



EDITED BY
VINCENT W. S. WONG
ROBERT SCHOBER
DERRICK WING KWAN NG
LI-CHUN WANG

KEY
TECHNOLOGIES
FOR 5G
WIRELESS
SYSTEMS

Gain a detailed understanding of the protocols, network architectures, and techniques being considered for 5G wireless networks with this authoritative guide to the state of the art.

- Get up to speed with key topics such as cloud radio access networks, mobile edge computing, full duplexing, massive MIMO, mmWave, NOMA, Internet of Things, M2M communications, D2D communications, mobile data offloading, interference mitigation techniques, radio resource management, visible light communication, and smart data pricing.
- Learn from leading researchers in academia and industry about the most recent theoretical developments in the field.
- Discover how each potential technology can increase the capacity, spectral efficiency, and energy efficiency of wireless systems.

Providing the most comprehensive overview of 5G technologies to date, this is an essential reference for researchers, practicing engineers, and graduate students working in wireless communications and networking.

Vincent W. S. Wong is a Professor in the Department of Electrical and Computer Engineering at the University of British Columbia, Canada, and a Fellow of the IEEE.

Robert Schober is an Alexander von Humboldt Professor and the Chair for Digital Communication at the Friedrich-Alexander University of Erlangen-Nuremberg, Germany. He is a Fellow of the IEEE, the Canadian Academy of Engineering, and the Engineering Institute of Canada.

Derrick Wing Kwan Ng is a Lecturer in the School of Electrical Engineering and Telecommunications at the University of New South Wales, Australia. He is an Associate Editor of *IEEE Communications Letters*.

Li-Chun Wang is a Professor in the Department of Electrical and Computer Engineering at National Chiao Tung University, Taiwan, and a Fellow of the IEEE.

"A valuable and comprehensive reference, providing insights for various essential aspects of the emerging 5G technologies."

Weihua Zhuang,
University of Waterloo

"The first comprehensive book I've seen on all the different candidate 5G cellular technologies."

Jeffrey Andrews,
University of Texas at Austin

"A comprehensive and in-depth book on the advanced research of key technologies for 5G."

Wen Tong, Huawei

WONG,
SCHOBER, NG,
AND WANG

KEY TECHNOLOGIES FOR
5G WIRELESS SYSTEMS

CAMBRIDGE

Key Technologies for 5G Wireless Systems

VINCENT W. S. WONG

University of British Columbia

ROBERT SCHÖBER

University of Erlangen-Nuremberg

DERRICK WING KWAN NG

University of New South Wales

LI-CHUN WANG

National Chiao-Tung University



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

4843/24, 2nd Floor, Ansari Road, Daryaganj, Delhi – 110002, India

79 Anson Road, #06-04/06, Singapore 079906

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

Information on this title: www.cambridge.org/9781107172418

10.1017/9781316771655

© Cambridge University Press 2017

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 2017

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

Names: Wong, Vincent W. S., editor.

Title: Key technologies for 5G wireless systems / edited by Vincent W.S. Wong [and 3 others].

Other titles: Key technologies for five G wireless systems

Description: Cambridge ; New York, NY : Cambridge University Press, 2017.

Identifiers: LCCN 2016045220 | ISBN 9781107172418 (hardback)

Subjects: LCSH: Wireless communication systems. | Machine-to-machine communications. | Internet of things.

Classification: LCC TK5103.2.K49 2017 | DDC 621.3845/6–dc23

LC record available at <https://lcn.loc.gov/2016045220>

ISBN 978-1-107-17241-8 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.

Key Technologies for 5G Wireless Systems

Gain a detailed understanding of the protocols, network architectures, and techniques being considered for 5G wireless networks with this authoritative guide to the state of the art.

- Get up to speed with key topics such as cloud radio access networks, mobile edge computing, full duplexing, massive MIMO, mmWave, NOMA, the Internet of Things, M2M communications, D2D communications, mobile data offloading, interference mitigation techniques, radio resource management, visible light communication, and smart data pricing.
- Learn from leading researchers in academia and industry about the most recent theoretical developments in the field.
- Discover how each potential technology can increase the capacity, spectral efficiency, and energy efficiency of wireless systems.

Providing the most comprehensive overview of 5G technologies to date, this is an essential reference for researchers, practicing engineers, and graduate students working in wireless communications and networking.

Vincent W. S. Wong is a Professor in the Department of Electrical and Computer Engineering at the University of British Columbia, Canada, and a Fellow of the IEEE.

Robert Schober is an Alexander von Humboldt Professor and the Chair for Digital Communication at the Friedrich-Alexander University of Erlangen-Nuremberg, Germany. He is a Fellow of the IEEE, the Canadian Academy of Engineering, and the Engineering Institute of Canada.

Derrick Wing Kwan Ng is a Lecturer in the School of Electrical Engineering and Telecommunications at the University of New South Wales, Australia. He is an Associate Editor of *IEEE Communications Letters*.

Li-Chun Wang is a Professor in the Department of Electrical and Computer Engineering at National Chiao Tung University, Taiwan, and a Fellow of the IEEE.

List of Contributors

Fumiyuki Adachi

Tohoku University, Japan

Lin Cai

University of Victoria, Canada

Lin X. Cai

Illinois Institute of Technology, USA

Giuseppe Caire

Technical University of Berlin, Germany

Miguel R. Castellanos

Purdue University, USA

Cheng Chen

The University of Edinburgh, United Kingdom

Yami Chen

China Mobile Research Institute

Man Hon Cheung

The Chinese University of Hong Kong, Hong Kong

Mung Chiang

Princeton University, USA

Martin Danneberg

Technische Universität Dresden, Germany

Zhiguo Ding

Lancaster University, United Kingdom

Lingjie Duan

Singapore University of Technology and Design, Singapore

Gerhard Fettweis

Technische Universität Dresden, Germany

Yunan Gu

University of Houston, USA

Sangtae Ha

University of Colorado at Boulder, USA

Harald Haas

The University of Edinburgh, United Kingdom

Wei Han

Hong Kong University of Science and Technology, Hong Kong

Zhu Han

University of Houston, USA

Hsiang Hsu

National Taiwan University, Taiwan

Jianwei Huang

The Chinese University of Hong Kong, Hong Kong

Jinri Huang

China Mobile Research Institute, China

Xueyan Huang

China Mobile Research Institute, China

Chih-Lin I

China Mobile Research Institute, China

Shi Jin

Southeast University, China

Carlee Joe-Wong

Carnegie Mellon University, USA

George K. Karagiannidis

Aristotle University of Thessaloniki, Greece

Vincent Lau

Hong Kong University of Science and Technology, Hong Kong

Jemin Lee

Daegu Gyeongbuk Institute of Science and Technology, Korea

Ben Liang

The University of Toronto, Canada

Wei Liang

Lancaster University, United Kingdom

Shao-Yu Lien

National Formosa University, Taiwan

An Liu

Hong Kong University of Science and Technology, Hong Kong

Liang Liu

University of Toronto, Canada

David J. Love

Purdue University, USA

Germán Corrales Madueño

Aalborg University, Denmark

Jon W. Mark

University of Waterloo, Canada

Michail Matthaiou

Queen's University Belfast, United Kingdom

Maximilian Matthe

Technische Universität Dresden, Germany

Abolfazl Mehbodniya

Tohoku University, Japan

Derrick Wing Kwan Ng

The University of New South Wales, Australia

Koralia N. Pappi

Aristotle University of Thessaloniki, Greece

H. Vincent Poor

Princeton University, USA

Petar Popovski

Aalborg University, Denmark

Nuno Pratas

Aalborg University, Denmark

Tony Q.S. Quek

Singapore University of Technology and Design, Singapore

Rongwei Ren

China Mobile Research Institute, China

Taneli Riihonen

Aalto University, Finland

Robert Schober

Friedrich-Alexander-University Erlangen-Nürnberg, Germany

Soumya Sen

University of Minnesota, USA

Xuemin Shen

University of Waterloo, Canada

Osvaldo Simeone

New Jersey Institute of Technology, USA

Jiho Song

Purdue University, USA

Lingyang Song

Peking University, China

Čedomir Stefanović

Aalborg University, Denmark

Chee Wei Tan

The City University of Hong Kong, Hong Kong

Li-Chun Wang

National Chiao-Tung University, Taiwan

Risto Wichman

Aalto University, Finland

Vincent W. S. Wong

The University of British Columbia, Canada

Jie Xu

Guangdong University of Technology, China, and Singapore University of Technology and Design, Singapore

Howard H. Yang

Singapore University of Technology and Design, Singapore

Haoran Yu

The Chinese University of Hong Kong, Hong Kong

Wei Yu

University of Toronto, Canada

Dan Zhang

Technische Universität Dresden, Germany

Rui Zhang

National University of Singapore, and Institute for Infocomm Research, A*STAR, Singapore

Liang Zheng

Princeton University, USA

Preface

Mobile devices (e.g., smartphones and tablets) have become a commodity in our daily lives. While these devices already support many different types of applications and services, there will be a continual increase in demand for mobile data traffic due to web applications, real-time and streaming video traffic, and applications related to the Internet of Things (IoT). The future fifth generation (5G) wireless cellular systems aim not only to provide a higher aggregate throughput, but also to support applications which have stringent quality of service (QoS) requirements, such as seamless mobility, ultra-low latency (e.g., Tactile Internet), and high reliability (e.g., vehicular communications). Further improvements in spectrum efficiency, energy efficiency, and cost per bit are also important. In order to meet these demands, fundamental changes to the network architecture and all layers of the protocol stack compared with fourth generation (4G) wireless systems are needed.

This book aims to provide a comprehensive treatment of the ongoing research into and state-of-the-art techniques for addressing the challenges arising from the design of 5G wireless systems. Written by leading experts on the subject, this book includes 22 chapters, which cover various aspects of 5G systems, including network architecture design, physical layer techniques, algorithms, and network protocol design. Chapter 1 serves as an introductory chapter and provides an overview of the different key technologies related to 5G systems. Each of the other chapters tackles one specific challenge for system design. The chapters can be read independently.

This book will be of interest to a readership from the communications, signal processing, and networking communities. The primary audience for this book is researchers and engineers who are interested in studying advanced communication and networking techniques, as well as state-of-the-art research on 5G systems. This book will serve as a resource for self-study and as a reference book for researchers and engineers involved in the design of wireless communication systems. It is also suitable for graduate students who are interested in 5G systems and the related communication and networking issues. It may serve as a reference book for graduate-level courses for students in electrical engineering, communication engineering, and networking.

We would like to thank all the authors for their outstanding contributions and their timeliness in completing their respective chapters. In addition, we would like to thank Elizabeth Horne and Heather Brolly from Cambridge University Press for their valuable advice throughout the production of this book. Last but not least, we would like to thank

the Natural Sciences and Engineering Research Council of Canada (NSERC) for its financial support.

Vincent W. S. Wong
Robert Schober
Derrick Wing Kwan Ng
Li-Chun Wang

Contents

<i>List of Contributors</i>	<i>page</i> xvi
<i>Preface</i>	xxi

1	Overview of New Technologies for 5G Systems	1
	Vincent W. S. Wong, Robert Schober, Derrick Wing Kwan Ng, and Li-Chun Wang	
1.1	Introduction	1
1.2	Cloud Radio Access Networks	3
1.3	Cloud Computing and Fog Computing	4
1.4	Non-orthogonal Multiple Access	4
1.5	Flexible Physical Layer Design	6
1.6	Massive MIMO	7
1.7	Full-Duplex Communications	9
1.8	Millimeter Wave	12
1.9	Mobile Data Offloading, LTE-Unlicensed, and Smart Data Pricing	13
1.10	IoT, M2M, and D2D	14
1.11	Radio Resource Management, Interference Mitigation, and Caching	16
1.12	Energy Harvesting Communications	17
1.13	Visible Light Communication	19
	Acknowledgments	20
	References	20

Part I	Communication Network Architectures for 5G Systems	25
---------------	---	-----------

2	Cloud Radio Access Networks for 5G Systems	27
	Chih-Lin I, Jinri Huang, Xueyan Huang, Rongwei Ren, and Yami Chen	
2.1	Rethinking the Fundamentals for 5G Systems	27
2.2	User-Centric Networks	29
2.3	C-RAN Basics	29
2.3.1	C-RAN Challenges Toward 5G	30
2.4	Next Generation Fronthaul Interface (NGFI): The FH Solution for 5G C-RAN	31
2.4.1	Proof-of-Concept Development of NGFI	33

2.5	Proof-of-Concept Verification of Virtualized C-RAN	35
2.5.1	Data Packets	37
2.5.2	Test Procedure	38
2.5.3	Test Results	39
2.6	Rethinking the Protocol Stack for C-RAN	40
2.6.1	Motivation	40
2.6.2	Multilevel Centralized and Distributed Protocol Stack	40
2.7	Conclusion	45
	Acknowledgments	46
	References	46
3	Fronthaul-Aware Design for Cloud Radio Access Networks	48
	Liang Liu, Wei Yu, and Osvaldo Simeone	
3.1	Introduction	48
3.2	Fronthaul-Aware Cooperative Transmission and Reception	49
3.2.1	Uplink	51
3.2.2	Downlink	57
3.3	Fronthaul-Aware Data Link and Physical Layers	61
3.3.1	Uplink	63
3.3.2	Downlink	69
3.4	Conclusion	73
	Acknowledgments	74
	References	74
4	Mobile Edge Computing	76
	Ben Liang	
4.1	Introduction	76
4.2	Mobile Edge Computing	77
4.3	Reference Architecture	79
4.4	Benefits and Application Scenarios	80
4.4.1	User-Oriented Use Cases	80
4.4.2	Operator-Oriented Use Cases	81
4.5	Research Challenges	82
4.5.1	Computation Offloading	82
4.5.2	Communication Access to Computational Resources	83
4.5.3	Multi-resource Scheduling	84
4.5.4	Mobility Management	85
4.5.5	Resource Allocation and Pricing	85
4.5.6	Network Functions Virtualization	86
4.5.7	Security and Privacy	86
4.5.8	Integration with Emerging Technologies	87
4.6	Conclusion	88
	References	88

5	Decentralized Radio Resource Management for Dense Heterogeneous Wireless Networks	92
	Abolfazl Mehdodniya and Fumiyuki Adachi	
5.1	Introduction	92
5.2	System Model	93
5.2.1	SINR Expression	95
5.2.2	Load and Cost Function Expressions	95
5.3	Joint BSCSA/UECSA ON/OFF Switching Scheme	96
5.3.1	Strategy Selection and Beacon Transmission	96
5.3.2	UE Association	96
5.3.3	Proposed Channel Segregation Algorithms	98
5.3.4	Mixed-Strategy Update	100
5.4	Computer Simulation	101
5.5	Conclusion	104
	Acknowledgments	104
	References	105
	Part II Physical Layer Communication Techniques	107
6	Non-Orthogonal Multiple Access (NOMA) for 5G Systems	109
	Wei Liang, Zhiguo Ding, and H. Vincent Poor	
6.1	Introduction	110
6.2	NOMA in Single-Input Single-Output (SISO) Systems	112
6.2.1	The Basics of NOMA	112
6.2.2	Impact of User Pairing on NOMA	113
6.2.3	Cognitive Radio Inspired NOMA	116
6.3	NOMA in MIMO Systems	120
6.3.1	System Model for MIMO-NOMA Schemes	121
6.3.2	Design of Precoding and Detection Matrices with Limited CSIT	123
6.3.3	Design of Precoding and Detection Matrices with Perfect CSIT	126
6.4	Summary and Future Directions	128
	References	130
7	Flexible Physical Layer Design	133
	Maximilian Matthé, Martin Danneberg, Dan Zhang, and Gerhard Fettweis	
7.1	Introduction	133
7.2	Generalized Frequency Division Multiplexing	135
7.3	Software-Defined Waveform	137
7.3.1	Time Domain Processing	138
7.3.2	Implementation Architecture	138
7.4	GFDM Receiver Design	141
7.4.1	Synchronization Unit	142
7.4.2	Channel Estimation Unit	144
7.4.3	MIMO-GFDM Detection Unit	145