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Y. Thomas Hou, Yi Shi and Hanif D. Sherali
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Applied Optimization Methods for Wireless Networks

Written in a unique style, this book is a valuable resource for faculty, graduate students, and researchers in the communications and networking area whose work interfaces with optimization. It teaches you how various optimization methods can be applied to solve complex problems in wireless networks. Each chapter reviews a specific optimization method and then demonstrates how to apply the theory in practice through a detailed case study taken from state-of-the-art research.

You will learn various tips and step-by-step instructions for developing optimization models, reformulations, and transformations, particularly in the context of cross-layer optimization problems in wireless networks involving flow routing (network layer), scheduling (link layer), and power control (physical layer). Throughout, a combination of techniques from both Operations Research and Computer Science disciplines provides a holistic treatment of optimization methods and their applications.

Each chapter includes homework exercises, with Powerpoint slides available online for students and instructors, and a solutions manual for instructors only. To access the materials, please visit www.cambridge.org/hou.

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To our parents
and
Our wives Tingting, Meiyu, and Semeen

Contents

Preface

Reasons for writing the book In recent years, there has been a growing trend in applying optimization approaches to study wireless networks. Such an approach is usually necessary when the underlying goal is to pursue fundamental performance limits or theoretical results. This book is written to serve this need and is mainly targeted to graduate students who are conducting theoretical research in wireless networks using optimization-based approaches. This book will also serve as a very useful reference for researchers who wish to explore various optimization techniques as part of their research methodologies.

To prepare a graduate student in either electrical and computer engineering (ECE) or computer science (CS) to conduct fundamental research in wireless networks, an ideal roadmap would include a series of graduate courses in operations research (OR) and CS, in addition to traditional communications and networking courses in ECE. These OR and CS courses would include (among others) linear programming, nonlinear programming, integer programming from OR, and complexity theory and algorithm design and analysis from CS. Today, these courses are typically offered as core courses within the respective disciplines. Instructors in OR and CS departments typically have little knowledge of wireless networks and are unable to make a connection between the mathematical tools and techniques in these courses and problem-solving skills in wireless networks. ECE/CS students often find it difficult to see how these courses would benefit their research in wireless networks. Due to this gap between teaching scopes and learning expectations, we find that the learning experience of our ECE/CS students in these courses is passive (or "blind") at best, as they do not have a clear picture of how these courses will benefit their research.

One approach to bridge this gap is to offer a course that reviews a collection of mathematical tools from OR and CS (with a focus on optimization techniques) and shows how they can be used to address some challenging problems in wireless networks. This book is written for this purpose.

Each chapter in this book starts with a brief pointer to the underlying optimization technique (with references to tutorials or textbooks so that students can do an in-depth study in a formal course or on their own). The chapter then immediately delves into a detailed case study in wireless networks to which the technique will be applied. The focus in each chapter is to show how the underlying technique can be used to solve a challenging problem in wireless networks. To achieve this goal, we offer details on how to formulate a research problem into a formal optimization model, reformulate or transform it in order to improve mathematical tractability, and apply the underlying optimization technique (with necessary customizations that are specific to the underlying problem) to derive an optimal or near-optimal solution.

We have taught this course a number of times to ECE and CS graduate students at Virginia Tech, using chapters from this book. The response from the students has been overwhelmingly positive. In particular, we find that:

- For a graduate student (regardless of whether they have taken related OR or CS courses), this course opens a new landscape or perspective on what optimization techniques are available and how they can be applied to solve hard problems in wireless networks;
- For those graduate students who are currently taking or will take the aforementioned OR and CS courses, this course will help them better appreciate the mathematical techniques in such OR and CS courses. The student will also have a better purpose and a stronger motivation when she takes these core courses in her future study.

We recognize that a single-volume book cannot possibly cover all techniques exhaustively. Neither is it our intention to cover everything in one book. Nevertheless, we have organized this book into four parts, where every chapter focuses on a single technique. We hope this organization will serve our purpose of offering a first course on this important subject of *Applied Optimization Methods in Wireless Networks*. Our experience shows that after taking this course, students become substantially more mature mathematically. Most of them are able to consciously develop their learning paths into many areas in OR and CS not covered in this book in order to further expand their own mathematical capabilities. This is an important ingredient in their life-long learning and discovery.

Finally, the idea of having a book that offers a systematic coverage of optimization techniques and their applications in wireless networks is a very natural one. Unfortunately (and quite surprisingly), after a rather thorough survey of the market (when we presented our initial proposal to our publisher), we found that there were hardly any such books available. The closest book that we can find that by Dimitri Bertsekas: *Network Optimization: Continuous* *and Discrete Models* (Athena Scientific, 1998). But that book still falls short in showing students suitable case studies that are relevant to modern wireless networks.

On the other hand, most other books addressing network optimization follow a problem-oriented approach (vs. our method-oriented approach). They do not offer a systematic treatment of the underlying optimization techniques like we do in this book. To make this point clear, we quote the following text from the preface of the book *Combinatorial Optimization in Communication Networks,* edited by Maggie Xiaoyan Cheng, Yingshu Li, and Ding-Zhu Du (Springer, 2006), to explain why the problem-oriented approach was adopted by most authors:

> Two approaches were considered: optimization method oriented (starting from combinatorial optimization methods and finding appropriate network problems as examples) and network problem oriented (focusing on specific network problems and seeking appropriate combinatorial optimization methods to solve them). We finally decided to use the problem-oriented approach, mainly because of the availability of papers: most papers in the recent literature appear to address very specific network problems, and combinatorial optimization comes as a convenient problem solver.

Such a problem-oriented approach offers a convenient way of composing a book quickly (i.e., by assembling some research papers in the literature into an edited volume). But books based on such a problem-oriented approach, although useful as a reference book, do not teach graduate students optimization techniques in a systematic manner. This critical dearth in the existing literature was our main motivation for writing this book and bringing it to the community.

Acknowledgments

This book is the fruit of close collaboration among the three authors for more than ten years. We would like first to thank the former and current members of our research group. In particular, many thanks to: Jia (Kevin) Liu, whose work led to Chapter 3, Sushant Sharma, whose work led to Chapter 4, Liguang Xie, whose work led to Chapter 7, Dr. Shiwen Mao, whose work led to Chapter 11. We want to thank Huacheng Zeng, Liguang Xie, Xu Yuan, and Canming Jiang for their help in proofreading some of the chapters. They also contributed to the preparation and revision of the solution manual and Powerpoint Slides. Without their help, this book would not have reached its current shape. Some other former and current members of our group, whose names were not mentioned above but who contributed to this book in many other ways, include Sastry Kompella, Cunhao Gao, Tong Liu, Xiaojun Wang, Xiaolin Cheng, Dr. Rongbo Zhu, Dr. Lili Zhang, and Dr. Wangdong Qi.

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We want to thank Dr. Phil Meyler, Publishing Development Director of Cambridge University Press, who showed a genuine interest in the initial conception of this book and encouraged us to move forward for a book proposal. He has also been extremely patient with us when we requested a one year extension for the final delivery of our manuscript. We thank him for his trust, patience, and understanding, which allowed us to work on our schedule to bring this book to reality. Looking back, we feel really lucky that we chose the best publisher for this book. During the manuscript preparation stage, we worked with three different Assistant Editors of Cambridge University Press – Elizabeth Horne, Kirsten Bot, and Sarah Marsh. We thank all three of them, who worked diligently with us at each step along the way to make this book a polished product.

Tom Hou would like to thank Scott Midkiff, who recruited him to join the Electrical and Computer Engineering Department at Virginia Tech in 2002. Over the years, Scott has been a great colleague, a close friend, a resourceful mentor, and, most recently, a supportive department head. The environment that Scott and the department were able to offer has been instrumental to Tom's success in research and scholarship.

Finally, we would like to thank the National Science Foundation (NSF) and the Office of Naval Research (ONR), whose funding support of our research over the years led to this book.

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A highlight of this book is to include, in each chapter, a comprehensive presentation of a case study that demonstrates how the particular optimization method can be applied in solving a wireless networking problem. These case studies are based on a number of papers written by the authors. The following list acknowledges these publications and their respective journals and publishers on a chapter-by-chapter basis. Portions of these papers have been adapted with permission from the publishers as required. All rights are reserved as stipulated by the various copyright agreements.

Chapter 2
Y.T. Hou, Y. Shi, and H.D. Sherali, "Rate allocation and network lifetime problems for wireless sensor networks," *IEEE/ACM Transactions on Networking*, vol. 16, no. 2, pp. 321–334, April 2008. Copyright © 2008 by, and with kind permission from, IEEE.

Chapter 3
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Chapter 4
S. Sharma, Y. Shi, Y.T. Hou, and S. Kompella, "An optimal algorithm for relay node assignment in cooperative ad hoc networks," *IEEE/ACM Transactions on Networking*, vol. 19, issue 3, pp. 879–892, June 2011. Copyright © 2011 by, and with kind permission from, IEEE.

Chapter 5
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Chapter 6
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Chapter 7
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Chapter 11
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