

Cambridge University Press

978-1-107-06357-0 - Wireless Device-to-Device Communications and Networks

Lingyang Song, Dusit Niyato, Zhu Han and Ekram Hossain

Frontmatter

[More information](#)

## Wireless Device-to-Device Communications and Networks

Covering the fundamental theory together with the state of the art in research and development, this practical guide provides the techniques needed to design, analyze, and optimize device-to-device (D2D) communications in wireless networking.

With an ever-increasing demand for higher-data-rate wireless access, D2D communication is set to become a key feature supported by next-generation cellular networks. This book introduces D2D-based wireless communications from the physical-, MAC-, network-, and application-layer perspectives, providing all the key background information before moving on to discuss real-world applications as well as potential future developments. Key topics are discussed in detail, such as dynamic resource sharing (e.g., of spectrum and power) between cellular and ad-hoc D2D communications to accommodate larger volumes of traffic and provide better service to users. Readers will understand the practical challenges of resource management, optimization, security, standardization, and network topology, and learn how the design principles are applied in practice.

**Lingyang Song** is Professor of Wireless Communications at Peking University, China, where he has worked since 2009. His main research interests include cooperative and cognitive communications, physical-layer security, smart grids, and mobile social networks. He is the recipient of the 2012 IEEE Asia Pacific Young Researcher Award and the 2012 NSFC Outstanding Young Investigator Award.

**Dusit Niyato** is an Associate Professor in the School of Computer Engineering at the Nanyang Technological University (NTU), Singapore. He has won international awards including the IEEE Communications Society Asia Pacific Young Researcher Award and the 2011 IEEE Communications Society Fred W. Ellersick Prize. He works in various research areas, including cognitive radio, mobile cloud computing, machine-to-machine communications, performance analysis, and optimization of wireless networks.

**Zhu Han** is an Associate Professor in the Electrical and Computer Engineering Department at the University of Houston, Texas. He received an NSF CAREER award in 2010 and the IEEE Fred W. Ellersick Prize in 2011. He co-authored papers that won the best paper award at the IEEE International Conference on Communications 2009, the 7th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt09), and the IEEE Wireless Communication and Networking Conference, 2012. He is an IEEE Fellow.

**Ekram Hossain** is a Professor in the Department of Electrical and Computer Engineering at the University of Manitoba, Canada, where his current research interests include the design, analysis, and optimization of wireless/mobile communications networks, cognitive radio systems, and network economics. He has received several awards, including the 2010 and the 2014 University of Manitoba Merit Award (for Research and Scholarly Activities), the 2011 IEEE Communications Society Fred W. Ellersick Prize Paper Award, and the IEEE Wireless Communications and Networking Conference 2012 Best Paper Award.

Cambridge University Press  
978-1-107-06357-0 - Wireless Device-to-Device Communications and Networks  
Lingyang Song, Dusit Niyato, Zhu Han and Ekram Hossain  
Frontmatter  
[More information](#)

---

Cambridge University Press

978-1-107-06357-0 - Wireless Device-to-Device Communications and Networks

Lingyang Song, Dusit Niyato, Zhu Han and Ekram Hossain

Frontmatter

[More information](#)

# Wireless Device-to-Device Communications and Networks

LINGYANG SONG

Peking University, Beijing

DUSIT NIYATO

Nanyang Technological University, Singapore

ZHU HAN

University of Houston, Texas

EKRAM HOSSAIN

University of Manitoba, Canada



CAMBRIDGE  
UNIVERSITY PRESS

Cambridge University Press  
978-1-107-06357-0 - Wireless Device-to-Device Communications and Networks  
Lingyang Song, Dusit Niyato, Zhu Han and Ekram Hossain  
Frontmatter  
[More information](#)

CAMBRIDGE  
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom  
Cambridge University Press is part of the University of Cambridge.  
It furthers the University’s mission by disseminating knowledge in the pursuit of  
education, learning and research at the highest international levels of excellence.  
[www.cambridge.org](http://www.cambridge.org)  
Information on this title: [www.cambridge.org/9781107063570](http://www.cambridge.org/9781107063570)

© Cambridge University Press 2015  
This publication is in copyright. Subject to statutory exception  
and to the provisions of relevant collective licensing agreements,  
no reproduction of any part may take place without the written  
permission of Cambridge University Press.

First published 2015  
Printed in the United Kingdom by TJ International Ltd., Padstow, Cornwall  
*A catalogue record for this publication is available from the British Library*

*Library of Congress Cataloguing in Publication data*  
Song, Lingyang.  
Wireless device-to-device communications and networks / Lingyang Song,  
Peking University, Beijing, Dusit Niyato, Nanyang Technical University, Singapore,  
Zhu Han, University of Houston, Texas, Ekram Hossain, University of Manitoba, Canada.  
pages   cm  
Includes bibliographical references and index.  
ISBN 978-1-107-06357-0  
1. Machine-to-machine communications.   I. Title.  
TK5105.67.S66   2015  
004.6’1–dc23

2014035056

ISBN 978-1-107-06357-0 Hardback  
Cambridge University Press has no responsibility for the persistence or accuracy  
of URLs for external or third-party internet websites referred to in this publication,  
and does not guarantee that any content on such websites is, or will remain,  
accurate or appropriate.

Cambridge University Press  
978-1-107-06357-0 - Wireless Device-to-Device Communications and Networks  
Lingyang Song, Dusit Niyato, Zhu Han and Ekram Hossain  
Frontmatter  
[More information](#)

---

**Dedications**  
**To my family, Zhu Han**  
**To Suprova Hossain and Nirvoy Lalon, Ekram Hossain**

Cambridge University Press  
978-1-107-06357-0 - Wireless Device-to-Device Communications and Networks  
Lingyang Song, Dusit Niyato, Zhu Han and Ekram Hossain  
Frontmatter  
[More information](#)

---

Contents

<i>Preface</i>	<i>page xv</i>
<b>Part I Introduction</b>	<b>1</b>
<b>1 Basics of D2D communications</b>	<b>3</b>
1.1 Overview of D2D communications	3
1.2 Key technologies for D2D communications	5
1.2.1 Configuration of D2D communications	5
1.2.2 Device synchronization and discovery	5
1.2.3 Mode selection	6
1.2.4 Spectrum sharing and resource management	6
1.2.5 Power control	7
1.2.6 Uplink and downlink transmission with MIMO	7
1.3 Device-to-device local area networks	8
1.4 D2D direct: a simulation scenario	9
1.5 Issues and challenges in D2D communications	15
1.6 Chapter summary	15
<b>Part II Techniques for modeling and analysis of D2D communications</b>	<b>17</b>
<b>2 Optimization</b>	<b>19</b>
2.1 Constrained optimization	19
2.1.1 Basic definition	19
2.1.2 The Lagrangian method	22
2.1.3 Optimality	23
2.1.4 The primal–dual algorithm	26
2.2 Linear programming and the simplex algorithm	27
2.3 Convex programming	30
2.3.1 Quadratic, geometric, and semidefinite programming	30
2.3.2 The gradient method, the Newton method, and their variations	32
2.3.3 The alternating-direction method-of-multipliers algorithm	35
2.4 Nonlinear programming	36

2.4.1	The barrier/interior-point method	37
2.4.2	The Monte Carlo method	38
2.4.3	Simulated annealing	39
2.4.4	Genetic algorithms	40
2.4.5	Swarm intelligence	40
2.5	Integer programming	41
2.5.1	General formulation	42
2.5.2	The knapsack problem	45
2.5.3	Relaxation and decomposition	48
2.5.4	An enumerative technique: the branch-and-bound approach	49
2.5.5	Cutting planes	52
2.5.6	Benders' decomposition	54
2.6	Dynamic programming and Markov decision processes	55
2.6.1	A general definition of dynamic programming	55
2.6.2	Markov decision processes	57
2.7	Stochastic programming	59
2.7.1	Problem definition	59
2.7.2	Chance constraint, sampling method, and variation	61
2.7.3	Recourse	61
2.8	Sparse optimization	63
2.8.1	Sparse-optimization models	63
2.8.2	A list of sparse-optimization algorithms	65
3	<b>Game theory</b>	67
3.1	Basics of game theory	67
3.2	The noncooperative static game	69
3.2.1	The normal form of a static game	70
3.2.2	Nash equilibrium, Pareto optimality, and mixed strategy	71
3.2.3	Social optimum: price of anarchy and referee	73
3.3	The dynamic game	74
3.3.1	Sequential games, and games in extensive form	74
3.3.2	Repeated games	76
3.3.3	Stochastic games	78
3.3.4	Differential control/games	79
3.4	Cooperative game theory – bargaining games	83
3.4.1	Bargaining solutions	84
3.4.2	Applications of bargaining games	86
3.5	Cooperative game theory – coalitional games	88
3.5.1	Characteristic function and core	88
3.5.2	Fairness	89
3.5.3	The merge/split algorithm	90
3.6	Matching theory	92
3.6.1	One-to-one matching	92
3.6.2	Many-to-one matching	93



	Contents	ix
3.6.3	Many-to-many matching	96
3.7	Auction theory	97
3.7.1	Auction basics	97
3.7.2	Mechanism design	101
3.7.3	VCG auctions	106
3.7.4	Share auctions	107
3.7.5	Double auctions	109
3.8	Contract theory	110
3.8.1	Information and incentives	111
3.8.2	Bilateral contracting	112
3.9	Bayesian games with imperfect information	113
3.9.1	Bayesian games in normal form	114
3.9.2	Bayesian games in extensive games	116
3.10	Other special types of games	118
3.10.1	Zero-sum games	118
3.10.2	Potential games	120
3.10.3	Super-modular games	121
3.10.4	Correlated equilibrium	122
3.10.5	Satisfaction equilibrium	124
<b>Part III</b>	<b>Resource management, cross-layer design, and security for D2D communications</b>	<b>127</b>
<b>4</b>	<b>Mode selection and resource allocation for D2D communications underlying cellular networks</b>	<b>129</b>
4.1	Introduction	129
4.2	LTE-A networks and D2D communications	131
4.2.1	An overview of LTE-A networks	131
4.2.2	D2D communications in LTE-A networks	132
4.3	Research issues and challenges for D2D communications underlying LTE-A networks	134
4.3.1	Mode selection	134
4.3.2	Transmission scheduling	134
4.3.3	Power control and power efficiency	135
4.3.4	Distributed resource allocation	135
4.3.5	Coexistence with heterogeneous networks	135
4.3.6	Cooperative communications	136
4.3.7	Network coding	136
4.3.8	Interference cancellation and advanced receivers	136
4.3.9	Multiple-antenna technology and multiple-input and multiple-output (MIMO) schemes	137
4.3.10	Mobility management and handoff	137
4.3.11	Robust resource allocation	138

x	<b>Contents</b>	
4.4	The state of the art of D2D communications underlying LTE/LTE-A networks	138
4.4.1	Mode selection	138
4.4.2	Power control	139
4.4.3	Distributed resource allocation	139
4.4.4	Interference cancellation	140
4.4.5	MIMO-based D2D communications	140
4.5	Mode selection based on a coalitional game model	140
4.5.1	The system model and assumptions	140
4.5.2	The coalitional game model	141
4.5.3	Strategies of the D2D links	143
4.5.4	Coalition formation	145
4.5.5	Numerical results	147
4.6	Joint mode selection and resource allocation for D2D communications	148
4.6.1	The network model	149
4.6.2	Feasible access patterns	149
4.6.3	Constraints of feasible access patterns	150
4.6.4	Column generation for joint mode selection and resource allocation	151
4.7	Numerical results	157
4.8	Chapter summary	158
5	<b>Interference coordination for D2D communications</b>	160
5.1	Interference analysis	160
5.2	Interference avoidance	160
5.3	Power control	161
5.3.1	Network-controlled power control	161
5.3.2	Power control using MIMO	164
5.4	Chapter summary	172
6	<b>Subchannel allocation and time-domain scheduling for D2D communications</b>	173
6.1	Subchannel allocation	173
6.1.1	Centralized (operator-managed) subchannel allocation	173
6.2	Time-domain scheduling	190
6.2.1	Stackelberg game-based scheduling in the time domain	190
6.2.2	Joint frequency–time-domain scheduling	196
6.3	Capacity offloading through D2D local area networks	201
6.4	Chapter summary	203
7	<b>Cross-layer design for device-to-device communication</b>	205
7.1	An overview of cross-layer design	205
7.1.1	Definitions and approaches	206
7.1.2	The cross-layer coordination model	208

	Contents	xi
7.1.3	Cross-layer implementation	211
7.1.4	Cross-layer design considerations and challenges	212
7.2	Cross-layer optimization	213
7.2.1	Opportunistic scheduling	213
7.2.2	OFDMA wireless networks	215
7.2.3	Cross-layer congestion control and scheduling	219
7.3	Cross-layer design for vehicular ad-hoc networks	222
7.3.1	Physical and MAC layers	222
7.3.2	Physical and network layers	223
7.3.3	Network and MAC layers	224
7.3.4	Transport, network, and MAC layers	226
7.4	Cross-layer design in D2D communication	227
7.4.1	Information correlation routing	227
7.4.2	Cross-layer routing in wireless sensor networks	230
7.4.3	Cross-layer distributed scheduling for peer-to-peer video streaming	232
7.5	Chapter summary	235
<b>8</b>	<b>Security for D2D communications</b>	237
8.1	Location security	237
8.1.1	Problem overview	237
8.1.2	Literature	238
8.2	Data-transmission security	240
8.2.1	The system model and problem formulation	241
8.2.2	Graph-based resource allocation	243
8.2.3	Simulation results	247
8.3	Chapter summary	251
	<b>Part IV Applications of D2D communications</b>	253
<b>9</b>	<b>Vehicular ad-hoc networks</b>	255
9.1	Introduction	255
9.2	Vehicular networks	256
9.2.1	ITS applications	256
9.2.2	Vehicular network architecture and IEEE 802.11p	257
9.2.3	VANETs	262
9.3	D2D communications in vehicular networks	268
9.3.1	An intracluster device-to-device retransmission algorithm	268
9.3.2	BitTorrent-based wireless access in vehicular networks	273
9.3.3	Problem formulation	275
9.3.4	Data transfer from roadside units	278
9.3.5	Optimal channel access in vehicular networks	279
9.4	Chapter summary	290

xii	<b>Contents</b>	
<b>10</b>	<b>Mobile social networks</b>	294
10.1	Introduction	294
10.2	An overview of mobile social networks	295
10.2.1	Types and components of mobile social networks	295
10.2.2	Social-network analysis	297
10.3	Community detection	301
10.3.1	Dynamic community detection	302
10.3.2	Mobility-based distributed community detection	305
10.3.3	Influence-based community detection	307
10.4	Social-aware data routing and dissemination	309
10.4.1	A routing protocol based on betweenness and similarity	310
10.4.2	A routing protocol based on community and degree centrality	311
10.4.3	Friendship-based routing	313
10.4.4	Geocommunity-based routing	315
10.5	Cooperative content delivery in mobile social networks	317
10.5.1	Mobile social networks with content providers and a network operator	319
10.5.2	The Markov chain model of content forwarding among mobile nodes	321
10.5.3	Performance measures	323
10.5.4	Controlled coalitional-game formulation	324
10.5.5	Performance evaluation	331
10.6	Chapter summary	334
<b>11</b>	<b>Machine-to-machine (M2M) communications</b>	338
11.1	Introduction	338
11.2	Machine-to-machine (M2M) communications	338
11.2.1	Machine-type communications in LTE-A networks	339
11.2.2	An overview of the random-access procedure	340
11.3	RACH overload control mechanisms	344
11.3.1	Grouping of MTC devices	346
11.3.2	An access-class-barring-based scheme	347
11.3.3	Separation of random-access preambles	349
11.3.4	Dynamic allocation of random-access resources	349
11.3.5	A qualitative comparison of random-access overload control approaches	351
11.4	Performance modeling of the random-access channel (RACH)	353
11.4.1	The network model	353
11.4.2	MTC user equipment and its packet transmission	354
11.4.3	Coexistence of MTC and H2H user equipments	354
11.4.4	A queueing model	355
11.4.5	The state space and transition matrix for queueing at each MTC UE	355

	Contents	xiii
11.4.6	Queueing performance measures at an MTC user equipments	360
11.4.7	An iterative algorithm	362
11.4.8	Numerical results	363
11.5	Chapter summary	367
<b>Part V</b>	<b>Standardization of D2D communications</b>	<b>369</b>
<b>12</b>	<b>Network-controlled D2D over LTE/LTE-A</b>	<b>371</b>
12.1	D2D communications in LTE-A networks	371
12.2	Requirements and working assumptions	372
12.2.1	Operational requirements	372
12.2.2	Charging requirements	373
12.2.3	Security requirements	373
12.3	Key working scenarios	374
12.4	LTE-A architecture enhancements to support proximity-based services (ProSe)	376
12.5	Performance evaluation	379
12.6	Application in proximity services	381
12.6.1	Proximity discovery over E-UTRA	382
12.6.2	Proximity communications over E-UTRA	383
12.6.3	Public-safety services	385
12.7	Chapter summary	388
	<i>References</i>	390
	<i>Index</i>	412

Cambridge University Press  
978-1-107-06357-0 - Wireless Device-to-Device Communications and Networks  
Lingyang Song, Dusit Niyato, Zhu Han and Ekram Hossain  
Frontmatter  
[More information](#)

---

## Preface

Now that more and more new mobile multimedia-rich services are becoming available to mobile users, there is an ever-increasing demand for higher-data-rate wireless access. Therefore, new wireless technologies such as Long Term Evolution Advanced (LTE-A) and WiMAX have been introduced, which are capable of providing high-speed, large-capacity, and guaranteed-quality-of-service (QoS) mobile services. Apart from the new technologies, new techniques such as small-cell networks and heterogeneous networks (HetNets) have also been developed, which are able to improve network capacity by reducing cell size and effectively controlling the interference. However, all these attempts still rely on a centralized network topology, which entails mobile devices communicating with a base station or access point. Such a centralized network topology is inherently limited by the capabilities of the base station and access point, which could be congested due to the presence of a large number of communicating devices. Also, the base station and access point might not have complete information about transmission parameters among devices, which is required in order to achieve the optimal network performance. To mitigate this problem, the concept of device-to-device (D2D) communications has been introduced to allow local peer-to-peer transmission among mobile devices offloading traffic from the base station and access point. Also, it is crucial to increase the wireless network capacity to accommodate the bandwidth-consuming mobile applications and services. Device-to-device communications is a promising concept to improve user experience and resource utilization in cellular networks, operating in both licensed and unlicensed spectrum bands.

The D2D communications can underlay or overlay a cellular network, using the same resources to improve the system throughput. Specifically, besides cellular operation, where user equipment (UE) is served by the network via the evolved NodeBs (eNBs) in the LTE architecture, UEs may communicate with each other directly over the D2D links. The UE in D2D connections still has to be loosely controlled by the eNBs in a network-controlled manner, thus continuing cellular operation. The eNBs can control the resources used for the cellular and D2D links. The eNBs can also set constraints on the transmission parameters (e.g., transmit power and communication duration) of D2D transmitters to limit the interference experienced at the cellular receivers.

Numerous researchers and wireless engineers have postulated that D2D communications will become a key feature supported by next-generation cellular networks. D2D communication has the following advantages. One can

- extend coverage,
- offload in cellular networks,
- improve energy efficiency,
- increase throughput and spectrum efficiency, and
- create new services such as social/vehicular ad-hoc networking services, etc.

The design, analysis, and optimization of D2D communications and networking require multidisciplinary knowledge, namely knowledge of wireless communications and networking, signal processing, artificial intelligence (e.g., for learning), decision theory, optimization, and economic theory. Therefore, a book containing the basic concepts/theories for addressing the research advances that enable D2D communications in cellular networks as well as the state of the art of research and development and related information will be very useful for researchers and engineers.

This book summarizes the state of the art of research on D2D communications coexisting with cellular networks from physical-, MAC-, network-, and application-layer perspectives. The key features of this book are as follows:

- a unified view of D2D communications and networking,
- a comprehensive review of the state-of-the-art research and key technologies for D2D communications networks,
- coverage of a wide range of techniques for design, analysis, optimization, and applications of D2D communications networks,
- outlining the key research issues related to D2D communications and networking, and
- Standardization activities on D2D communications.

This book is divided into five parts: Part I (Introduction), Part II (Techniques for modeling and analysis of D2D communications), Part III (Resource management, cross-layer design, and security for D2D communications), Part IV (Applications of D2D communications), and Part V (Standardization of D2D communications). Part I contains Chapter 1, which provides an introduction to D2D communications. The topics include the different methods for configuration or access, device synchronization and discovery, spectrum sharing and resource management, power control, and D2D local area networks. Also, a simulation scenario for D2D communications is described.

In Part II, which consists of Chapters 2 and 3, different techniques that can be applied to the problem of design, analysis, and optimization of D2D communications are introduced. In particular, the optimization techniques which are useful to obtain the optimal resource-management schemes for D2D communications are discussed in Chapter 2. Major variations of optimization techniques (e.g., unconstrained and constrained optimization, nonlinear optimization, combinatorial optimization) are presented. Also, stochastic optimization based on dynamic programming, the Markov decision process (MDP), and stochastic programming are discussed. In Chapter 3, the



game-theory techniques are discussed. The basics of different game-theoretic models, namely noncooperative game, repeated game, cooperative game (i.e., bargaining game, coalition game), and evolutionary game models as well as the basics of matching theory and auction theory are presented.

Part III, which consists of Chapters 4–8, deals with radio-resource management, cross-layer design, and security for D2D communications. Chapter 4 presents a framework for mode selection for D2D communications that is based on a coalitional game. Also, a model for joint mode selection and resource allocation is developed. Chapter 5 focuses on interference coordination for D2D communications. A network-assisted power control scheme that considers both interference reduction and power saving is proposed. Chapter 6 introduces methods for subcarrier allocation and time-domain scheduling for D2D communications. Chapter 7 provides an overview of cross-layer design concepts and discusses the challenges in adopting these concepts to develop new protocols. Several examples of cross-layer design are also illustrated. Chapter 8 studies the security issues that arise during the neighbor-discovery phase and data-transmission phase of D2D communications. The concept of physical-layer security is discussed as a method for secure D2D communications.

Part IV, which consists of Chapters 9–11, deals with several application scenarios of D2D communications. In particular, applications of D2D communications in the context of vehicular ad-hoc networks (VANETs) are discussed in Chapter 9. In Chapter 10, application of D2D communications for cooperative content delivery in mobile social networks is discussed. Chapter 11 deals with the paradigm of machine-to-machine (M2M) communications, noting that D2D communications can be considered as a type of M2M communication when the D2D users are in close mutual proximity.

Part V consists of Chapter 12, which introduces the motivation, requirements, and application scenarios for using D2D communications over LTE/LTE-A networks. Also, this chapter introduces the key methods and system parameters to evaluate the performance of D2D communications (at both link and system levels) by computer simulations.

Since each chapter in this book is quite independent, skipping any chapter in this book will not affect your ability to follow the rest of the book.

The authors would like to acknowledge the research support from the National Science Foundation (NSF), USA, and the Natural Sciences and Engineering Research Council of Canada (NSERC) during the course of this book project.

**Lingyang Song**  
**Dusit Niyato**  
**Zhu Han**  
**Ekram Hossain**