

Wireless Networks

Series Editor

Xuemin Sherman Shen, University of Waterloo, Waterloo, ON, Canada

The purpose of Springer's Wireless Networks book series is to establish the state of the art and set the course for future research and development in wireless communication networks. The scope of this series includes not only all aspects of wireless networks (including cellular networks, WiFi, sensor networks, and vehicular networks), but related areas such as cloud computing and big data. The series serves as a central source of references for wireless networks research and development. It aims to publish thorough and cohesive overviews on specific topics in wireless networks, as well as works that are larger in scope than survey articles and that contain more detailed background information. The series also provides coverage of advanced and timely topics worthy of monographs, contributed volumes, textbooks and handbooks.

**** Indexing: Wireless Networks is indexed in EBSCO databases and DPLB ****

Xiang Cheng • Shijian Gao • Liuqing Yang

mmWave Massive MIMO Vehicular Communications

 Springer

Xiang Cheng
Peking University
Beijing, China

Shijian Gao
University of Minnesota
Minneapolis, MN, USA

Liuqing Yang
The Hong Kong University of Science and
Technology
Guangzhou, Guangdong, China

ISSN 2366-1186

Wireless Networks

ISBN 978-3-030-97507-4

<https://doi.org/10.1007/978-3-030-97508-1>

ISSN 2366-1445 (electronic)

ISBN 978-3-030-97508-1 (eBook)

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2023

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The automobile industry is currently shifting from “driving by humans” to “driving by intelligence.” Such a transformative evolution is primarily propelled by fast-increasing onboard sensors, with which the vehicles are gaining unprecedented degrees of intelligence. Numerous sensors will inevitably bring in massive sensory data, making reliable and swift information transfer an urgent and crucial issue. Existing wireless solutions include DSRC and LTE-V2X, both permitting low-volume message delivery. However, due to the limited bandwidth, they are still far from meeting the Gbps-level data rate regulated by the automobile industry. The current limitation inevitably motivated the exploration of the mmWave band, where vast spectrum resources are available for high-speed information transfer. Besides the bandwidth merit, mmWave’s inherent short wavelength allows a natural combination with massive MIMO for higher diversity and multiplexing gain. In theory, alternating the operating frequency does not need to change the wireless regime, but the fact is that many implementing concerns, such as power consumption and hardware expenditure, prohibit mmWave systems from inheriting classic fully-digital transceivers. Instead, an economical yet restricted structure, namely the hybrid beamformer, comes into practical use. In conjunction with the higher signal dimensions and complicated channel environments, the compromised hardware architecture requires a paradigm-shifting design to underpin mmWave communication. Against this background, this book will showcase a comprehensive picture regarding advanced mmWave massive MIMO techniques, hoping to provide promising physical-layer solutions to vehicular communications in the 5G and Beyond era.

The book is organized as follows. Chapter 1 overviews vehicular communications and elaborates the necessity of mmWave technologies. Chapter 2 introduces state-of-the-art mmWave channel modeling, with space-time-frequency and non-stationary features taken into account. Based on the insights from channel modeling, Chap. 3 presents an efficient channel estimator dedicated to mmWave transceivers with hybrid structures, which is capable of combating doubly selective massive MIMO mmWave channels. The obtained channel state information opens the door to a generic mmWave multi-user transceiver design, with the detailed strategies

presented in Chap. 4. Driven by the pursuit of lower error rate and higher energy efficiency, Chaps. 5 and 6 explore the potential use of index modulation in hybrid mmWave systems. Although both chapters will deal with the doubly selective channels, Chap. 5 focuses on the uplink multi-user access, whereas Chap. 6 spotlights on downlink multi-user transmission. Despite our best effort, the above content covers just a tip of the iceberg of mmWave vehicular communication. Thus, some open problems and promising directions will be discussed at the end of each chapter for future studies.

This book is mainly oriented to researchers, graduated students, and professors relevant to this field. Nevertheless, it also serves as a great introduction to state-of-the-art mmWave vehicular communications for those outside this field but aspire to pursue new interdisciplinary directions.

We would like to thank Ms. Yajun Fan, Mr. Ziwei Huang, and Mr. Zonghui Yang for their inspiring discussions on the research work presented in this book. Finally, we would like to thank the continued support from the National Natural Science Foundation of China under Grant 62125101 and the National Science Foundation under Grants ECCS-2102312 and CNS-2103256.

Beijing, China
Minneapolis, MN, USA
Guangzhou, China

Xiang Cheng
Shijian Gao
Liuqing Yang

Contents

1	Millimeter-Wave Vehicular Communications	1
1.1	Overview of Vehicular Communications	1
1.2	Necessity of Millimeter-Wave Technology	4
1.3	Characteristics of Millimeter-Wave Systems	5
1.4	Organization of the Monograph	5
	References	6
2	Millimeter-Wave Massive MIMO Vehicular Channel Modeling	7
2.1	Introduction of Vehicular Channel Model	7
2.1.1	Vehicular Channel Characteristics	7
2.1.2	Recent Vehicular Channel Model	8
2.1.3	Contributions of Proposed Vehicular Channel Model	11
2.2	A 3D Non-Stationary Vehicular Channel Model	12
2.2.1	Model-Related Parameters	12
2.2.2	Channel Impulse Response	17
2.3	Vehicular Channel Space-Time-Frequency Non-stationary Modeling	19
2.3.1	Generation of Dynamic Correlated Clusters and Static Correlated Clusters	19
2.3.2	Time-Array Evolution of Dynamic Correlated Clusters and Static Correlated Clusters	22
2.4	Simulations	27
2.4.1	Statistical Properties Analysis	27
2.4.2	Simulation Setting	29
2.4.3	Simulation Results of the Proposed Model	30
2.4.4	Model Validation	31
2.4.5	Model Application	33
2.5	Discussions and Summary	35
	References	36
3	Millimeter-Wave Vehicular Channel Estimation	39
3.1	Background	39
3.1.1	Necessity of Doubly-Selective Channel Estimator	39

3.1.2	Design Objectives and Proposed Approaches	40
3.2	System and Channel Models	41
3.2.1	System Model	41
3.2.2	Channel Models	42
3.2.3	Input-Output Relationship	43
3.3	Channel Estimation via Exploiting Double Sparsity	44
3.3.1	Proposed Training Pattern	45
3.3.2	Identification of Effective Taps	46
3.3.3	Identification of Effective Beams	48
3.3.4	Identification of Beam Amplitudes	52
3.4	Simulations	54
3.4.1	Tap Identification	55
3.4.2	NMSE in Static Wideband Channels	56
3.4.3	NMSE in Frequency-Flat Time-Varying Channels	57
3.5	Discussions and Summary	60
	References	60
4	Generic Millimeter-Wave Multi-User Transceiver Design	63
4.1	Background	63
4.1.1	Introduction of Multi-User Massive MIMO	63
4.1.2	Design Objectives and Proposed Approach	64
4.2	System Description and Problem Formulation	65
4.2.1	System and Channel Models	65
4.2.2	Input-Output Relationship	67
4.2.3	Problem Formulation	68
4.2.4	Design Strategy	69
4.3	Mutual Information (MI) Bounds	70
4.3.1	MI Upper-Bound	70
4.3.2	MI Lower-Bound	71
4.3.3	MI Relationship	71
4.3.4	HBD Optimality	72
4.4	Transceiver Design	73
4.4.1	Analog-Domain Processing	73
4.4.2	Digital-Domain Processing	76
4.5	Simulations	78
4.5.1	MI in Frequency-Selective Channels	78
4.5.2	MI Versus APS Resolution	78
4.5.3	MI Versus RF Chains	80
4.5.4	MI Versus UEs and Antennas	80
4.5.5	MI in Other Configurations	82
4.6	Discussions and Summary	82
	References	83
5	Millimeter-Wave Index Modulation for Vehicular Uplink Access	85
5.1	Introduction of Index Modulation (IM)	85
5.1.1	IM in Spatial-Domain	86

5.1.2	IM in Digital-Domain	87
5.1.3	IM in Beam-space-Domain	87
5.2	Wideband Generalized Beam-space Modulation (wGBM)	88
5.2.1	Design Motivation	88
5.2.2	System and Channel Models	89
5.2.3	wGBM Transceiver Over Static Channels	92
5.2.4	Performance Analysis	96
5.2.5	wGBM Accommodating Doppler	99
5.3	Extension to Multi-User Setup	102
5.3.1	Design Challenges	102
5.3.2	System Description	102
5.3.3	wGBM wMU Transceiver in Static Channels	105
5.3.4	wGBM wMU Accommodating Doppler	106
5.4	Simulations	107
5.4.1	Energy Efficiency	107
5.4.2	Error Performance in Doubly-Selective Channels	109
5.4.3	More Test in Low Vehicular Traffic Density (VTD) Slow-Mobility Non-stationary Channels	113
5.5	Discussions and Summary	114
	References	115
6	Millimeter-Wave Index Modulation for Vehicular Downlink	
	Transmission	119
6.1	Background	119
6.2	Wideband Precoded Beam-space Modulation (wPBM)	121
6.2.1	System and Channel Models	121
6.2.2	wPBM Transceiver Design	122
6.2.3	Analog-Domain Processing	124
6.2.4	Digital-Domain Processing	125
6.3	Extension to Multi-User Setup	127
6.3.1	Design Motivation	127
6.3.2	Overall Strategy	128
6.3.3	System and Channel Models	128
6.3.4	wPBM wMU Transceiver Design	131
6.4	Simulations	134
6.4.1	BER in Doubly-Selective Channels	134
6.4.2	BER in Low Vehicular Traffic Density (VTD) Slow-Mobility Non-stationary Channels	138
6.5	Discussions and Summary	138
	References	139
	Index	141

Acronyms

3GPP	The 3rd Generation Partnership Project
ADC	Analog-to-Digital Converter
APEP	Average Pairwise Error Probability
APS	Analog Phase Shifter
BER	Bit Error Rate
BS	Base Station
CDL	Clustered Delay Line
CP	Cyclic Prefix
CS	Compressed Sensing
D2D	Device-to-Device
DAC	Digital-to-Analog Converter
DSRC	Dedicated Short-Range Communications
FFT	Fast Fourier Transform
GMD	Geometric Mean Decomposition
GPS	Global Positioning System
IFFT	Inverse Fast Fourier Transform
IM	Index Modulation
ITS	Intelligent Transportation System
IV	Internet of Vehicles
LTE	Long-Term Evolution
MIMO	Multiple-Input Multiple-Output
MS	Mobile Station
NMSE	Normalized Mean Square Error
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OMP	Orthogonal Matching Pursuit
PSD	Power Spectrum Density
QoS	Quality of Service
RF	Radio Frequency
RSU	Roadside Unit
SM	Spatial Modulation

SNR	Signal-to-Noise Ratio
SVD	Singular Value Decomposition
TDL	Tapped Delayed Line
UE	User Equipment
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad hoc Network
VCN	Vehicular Communication Network