

# **Preface**

## **Introduction**

Mobile and wireless communication systems are a prominent communications technology of the twenty-first century with profound economic and social impacts in practically all parts of the world. The current state of wireless communication systems allows for a much wider scope of applications than what it used to be originally, that is, to be a mobile extension of the public switched telephone network. The convergence of mobile systems and the Internet has become a reality as new radio access technologies emerged with improved coverage, capacity, and latency. While the need and desire to develop and establish a truly mobile Internet dates back to the mid-1990s, it is only recently that mobile broadband has taken off to become a prominent part of the whole mobile communications business.

This book is about some of the latest developments in wireless access technology, and underlying breakthroughs, that are part of or can be applied to Fourth generation mobile communication systems onwards, in order to keep up with the increasing demand for mobile data.

The specific focus of the book is on the two lower layers of the ISO/OSI layered model, that is, the physical and data link layers, in particular the media access control sublayer of the latter. A common thread throughout the book is cross-layer optimization between these layers. These two layers are of specific importance in wireless systems, as opposed to many of its wired counterparts. This is fundamentally due to spectrum shortage, limited signal coverage, the broadcast nature of interference, and time variability of the wireless channel response. As a consequence, much of the improvements in coverage, capacity, and latency of modern wireless systems are due to new approaches for tackling old problems in high capacity radio communications in these two lower layers.

## **Intended Audience and Usage**

This book is intended for researchers in the field of wireless communications, more specifically to those involved with the design and optimization of current and emerging wireless access technologies for mobile communications. Graduate

students working on subjects such as radio resource allocation (RRA) and management (RRM), interference management, Orthogonal Frequency Division Multiple Access (OFDMA) and Multiple-Input-Multiple-Output (MIMO) systems, as applied to fourth generation systems and beyond, will benefit from the state-of-the-art concepts, methods, examples, and case studies presented. Every chapter, in addition to having a clear ambition to address the state of the art of the corresponding subject, discusses basic concepts in the introductory sections and gives references for the interested reader to deepen his/her understanding. All chapters can be used independently as a complement to a graduate-level “Advanced” Wireless Communications course, where each separate chapter can be used as basis to a supervised study or a seminar.

The book should also be of interest to the practitioner or to engineers involved in standardization efforts. The attention to technical details from standards is given in several chapters when performance results and case studies are presented as resulting from the application of selected techniques. The idea in many instances is to demonstrate how advanced concepts can be adapted to be applicable in more realistic scenarios.

Finally, almost every chapter of the book sheds light, direct or indirectly, on the subject of performance evaluation of wireless systems by means of analytical approaches and of system and link-level simulations. As the complexity of wireless systems grows, efficient and correct methods for modeling and analyzing performance of these systems is becoming a fundamental discipline on its own.

## **Organization of the Book**

This book brings a total of 11 chapters and, for the sake of clarity of presentation, these chapters are organized into two parts. The parts are named “Resource Allocation” and “MIMO” after the book’s title and as the focus is on two layered model mentioned above. Such type of division is becoming increasingly artificial as cross-layer optimizations are commonplace and multiple antennas at network nodes can be seen as “resources” to be managed. Therefore, some of the chapters could well be placed in both parts.

## **Part I: Resource Allocation**

Radio Resource Allocation (RRA) has its roots in frequency reuse planning of First generation cellular systems. Its fundamental goal is to increase spectrum efficiency.

More efficient utilization of the radio spectrum plays such an important role because spectrum is simultaneously a very scarce and widely shared resource.

In the evolution towards 3G systems, RRA became a discipline on its own, encompassing a variety of techniques such as power control, frequency hopping,

dynamic channel allocation, and being integrated into more advanced multi-antenna concepts, such as beamforming and MIMO solutions.

The explosion of mobile broadband and the demand for high data-rate packet switched services has required a new set of RRA techniques able to handle capacity challenging scenarios. These new RRA approaches started off by borrowing concepts from wired data networks, such as packet scheduling and congestion control, but that were reformulated and adapted to the wireless environment.

More recently, with the emergence of 4G, noticeably in the form of 3GPP's Long Term Evolution (LTE) standards, a highly configurable radio access technology based on OFDMA has been made available. This has, again, widened the scope of RRA. By means of advanced optimization approaches, RRA is now possible with fine granularity, increasing the efficiency-potential of spectrum usage to unprecedented levels. This is mainly due to a clever exploitation of the multidimensional (spatial, frequency, time, and multiuser) diversity by RRA algorithms. To mention one example of such, MIMO techniques, once restricted to the single-user case, are now considered an inherent part of RRA at a network level.

Advances in computing power and energy efficiency at mobile devices are also an important enabler for the actual implementation of sophisticated RRA algorithms. Nevertheless, computational complexity is still an issue that should be considered when evaluating the applicability of RRA proposed solutions. Another aspect that deserves attention is the demand for channel state information and control signaling at multiple network nodes (e.g., mobile devices and base stations). Since the dimensionality of RRA problems has grown in OFDMA-based systems such as LTE, one must verify if the algorithm's demand for such information are realistic in order not to overburden the system's backhaul. These and other practical issues are treated in most of the chapters in this book when RRA approaches are presented.

**Chapter 1** revisits many of the issues concerning RRM with a focus on the upcoming systems embodying the Coordinated Multipoint (CoMP) technology. CoMP-based systems have attracted special attention due to their potential benefits in terms of spectral efficiency and coverage. As a part of 3GPP Long Term Evolution—Advanced, CoMP technology promises substantial improvement of the users' experience at the expense of requiring a reliable and efficient connection among the evolved Node Bs (eNBs). Provided that multiple users and eNBs are coordinated using a suitable technique, the concerns about interference can be greatly alleviated and, consequently, also the restrictions on sharing radio resources. In this chapter, the authors explore the grouping of users and eNBs in two different occasions. First they address coordinated strategies of grouping and scheduling users in order to improve the system performance; afterwards, clustering of eNBs is described as an attractive approach to deal with the processing and signaling overheads brought by CoMP. The chapter presents an analysis of different algorithms, as well as case studies illustrating some key concepts through computer simulations.

**Chapter 2** starts by recognizing that cellular networks have experienced a strong development in the past decades and now face an important challenge that is a steep increase of mobile traffic expected for the next years. In this context, cellular operators have as objective to increase the number of satisfied users in the system and consequently their revenues, whereas users or subscribers aim at having fulfilled their expected Quality of Service (QoS). In order to increase the number of satisfied users in the system the authors identify the RRA as a key functionality. RRA is responsible for managing and distributing the available scarce resources of the radio interface to the active connections. In this chapter the authors present RRA strategies to increase the number of satisfied users in cellular networks based on two approaches: heuristic and utility-based strategies. While the heuristic design provides simple and quick solutions to the RRA problems, the utility-based approach is a flexible and general tool for RRA design.

Authors in **Chap. 3** recognize that the increasing demand for rich multimedia services and the scarcity of electromagnetic spectrum has motivated the research of technologies able to increase the capacity of wireless systems without requiring additional spectrum. In this context, Device-to-Device (D2D) communication represents a promising technology. By enabling direct and low-power communication among devices, D2D communication leads to an increased and intelligent spatial reuse of radio resources allowing offloading the network of data transport. As a result, the overall system's capacity and specially the spectral efficiency is increased; and the proximity between devices allows data transfer with low delays and high rates without requiring extra power from devices' batteries. Other benefits of D2D communication especially while underlying a cellular network encompasses the reuse gain and hop gain, which are further detailed in this chapter. However, in order to realize the potential gains of D2D communications as a secondary network of the cellular (primary) one, some key issues must be controlled. First, at each transmission request for a D2D-capable device, it is necessary to determine the neighbors, i.e., other D2D-capable devices that are in the vicinity of the latter and therefore may establish a D2D communication. Then, once neighbors are discovered and the target device is in the neighbors' poll, the actual link (channel) conditions must be evaluated. If beneficial, RRA techniques are employed so that the co-channel interference caused in cellular devices is mitigated. Such techniques may be summarized as: band selection, grouping, mode selection, and power control. In this chapter, the authors focus attention on the RRA for D2D communications underlying an LTE-like network, and the main RRA techniques to mitigate the co-channel interference so generated. Namely, it is shown the basis for grouping, mode selection, and power control techniques, and presented results that highlight their benefits.

Authors in **Chap. 4** propose that wireless mobile network optimization is a complex task that consists in achieving different design objectives such as spectral efficiency, energy efficiency, fairness, and QoS. Then, RRA is responsible for managing the available resources in the radio access interface and, therefore, is an important tool for optimizing networks and achieving the designed objectives mentioned previously. However, in general all these network design objectives

cannot be achieved at the same time by RRA strategies. In fact, different RRA strategies can be designed to maximize one objective in detriment of the other as well as to balance the objectives. In this chapter the authors deal with important trade-offs between contradicting objectives in modern wireless mobile networks: capacity versus fairness and capacity versus QoS. The authors then present RRA strategies that can achieve static and adaptive performances when the previously mentioned trade-offs are considered. In order to design these RRA strategies, the authors consider heuristics and utility-based solutions.

**Chapter 5** is focused on designing efficient, low-complexity cooperative diversity schemes from different perspectives and it is divided into four parts. In the first part, assuming a general multi-source, multi-relay cooperative system, a new efficient scheme for the combined use of cooperative diversity and multiuser diversity is proposed. The proposed scheme significantly reduces the amount of necessary channel estimation while achieving comparable outage performance to that using the joint selection scheme. In the second part, two spectrally efficient schemes for the diversity exploitation of downlink cooperative cellular networks are proposed. By scheduling the user with the best direct link to access the channel, an incremental decode-and-forward relaying scheme is first presented. To further enhance the transmission robustness against fading, an improved scheme is also proposed, which substantially utilizes opportunistic scheduling mechanism when the direct transmission fails. In the third part, new and efficient link selection schemes for selection relaying systems with transmit beamforming are proposed. Two distributed link selection schemes are presented that invoke a distributed decision mechanism and rely on the success/fail signaling feedback between terminals. In the fourth part, a novel distributed transmit antenna selection for dual-hop amplify-and-forward relaying systems is proposed. A multi-antenna source transmits information to a single-antenna destination by using a single-antenna half-duplex relay. By invoking local channel information exploitation/decision mechanism along with decision feedback between terminals, a distributed antenna selection scheme is formulated. Compared with the optimal/suboptimal antenna selection, the proposed scheme can maintain a low and constant delay/feedback overhead irrespective of the number of transmit antennas.

In **Chap. 6** authors address distributed parameter coordination methods for wireless communication systems. The authors present two distributed algorithms for the problem of precoder selection. The first and simplest method is the greedy solution in which each communication node in the network acts selfishly. The second method and the focus of this chapter is based on a message-passing algorithm, namely minsum algorithm, in factor graphs. Three kinds of precoding codebooks are considered: transmit antenna selection, fixed-beam selection, and LTE precoder selection. Evaluations on the potential of such an approach in a wireless communication network are provided and its performance and convergence properties are compared with those of a baseline selfish/greedy approach. Simulation results are presented and discussed, which show that the graph-based technique generally obtains gain in sum rate over the greedy approach at the cost of a larger message size. For instance, the percentage gain in sum rate over the

greedy is about 33 % within 5 iterations in a 7-cell network considering single-layer LTE precoders. Besides, the graph-based method usually reaches the global optima in an efficient manner. Methods of improving the rate of convergence of graph-based distributed coordination technique and reducing its associated message size are therefore important topics for wireless communication networks.

## Part II: MIMO Systems

The significant improvements at the physical layer have been instrumental for the increase of the wireless link capacity over the last decade. OFDM itself, already a popular modulation mechanism in fixed digital subscriber lines, has been combined with the use of multiple antennas at both ends of wireless links, in so-called Multiple-Input-Multiple-Output (MIMO) schemes. MIMO has changed the way wireless engineers face the fundamental capacity limits of the wireless channel by exploiting fading variability in favor of it. This fact also illustrates the major challenge—how can a wireless system be designed that allows for a practical implementation in the presence of such potentially fast fading propagation channels between and among the multitude of employed antennas? The main aspects to take into consideration is how to make such a system design both observable and controllable—the former, important in order to generate the appropriate amount of radio network measurements and the associated signaling and the latter, is significant in the sense of keeping the interference levels under control on a system level.

MIMO has been originally proposed as a single-user point-to-point technique for increasing spectral efficiency by means of a clever exploitation of multipath scattering. However, a related and somewhat parallel approach known as SDMA (Spatial Division Multiple Access) already pointed out the possibility of using the space domain for organizing multiple users sharing a given spectrum. The evolution of MIMO toward multi-user settings can be seen, in retrospect, relatively straightforward. Enablers for this widened MIMO scope include better characterization of the spatial domain of wireless channels and the increased computational processing capabilities of both base stations and mobile terminals.

Following the same path but maybe not so obvious is the evolution of MIMO to the network level, where virtual antenna arrays can be formed by the cooperation of multiple single or multi-antenna nodes (base stations, terminals, and relays). Another recent technique that originated in such a multi-user multi-antenna context is the Interference Alignment (IA) approach, in which different transmitter-receiver pairs cooperate in order to align the interference within the same subspace at each receiver. Although IA is not restricted to the spatial domain, it has found application in different MIMO scenarios, such as the MIMO interference channel present in multi-antenna wireless cellular networks.

This evolution of MIMO has renewed the interest on problems such as transmit and receive algorithms for signal coding, multiplexing, and parameter estimation

and corresponding computational complexities; spectrum reuse versus interference control; and backhaul capacity for inter-exchange of channel state information, among others.

Chapters in the second part present MIMO research from several standpoints, from optimizing the placement of antennas within small terminals to transceiver architectures to several precoding approaches.

**Chapter 7** is focused in propagation and antenna aspects of MIMO systems. While the understanding and modeling of MIMO propagation channels have already reached a rather mature level, there are still many aspects to understand when it comes to including antenna design and more realistic modeling aspects in MIMO applications. This is in particular the case on the user equipment side, mainly due to the fundamental restrictions originating from the size of handheld or portable such devices. This is the focus of this chapter where authors devise an automated optimization method based on a genetic algorithm for the optimal placement of antennas within a limited volume and considering such aspects as the spatial directional channel models and antenna coupling. The objective is to maximize ergodic capacity while considering antenna polarization and pattern diversities. Antenna selection aspects are also considered during the optimization process.

In **Chap. 8** authors present tensor-based approaches for MIMO-OFDM systems combining space-frequency and time domain processing allowing iterative joint blind channel estimation and symbol decoding. First, they consider the case of multi-layered space-frequency codes (MLSFC) with an extended linear precoding technique (LCP). Then, a space-time-frequency signaling technique that combines space-frequency modulation with a time-varying linear precoding is developed. They show that both systems satisfy PARAllel FACtor (PARAFAC)-based models, which allow a blind joint channel and symbol estimation using iterative or closed-form receiver algorithms. For this system, they propose two closed-form semi-blind receivers that exploit differently the multilinear structure of the received signal, which is formulated as a nested PARAFAC model. For the first system, alternating least squares (ALS) and least squares Khatri-Rao factorization based (LS-KRF) receivers are proposed and compared. For the later system, and aiming at reducing pilot overhead, they develop a simplified closed-form PARAFAC (S-CFP) receiver coupled with a pairing algorithm that yields an unambiguous estimation of the transmitted symbols without the need of a pilot frame. Simulation results are shown to evaluate the performance of the proposed transceivers in terms of bit-error-rate and channel estimation accuracy.

**Chapter 9** is focused again on the CoMP technique which is expected to increase cell-average and cell-edge throughputs in 4G and beyond wireless systems. Joint processing (JP) is a branch of CoMP systems which can enhance the systems' performance, mainly by employing precoding algorithms based on channel state information at the transmitter (CSIT). Many research efforts focus on reducing feedback and optimizing precoding with partial CSIT. In this chapter, the precoder design for multi-user (MU) MIMO CoMP systems is discussed. First, some initial concepts are presented, such as the MIMO channel and some classical precoding techniques found in literature. Following, the availability of partial

channel knowledge at the transmitter is studied in order to design the precoder. Since the wireless channel is random and time-varying, it is difficult and often expensive to obtain perfect CSIT. Thus, considering partial CSIT is valuable for practical applications. In this context, two algorithms maximizing the first- and second-order approximations of the ergodic sum rate of an MU-MIMO CoMP system are presented. These algorithms consider, as partial CSIT, the channel mean and the spatial correlation among the antennas and show the potential of using statistical measurements of the channel for precoder design, instead of using full CSIT. The proposed algorithms are computationally simple, highly reduce feedback overheads, and have fast convergence. Simulation results show that the proposed algorithms are near-optimal compared to the iterative water-filling (optimal full CSIT) case and present only moderate and negligible sum rate losses for low and high SNR values, respectively.

In [Chap. 10](#) authors describe several aspects of the interference alignment (IA) technique with a focus on the spatial domain. The basic idea of IA consists in precoding the transmitted signals such that they are aligned at the receiver where they constitute interference, while at the same time disjointed from the desired signal. This alignment limits the generated interference to a subspace at each receiver which in turn leaves the remaining dimensions free from any interference. The number of dimensions free from interference corresponds to the number of Degrees of Freedom (DoF), or the multiplexing gain of the system. Most of the literature on IA considers an idealized scenario with perfect Channel State Information (CSI) available at the transmitter. The authors describe some well-known IA algorithms from the literature, also with simulation results for this idealized scenario. After that they provide some insights into the impact of imperfections, where CSI error and transmit antenna correlation are included into the channel model. Furthermore, it is analyzed extensions to IA to also obtain diversity gains, in which IA is jointly employed with antenna selection and user selection. In both cases subspace-related metrics are used for the selection: the chordal distance and the Fubini-Study distance. After that IA is analyzed with a system level view, where it is also provided some insights into complexity issues. Finally, some conclusions and research directions are provided.

In [Chap. 11](#) authors observe that increasing capacity shortfall and coverage issues are aggravated by inefficient fixed spectrum management policies and obsolete network structures. Then, the development of new technologies and spectrum management policies is seen as a necessary step to take, in order to cope with these issues. A significant research effort has been made since the beginning of the century, to investigate the advantages brought by the introduction of flexible management paradigms and new hierarchical approaches to network planning. The resulting tiered network layout may improve the capacity of current networks in several ways. In this chapter, the authors focus on the challenging problem arising when the two tiers share the transmit band, to capitalize on the available spectrum and avoiding possible inefficiencies. In this case, the coexistence of the two tiers is not feasible, if suitable interference management techniques are not designed to mitigate/cancel the mutual interference generated by the active transmitters in the network.



The authors show that by intelligently designing the transmit waveform by means of a special precoder, the two-tier coexistence problem is solved for several different network configurations. Such configurations range from single to multi-user, the latter being also possible for centralized and distributed cases.

## **Final Words**

I hope this book can be useful for students and practitioners working in the evolution of wireless communication systems toward a truly ubiquitous and affordable mobile broadband service.

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