Wireless Networks

Xiang Cheng
Shijian Gao
Liuqing Yang

mmWave Massive MIMO Vehicular Communications

Springer

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 ISSN 2366-1445 (electronic)
Wireless Networks
ISBN 978-3-030-97507-4 ISBN 978-3-030-97508-1 (eBook)
https://doi.org/10.1007/978-3-030-97508-1

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 — Xiang Cheng
Minneapolis, MN, USA — Shijian Gao
Guangzhou, China — Liuqing Yang

Contents

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

Chapter 1
Millimeter-Wave Vehicular Communications

Abstract This chapter works on presenting a background overview associated with vehicular communications and networking. The first part focuses on reviewing the recent advancements and progress booming in vehicular networking and standardization. As existing wireless solutions cannot guarantee safe, swift, and ubiquitous high-volume data transfer in future vehicular-to-everything communication, mmWave comes into play to help address the information bottleneck beyond the 5G era. Henceforth, the second part follows to provide a holistic overview of mmWave physical fundamentals and mmWave system properties. The chapter is concluded with a brief organization of this monograph studying mmWave vehicular communications.

Keywords Vehicular communication · Networking · mmWave · 5G · Standardization · Vehicular-to-everything

1.1 Overview of Vehicular Communications

The idea of intelligent vehicles (IV) was proposed more than three decades ago [1]. In the nascent stage of the relevant studies regarding IV, or its generalized form, intelligent transportation systems (ITS), the focus has been mostly on the conceptual aspects [2–4]. Thanks to the recent evolution booming in the automotive industry, IV is attracting increasing attention. From the perspective of vehicle itself, more sensors and antennas are now being mounted to augment its sensing and communication capabilities [5]. From the infrastructure aspect, numerous roadside units and cloud-based networks are now being deployed to underpin ubiquitous information exchange and storage [6, 7]. From the technological side, advanced communication regimes and deep learning methods play a crucial role in information transmission and interpretation [8]. From the administration level, scientific regulation and policy-making help to cope with the potential risks and boost the commercialization. It is envisioned that completely self-driving vehicles will be ready for practical deployment in the next decade (see the roadmap in Fig. 1.1).

X. Cheng et al., *mmWave Massive MIMO Vehicular Communications*,
Wireless Networks, https://doi.org/10.1007/978-3-030-97508-1_1

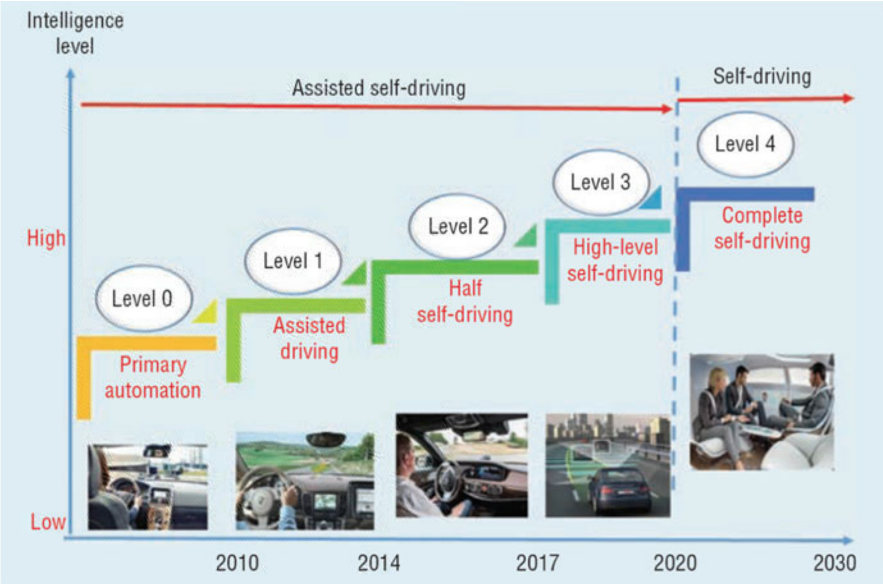

Fig. 1.1 The evolutionary roadmap of autonomous driving [9]

Although the success of IV relies on an array of technologies, vehicular communication and networking (VCN) still comes as a fundamental one. Such a claim is of no exaggeration. If one focuses on a single vehicle, its primary source of intelligence comes from parsing the sensing information, either via onboard sensors or shared by other vehicles. With hundreds of thousands of cars on the road, the amount of information flowing into the network would be astronomical. The data deluge, accompanied by many other challenges, such as driving safety, transportation efficiency, reaction promptness, as well as decision reliability, has posed a significant burden on the information tunnel, making the role of VCN much more crucial than ever [9].

The most representative type of VCN was rooted from the ad-hoc network architecture in the mobile environment, termed as vehicular ad-hoc network (VANET) [10, 11]. Both the industry and the academia have devoted considerable efforts to standardize VANET. The primary outcome is the well-known dedicated short-range communications (DSRC) standard. Although DSRC and its variations have been adopted by some major economic entities, widespread deployment still has a long way to go because the infrastructure expenditure is prohibitive. In fact, the financial issue is not the only bottleneck. Recall that DSRC stemmed from IEEE 802.11p. The latter exhibits weakness in scalability and mediocre QoS as the network size grows, limiting the performance in data rate and throughput. As a result, VANET can hardly satisfy the demanding vehicular communications needs.

In light of the deficiencies of VANET, another direction of standardizing VCN is to seek the power of cellular networks. Compared with VANET, cellular

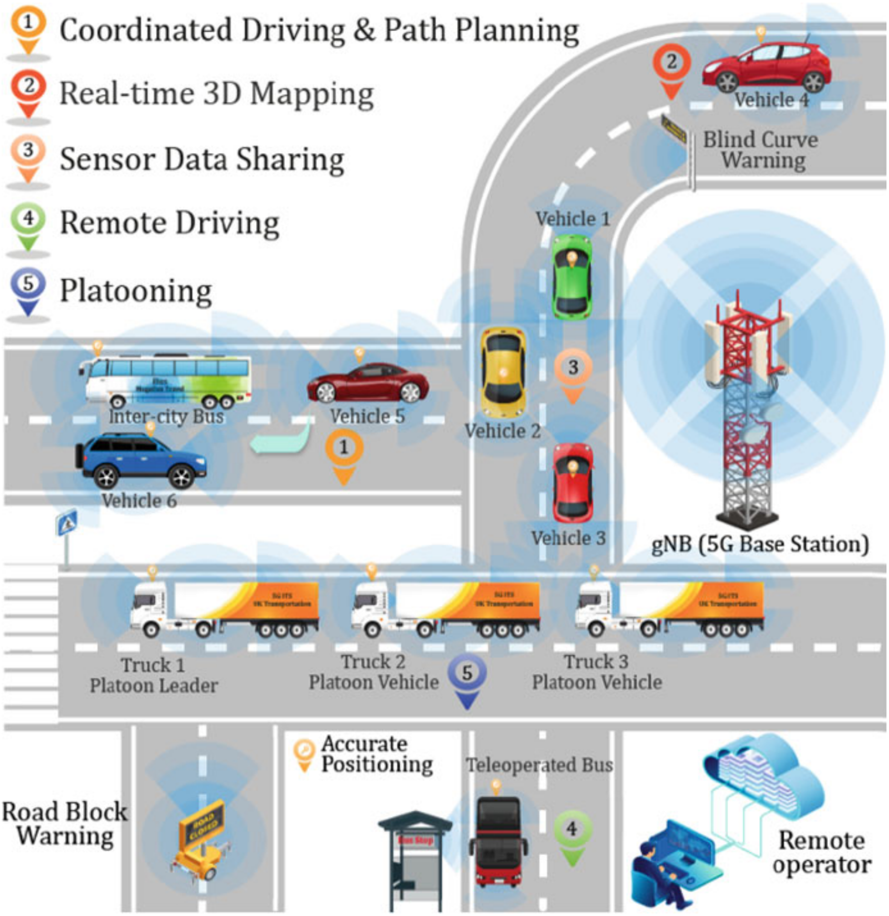

Fig. 1.2 Advanced use cases and services envisioned in 5G-V2X [12]

networks are undoubtedly far more mature in development, standardization, and commercialization. Over the past half century, cellular systems have evolved from the primitive 1G analog communication to today's 5G new radio (NR) that enables secure seamless wireless connections over a wide spatio-temporal span. The combination of state-of-the-art 5G cellular networks and vehicle-to-everything (V2X) communications, namely 5G-V2X, has been recognized as an overall enhanced alternative to VANET. Some promising use cases and services in 5G-V2X are shown in Fig. 1.2. There are three primary reasons that 5G-V2X is expected to become the new mainstream. First, it leverages the existing cellular infrastructures instead of building from scratch. Secondly, its centralized architecture makes it more capable in network control and traffic prioritization. Thirdly, it includes a vital feature termed as the proximity service (ProSe) that stems from device-to-device (D2D) communications. Hence it can replace DSRC to support vehicle-to-vehicle (V2V)