. With cooperation at all layers of the protocol stack, the network can achieve higher throughput, higher system reliability, higher energy efficiency, a lower bit-error rate, and a smaller packet loss rate. For cooperation at physical, medium access control (MAC), network, and application layers, various cooperative signaling methods are being widely explored and many new mechanisms are under development with respect to medium access, routing, location management, scheduling, energy management, etc.

This book provides a comprehensive treatment of the state-of-the-art of cooperative communications and networking techniques for cellular systems (e.g., Beyond 3G, Long-Term evolution systems). It consists of chapters covering different aspects of cooperative cellular wireless network design which include the following: architectures and protocols for cooperative cellular wireless networks; cooperative BS techniques (e.g., cooperative beamforming technique); radio resource management protocol design and network planning for relay-based cooperative cellular wireless systems (e.g., relaying strategies and protocols, resource allocation, energy management, network coding, and cross-layer issues); and the latest IEEE standardization activities pertaining to cooperative cellular wireless systems. The chapters are written by the distinguished researchers in these areas. This book is targeted at graduate students, or researchers working in the area of cellular wireless networks. It can also be used for self-study to become familiar with the state-of-the-art in cooperative communications for cellular wireless systems.

This book contains 17 chapters which have been organized into five parts. A brief account of each chapter in each of these parts is given next.

Part I: Introduction

In Chapter 1, Nosratinia and Hedayat outline the trends in research into cooperative cellular wireless networks, as well as some of the outstanding problems in this area. In particular, the issues related to BS cooperation (for both downlink and uplink transmission) and cooperation through dedicated wireless relays (fixed and mobile) are discussed from the physical layer perspective.

In Chapter 2, Moghaddari and Hossain focus on the resource allocation problem for cooperative communications in relay-based orthogonal frequency-division multiple access (OFDMA) and multiple-input multiple-output (MIMO) wireless networks. Starting with the basics of cooperative relay networks and strategies for relay-assisted transmission, a survey on the different approaches for radio resource allocation in OFDMA relay networks is provided. To this end, research issues on resource allocation in multihop MIMO relay networks and some related work in the literature are discussed.

Part II: Cooperative base station techniques

In Chapter 3, Hardjawana, Vucetic, and Li focus on BS cooperation for interference cancelation where each BS transmitter uses the transmitted signal information from other BS and channel state information to precode its own signal. A spectrally efficient cooperative downlink transmission scheme is designed by employing precoding and beamforming. The proposed scheme achieves fairness among different users in terms of symbol error rate.

In Chapter 4, Aktas *et al.* focus on an approach for implementing BS cooperation in a distributed manner via message passing in network MIMO systems. This approach is based on a graphical model (in particular, a factor graph) of the network MIMO communication processes. Both uplink and downlink transmissions are considered. As an example, a graph-based approach for distributed beamforming and power allocation is discussed.

In Chapter 5, Wang and Yeh discuss the antenna architectures for the network MIMO schemes based on BS cooperation in a multicellular system. One fundamental question when applying the network MIMO technique in such a high interference environment is: how many BSs should cooperate together to provide satisfactory signal-to-interference-plus-noise ratio (SINR) performance? Considering the interferences from the other cooperating groups, it is found that on top of the tri-sector directional antenna and fractional frequency reuse (FFR), the network MIMO based on the three-cell coordination strategy can outperform seven-cell-based network MIMO with omni-directional antenna. The authors also consider the effect of different cell sectorizations by using 120° and 60° beamwidths directional antennas.

Part III: Relay-based cooperative cellular wireless networks

In Chapter 6, Valenti and Reynolds focus on space-time block coding (STBC) strategies in a cooperative system to forward signals efficiently from multiple relays to the destination by exploiting the spatial diversity present in a multirelay network. Both decode-and-forward distributed STBC and amplify-and-forward distributed STBC are considered for a two-phase transmission protocol in a network with one source node, one destination node, and a set of relay nodes. The end-to-end outage probability, coding gain, and achievable diversity as well as the optimal ratio of the power used in the two phases of transmission are analyzed for different space-time codes. Unlike conventional space-time codes, the distributed space-time codes have to deal with the synchronization problem at the destination receiver. Delay diversity, delay-tolerant distributed space-time codes, and space-time spreading are some effective methods of dealing with this problem.

In Chapter 7, Raman *et al.* present a simulation study of the downlink of a cellular system with relays in order to evaluate peak and average power savings for a given target common rate requirement for users. In particular, three schemes, namely, the collaborative power addition (CPA) scheme, the power control-based collaborative power addition (PC-CPA) scheme, and an orthogonal relaying scheme are simulated. In the CPA scheme, when a relay receives the complete message, it collaborates with the BS to transmit the complete message to the user using its peak power. In the PC-CPA scheme, power control is performed jointly at the BS and RS. In the orthogonal relaying scheme, the BSs and the RSs transmit in orthogonal time slots. The peak power savings (at the BSs) are rate gains (for the users) and are observed to be better with the PC-CPA scheme.

In Chapter 8, Mallick *et al.* study the radio resource (i.e., bandwidth, transmit power) allocation problem in relay-based cooperative cellular wireless networks. For the different relaying schemes (i.e., amplify-and-forward, decode-and-forward) in single- and multiuser network scenarios, different optimization models for resource allocation and their solution approaches are described. Also, the problem of relay selection for individual communication between source and destination nodes is discussed. The problem of joint optimization of resource allocation and relay selection is an open research issue.

In Chapter 9, Yu, Kwon, and Shin study the resource (i.e., power, spectrum, and rate) allocation problem for OFDMA-based cooperative cellular wireless networks. Two types of cooperative networks are considered: the multicell network with BS cooperation where multiple BS cooperatively allocate power to the different frequency subchannels, and networks with RSs. With a view to maximizing the sum of utilities of multiple uses in a multicell network, a network utility maximization (NUM) framework is used to solve the scheduling, and the power, frequency, and rate allocation problem. A key observation here is that, with OFDMA, the network utility maximization problem often decomposes into a tone-by-tone optimization problem, which is easier to solve.

In Chapter 10, Ng and Schober focus on the problem of cross-layer scheduling design for two-way half-duplex amplify-and-forward relay-assisted OFDMA cellular networks. Such a scheduling scheme has to satisfy the different data rate and outage probability requirements of different users. Starting with the basics of cross-layer scheduling design and the related implementation challenges, the problem considered is formulated as a mixed combinatorial and non-convex optimization problem. In the problem formulation, the objective is to obtain the optimal power, rate, and subcarrier allocation policies while taking the imperfect channel state information (CSI) as well as heterogeneous QoS requirements of the users into account. The problem is then solved by dual decomposition. Also, a distributed iterative algorithm is designed to reduce the computational load at the relays.

In Chapter 11, Rost and Fettweis focus on the system-wide energy consumption in cooperative cellular networks. Two deployment scenarios are considered, namely, a macrocellular deployment and a microcellular deployment, both of which use OFDMA air interface for uplink/dowlink transmission in time-division duplex (TDD) mode. The system performance is simulated considering multicell MIMO transmission only (nonrelaying protocol), a relay only protocol, and an integrated approach (which supports both multicell MIMO and relaying). The achievable throughput performance, the energy saving potentials, and the deployment costs are compared. In addition, performance comparison is carried out between femto-cells and relaying.

In Chapter 12, Xu and Li study the potential application of network coding and the related issues in relay-based networks. Also, the idea of physical-layer network coding is discussed; this has the potential to improve the throughput performance of relay-based networks significantly. One key observation is that, since network coding is mostly applied at the lower layers of the protocol stack, the scheduling and resource allocation at the upper layers have to be coding-aware. Such a cross-layer approach for network coded cooperation may reap the benefits of network coding, however, at the expense of increased complexity.

Part IV: Game theoretic models for cooperative cellular wireless networks

In Chapter 13, Saad, Han, and Hjørungnes explore the application of coalitional game theory to model the various aspects of cooperative behavior in cellular wireless networks. For example, cooperation among the BSs can be modeled by a class of coalitional games, known as coalition formation games, and thereby, algorithms can be derived which help in analyzing the groups of cooperating BSs that will emerge in a given network scenario. As another example, network formation games, a class of coalitional graph games, can be used to model the interactions among RSs. The key message is that coalitional game theory provides a rich framework to design efficient, fair, and robust models for resource allocation and sharing in cooperative cellular wireless networks.

In Chapter 14, Marina *et al.* use game theory to analyze the *secrecy capacity* in cooperative networks in the presence of malicious users (e.g., eavesdroppers). The secrecy capacity refers to the maximum reliable data rate at which a perfectly secret communication is possible between a sender and a receiver. Three different communications scenarios are considered. In the first scenario, several friendly jammers help the source in transmitting data to a destination by jamming the eavesdropper. The interaction between the source and the friendly jammers is analyzed using a Stockholder type of game. In the second scenario, several relay nodes help the source by relaying the transmitted data in the presence of a malicious node, and this cooperation improves the secrecy capacity. In this cooperative system, the number and locations of the relay nodes determine the secrecy region, i.e., the geometric area in which the secrecy capacity is positive. In the last scenario, the eavesdroppers cooperate to improve their reception performance. A coalitional game-based model is proposed for forming cooperative groups among the eavesdroppers. This modeling will be useful to develop defense mechanisms against the eavesdroppers' cooperation.

Part V: Standardization activities

In Chapter 15, Moon, Clerckx, and Khan discuss the standard trends on cooperative communications in the Third Generation Partnership Project (3GPP) Long-Term Evolution Advanced (LTE-Advanced) system. In particular, an overview of the key technical features of LTE-Advanced Release 10 including carrier aggregation, cooperative multipoint transmission/reception (CoMP), extended multi-antenna systems, and wireless relays is provided. Carrier aggregation provides wider transmission bandwidth and makes full use of the existing fractional spectrum bands. The other techniques provide higher cell spectrum efficiency, better coverage, and lower handover interruption time. CoMP transmission refers to a new class of intercell interference mitigation technique, which is also called multicell MIMO, collaborative MIMO (Co-MIMO), or network MIMO. The basic idea is to extend the conventional single-cell-to-multiple-user transmission to a multiple-cell-to-multiple-user transmission through BS cooperation.

In Chapter 16, Kim *et al.* develop methods for partial information relaying in multiantenna decode-and-forward relay networks. These methods use a two-phase transmission strategy and exploit the asymmetric link conditions in cellular networks, where the source–relay link and the relay–destination link are relatively better than the source–destination link. With multiple antennas available at source, relay, and destination, multiple parallel data streams are transmitted which consist of basic data streams and superposition coded (SC) data streams. The relay forwards only the SC streams (i.e., partial information in the second hop). Two methods, namely, per-antenna superposition coding (PASC) and multilayer superposition coding (MLSC), are proposed for power allocation among basic and superposed layers, and across the spatial layers. It is observed that partial information relaying results in significant capacity gain over full information relaying. To this end, the authors summarize the issues, discussions, and current conclusions on relaying in the LTE-Advanced standard.

In Chapter 17, Cho *et al.* discuss the proposals and current conclusions on the CoMP technique in the 3GPP LTE-Advanced standard. Many companies and research groups are confident that CoMP systems are feasible in real systems and have put forth effort to find and evaluate what type of cooperation scheme should be standardized. The authors outline the issues discussed in the LTE-Advanced study group, for downlink CoMP, and present related simulation methodologies.