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Millimeter Wave Vehicular Communications: A Survey

Vutha Va
The University of Texas at Austin
vutha.va@utexas.edu

Takayuki Shimizu
TOYOTA InfoTechnology Center, U.S.A., Inc.
tshimizu@us.toyota-itc.com

Gaurav Bansal
TOYOTA InfoTechnology Center, U.S.A., Inc.
gbansal@us.toyota-itc.com

Robert W. Heath Jr.
The University of Texas at Austin
rheath@utexas.edu

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Vutha Va
The University of Texas at Austin
vutha.va@utexas.edu

Takayuki Shimizu
TOYOTA InfoTechnology Center, U.S.A., Inc.
tshimizu@us.toyota-itc.com

Gaurav Bansal
TOYOTA InfoTechnology Center, U.S.A., Inc.
gbansal@us.toyota-itc.com

Robert W. Heath Jr.
The University of Texas at Austin
rheath@utexas.edu

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Abstract

The large spectral channels at millimeter wave (mmWave) frequencies provide a means of achieving much higher data rates in vehicular communication systems. High data rates can be used for exchanging low-level sensing data (i.e., without much processing) or for infotainment applications to improve traffic safety and efficiency as well as user experience onboard. This monograph provides an overview of mmWave vehicular communication with an emphasis on results on channel measurements, the physical (PHY) layer, and the medium access control (MAC) layer. The main objective is to summarize key findings in each area, with special attention paid to identifying important topics of future research. In addition to surveying existing work, some new simulation results are also presented to give insights on the effect of directionality and blockage, which are the two distinguishing features of mmWave vehicular channels. A main conclusion of this monograph is that given the renewed interest in high rate vehicle connectivity, many challenges remain in the design of a mmWave vehicular network.

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1

Introduction

The automotive industry is at an inflection point between old and new technologies. More sensors are being incorporated into vehicles in an effort to realize safer and more efficient traffic. Communication technologies are being integrated into vehicles for safety applications such as blind spot warnings, do not pass warnings, and forward collision warnings; as well as non-safety related applications. Some examples include improving traffic efficiency, toll collections, and infotainment [61, 144]. Vehicles are becoming more automated, using sensing and communication to shift control further from the human driver to an automated driving computer. It is an exciting time to be working on new technologies for the automotive industry.

The increase in sensors and sensor complexity has a number of implications on the next generation of vehicles. These sensors will generate a huge amount of data that needs to be processed. For example, Google's self-driving car can generate up to 750 megabytes of sensor data per second [12]. There are predictions that cars with automated driving capabilities will generate up to 1 terabyte of data per single trip [117]. This sensor data places additional computational requirements on the vehicle and requires higher data rate connectivity in the vehicle.

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Although much prior work on automated driving at present envisions their independent and autonomous operation, there are many benefits to sharing rich sensor data such as LIDAR or visual camera images with other vehicles. One example is cooperative perception [65, 136]. By sharing images (LIDAR or camera) with neighboring vehicles, image processing algorithms could be applied to create satellite images of the surrounding traffic. Such satellite images would help extend a vehicle's perceptual range to cover its blind spot or reveal hidden objects (e.g., at the corner or visually blocked by a vehicle in front) which could enable smoother traffic. Another example is sharing raw Global Positioning System (GPS) signals to apply real-time kinematic method which can greatly improve relative positioning accuracy, versus sharing processed GPS coordinates [92]. These applications will require exchanging a large amount of data, anywhere from tens to thousands of megabits-per-second. Unfortunately, the state-of-the-art vehicular communication standard, the Dedicated Short-Range Communication (DSRC), can provide a theoretical maximum data rate of only 27 Mbps [61]. In real systems, due to the interference from the omni-directional transmission at DSRC band, observations from field tests show that practical data rates will be below 6 Mbps [61, 55].

The large spectral channels at millimeter wave (mmWave) bands make it a promising candidate to realize high data rates [108, 22]. One major barrier to deploying mmWave was the device cost. Thanks to the advancement of CMOS technology, low cost mmWave device production is now possible [109, 161]. This has led to explosion in interest in mmWave recently. It is being researched as a candidate for the fifth generation cellular network (5G) [17, 11], and it is already used in WPAN/WLAN standards such as WirelessHD [153] and IEEE 802.11ad [48]. The application of mmWave in the vehicular context is not new. Automotive radars operating in mmWave bands are already in the market [44].

Research on mmWave for vehicular communications started as early as the 1980s. For example, a European Intelligent Transportation System (ITS) project PROMETHEUS which ran from 1987-1994 was focusing on developing vehicle-to-vehicle (V2V) communication at 57

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GHz [143]. A summary of relevant ITS projects can be found in [143]. Later on in the late 1990s and early 2000s, there was another research effort by the Communications Research Laboratory at the Yokosuka Research Park (YRP) in Japan [119]. They implemented both vehicle-to-infrastructure (V2I) and V2V systems, and performed field tests showing the feasibility of using mmWave for vehicular communications [58]. Their V2I solution, however, was costly due to the need for very dense roadside unit (RSU) deployment (20 m separation between RSUs). Their V2V demonstration was conducted in ideal condition where the link is already established and there is no interference. While the initial result in [58] is promising, there are still many hurdles that need to be overcome to develop the physical (PHY) and medium access control (MAC) layers for mmWave communication systems that can provide both V2V and V2I capabilities, and more generally vehicle-to-everything (V2X).

This monograph provides a survey of mmWave vehicular networks including channel propagation measurements, proposed PHY solutions, and MAC proposals. We start with some background on mmWave communication in Chapter 2, followed by a review of potential applications of high data rate mmWave vehicular links in Chapter 3. Our conclusion is that data rate at least on the order of 100s of Mbps will be required, and DSRC will not be able to support these applications.

In Chapter 4, we proceed to review the state-of-the-art in measurements related to mmWave vehicular channels. Previous studies reported good fit with the two-ray model on flat road surfaces. In more realistic settings with road undulation, road surface curvature, and blockage by other vehicles, including other features in the environment can improve the accuracy of pathloss prediction. For example, the reflectivity on the road surface depends on the grazing angle [138]. The grazing angle will depend on the antenna height (mainly for V2I scenarios because low antenna heights for V2V will always yield small grazing angles) and the road surface curvature. Thus an improved model would be the ones that use variable reflective coefficient depending on the geometry. This chapter concludes with some proposals for future measurements.

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In Chapter 5, we describe existing work on PHY design for mmWave vehicular communications, covering both V2V and V2I networks. In the V2V context, we describe a line of work proposing to use a spread spectrum solution that enables both communication and ranging at the same time. The main feature in that design is the communication procedure that does not require prior knowledge of the spreading code of the receiver. In the V2I context, one of the main issues that was identified was the frequent handoff due to small cell size. The proposed solutions at present are based on the radio-over-fiber (RoF) architecture, where multiple RSUs are connected with fiber. These designs either eliminate or facilitate fast handoff among connected RSUs. The RoF architecture also provides opportunities for cooperation among the RSUs to provide better link quality. These solutions, however, consider only the single user case and do not take advantage of directional beams to improve spatial reuse. They also lack consideration of blockage. Finally, a summary followed by a discussion on future research challenges are provided such as designs considering hardware impairment and the need for frequent beam steering (due to vehicular mobility).

In Chapter 6, we review related work on MAC protocol design. Due to the lack of treatment on directionality, we also include a section on directional MACs (not necessarily at mmWave) besides the V2V and V2I categories. The main theme in most V2V context work was the design of mechanisms to access the channel while minimizing interference to other in vehicular environments. In the V2I context, the main theme was the design to reduce or enable fast handoff based on the RoF architecture. The V2V solutions rely on some form of carrier sensing but no adequate discussion was found on how the carrier sensing can be done if directional antenna is used. The V2I solutions use some form of superframe structure that enables the connected RSUs to act as one large cell. Handoff is only needed when crossing these large cells (not when crossing smaller RSU coverages) and thus can reduce handoff. Again, similar to the PHY design, consideration on spatial reuse and blockage are still missing. We conclude this chapter with a discussion of future research problems including MAC designs considering the effect

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of blockage and directionality, designs taking advantage of vehicular sensors, and beam alignment and tracking protocols.

In Chapter 7, we perform simulations using measured vehicle trace data available from the NGSIM project [35, 88] coupled with a channel model from the survey in Chapter 4. Our simulations aim at providing insights into the effect of directionality and blockage. We study two scenarios. The first one aims at showing the effect of blockage and quantifying the benefit of carrier sensing. The results show that with enough directionality, blockage only causes harm and the benefit of blockage in reducing interference becomes negligible. Our results also show that the benefit of carrier sensing decreases as the beamwidth decreases. The second scenario aims at showing the effect of mobility. The results show that due to mobility, the line-of-sight (LOS) connection cannot be maintained and this causes severe outage. Thus, for reliability relaying method or multiband approaches should be considered.

In Chapter 8, we provide several pointers for future research directions on other important issues for mmWave vehicular communications that are not the focus of this monograph. The topics include mobility models, advanced mmWave signal processing for spatial multiplexing, joint radar and communication, and security. In the mmWave vehicular context, the requirement on the mobility model will be different from that required at lower frequencies due to the use of directional beams and blockage effect. Thus there is a need for efficient and realistic microscopic mobility models. MmWave hardware has different constraints than those at lower frequencies. The difference stems from the use of very large arrays and very wide bandwidth in mmWave systems, which causes challenges in terms of hardware cost and power consumption. Because existing automotive radars use mmWave, a joint system enabling both radar and communication may provide a more cost-effective solution. An interesting problem here is a design that allows both systems to benefit from each other. Security issues, as in lower frequency systems, remain but directionality at mmWave frequencies might be helpful in some cases (e.g., resistance to eavesdropping). It should be clear that there is a bright future for research in mmWave communication for vehicular applications.

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Vehicular communications in the DSRC context at lower frequencies have been extensively studied [19, 54, 57, 74, 86, 124], but there are few surveys on mmWave vehicular communications [58, 75, 143]. The survey in [57] provides a comprehensive overview of vehicular networks including potential applications, existing architecture and standards, as well as PHY and MAC solutions. More rigorous treatments on the PHY and MAC design can be found in [19, 54, 124]. Insights on the vehicular propagation channels at lower frequencies can be found in [74, 86]. Work on mmWave, however, is limited. There are a few existing survey type of papers that have some discussion of mmWave application to vehicular networks such as [58, 75, 143]. The survey in [75, 143] have very limited discussion of technical aspect and only provide high level view. A nice summary of mmWave vehicular channel measurements was given in [58]; however, this mainly covered their own measurement efforts. Our survey focuses more on the technical aspect of mmWave vehicular communications.

The rest of the monograph is organized as follows. We describe background on mmWave communications in Chapter 2 and discuss potential applications of high data rate mmWave vehicular links in Chapter 3 to establish the requirements. Chapter 4, 5, and 6 summarize our survey on the mmWave channel measurements, PHY designs, and MAC designs, respectively. At the end of each of these three chapters, we also provide a discussion on future research problems. We present our simulation in Chapter 7, and discuss relevant topics which are important for mmWave vehicular networks but not focused in this survey in Chapter 8. Finally, Chapter 9 concludes the monograph.

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