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Ghafoor, Kayhan Zrar, Kong, Linghe, Zeadally, Sherali, Sadiq, Ali Safaa, Epiphaniou, Gregory, Hammoudeh, Mohammad , Bashir, Ali Kashif  and Mumtaz, Shahid (2020) Millimeter-Wave Communication for Internet of Vehicles: Status, Challenges and Perspectives. IEEE Internet of Things Journal, 7 (9). pp. 8525-8546. ISSN 2327-4662

DOI: <https://doi.org/10.1109/jiot.2020.2992449>

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Version: Accepted Version

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Millimeter-Wave Communication for Internet of Vehicles: Status, Challenges and Perspectives

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Abstract—Internet of Vehicles have attracted a lot of attention in the automotive industry and academia recently. We are witnessing rapid advances in vehicular technologies which comprise many components such as On-Board Units (OBUs) and sensors. These sensors generate a large amount of data, which can be used to inform and facilitate decision making (for example, navigating through traffic and obstacles). One particular focus is for automotive manufacturers to enhance the communication capability of vehicles to extend their sensing range. However, existing short range wireless access, such as Dedicated Short Range Communication (DSRC), and cellular communication, such as 4G, are not capable of supporting the high volume data generated by different fully connected vehicular settings. Millimeter-Wave (mmWave) technology can potentially provide terabit data transfer rates among vehicles. Therefore, we present an in-depth survey of existing research, published in the last decade, and we describe the applications of mmWave communications in vehicular communications. In particular, we focus on MAC and physical layers and discuss related issues such as sensing-aware MAC protocol, handover algorithms, link blockage, and beamwidth size adaptation. Finally, we highlight various aspects related to smart transportation applications, and we discuss future research directions and limitations.

Index Terms—mmWave communication, sensing, vehicular networks, wireless.

I. INTRODUCTION

WE have witnessed rapid developments in the field of connected vehicles in the last few years. These advances have been possible as a result of the convergence of intelligent computing techniques, vehicular networks and automotive software and hardware technologies. Researchers from both academia and industry develop and improve the design of vehicles that will rely on the communication among

cars and vehicles' sensing capabilities. The automotive industry foresees that autonomous vehicles will be on the road by 2020 [1]. The emergence of autonomous vehicles will impose significant requirements in terms of traffic security and system failure while providing many benefits. These services will have a significant impact on people and society as a whole by reducing traffic accidents, saving lives, improves traffic flow optimization, preserving sustainable environment and fulfilling the various requirements of drivers. With these indispensable applications, vehicular networks will serve as an important pillar for intelligent transportation. It is worth noting that there could be no smart city without reliable connected vehicles [2], [3]. In recent years, government sectors have increased their investments to improve traffic management and advances in vehicular communications. For instance, in 2016, the V2X market was valued 22 billion USD and is expected to reach 99.55 billion USD by 2025 [4].

As smart transportation becomes more widely deployed, a large number of sensors will be embedded into vehicles for safe driving purposes. These sensors (consisting of various types ranging from ultrasonic for distance measurement to complex radar-based sensors) will generate data at a high rate. Camera-based and radar-based sensor technologies make the vehicle smart and improve its communication capability [5], [6]. For example, LiDAR-enabled vehicles may approach a traffic accident area and transmits the scene to other nearby vehicles through Road Side Unit (RSU). This will help drivers to extend their vision and take advance decision prior to reaching hazard area similar to adaptive cruise control and reroute assistance. Such kind of radar-based sensing devices generate large amount of data at a high rate. More specifically, partial and fully automated vehicles require reliable, low

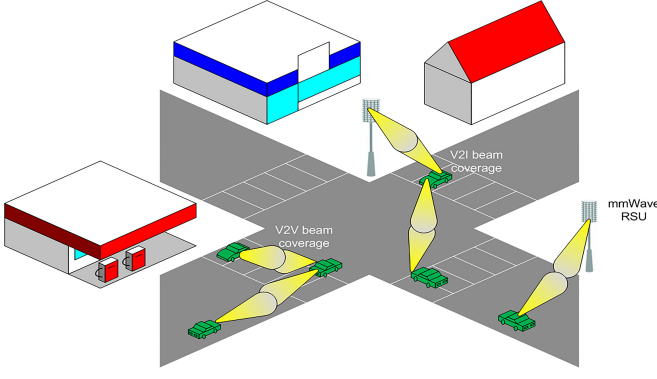


Fig. 1. Vehicle-to-Everything communications using mmWave

delay and high transmission data rate in order to satisfy the requirements of automotive-related applications.

At present, an existing popular communication protocol that supports vehicular networks is the DSRC [7]. Generally, the DSRC protocol supports Vehicle to Everything (V2X) communication architecture. Although, in theory, DSRC supports 27 Mbps and transmission range of 1000 meters, in practice it can only provide 2-6 Mbps [8]. In [9], the authors in adopted 3GPP's Long Term Evolution-Advanced (LTE-A) [10] in vehicular networks. LTE could support up to 100 Mbps and incurs lower communication latency (no less than 100 ms) as compared to DSRC. Therefore, neither DSRC nor LTE-A [11] can support the transfer of large amounts of data that will be generated by connected vehicles. Further, it is possible to enable efficient coexistence of DSRC and LTE to support IoV applications [?].

The mmWave frequency band is a promising candidate solution for intelligent vehicular networks. The significance of the mmWave spectrum lies in the fact that it is already implemented in wireless access (e.g. IEEE 802.11ad) technologies and new cellular devices are being equipped with mmWave support [12]. Future 5G cellular systems will support Device-to-Device (D2D) communication and high data transmission rates (thereby enabling Gigabit data transfer rates) among fully connected vehicles. For this frequency band, link quality can be improved by configuring a large number of antenna arrays. In fact, mmWave technology has long been used in the automotive industry [13] but recently, this frequency spectrum received revived interest to support fully connected vehicles applications, such as conveying driver's intention to other vehicles in the vicinity, cooperative perception, and comfort-related services. Fig. 1 shows the concept of V2X using mmWave. As it can be seen, every vehicle is embedded with multiple transceivers to overcome signal obstruction by surrounding obstacles.

The rest of this survey is organized as follows: Section II presents an extensive review on mmWave communication, vehicular sensing technology and communication protocols that are tailored for vehicular networks. Section III classifies state-of-the-art solutions for vehicular mmWave communications. Section V presents important applications of mmWave-enabled connected vehicles. Section VII discusses a few research chal-

lenges and possible solutions when mmWave is integrated with vehicular communications. Finally, section VIII concludes this work.

II. BACKGROUND

This section presents mmWave communication fundamentals and communication protocols for vehicular networks. We also present relevant surveys on vehicular networks and mmWave-enabled connected vehicles.

A. MmWave Communication & Internet of Vehicles

The use of the large spectrum of the underutilized mmWave frequency band has recently attracted the attention of many researchers in academia and industry [14], [15]. This communication technology is an innovative and a promising solution that can fulfil the demands of mobile user traffic. Conventionally, this technology has been used for indoor high quality video transmission and outdoor unicast communications. This constraint for mmWave frequency band is due to high propagation loss and costly devices.

MmWave provides a large spectral channel at the frequency band of 30-300 GHz. Integrated with Multiple-input Multiple-output (MIMO) and efficient modulation technique, mmWave can offer higher data rates as compared to existing wireless communication systems which operate below 6 GHz. The International Telecommunication Union (ITU) recommended a list of frequency bands between 24 GHz and 86 GHz [16] for mmWave communication. Then, the Federal Communications Commission (FCC) has proposed to standardize mmWave-enabled mobile communication in licensed frequency band of 28 GHz, 37 GHz and 39 GHz and recommended 64-71 GHz for unlicensed band [17]. Shortly after this FCC proposal, Japan [18] and Europe [19] revealed a new plan to standardize the 5G frequency band.

Internet of Vehicles (IoV) provide internet services to the passengers and drivers [20], [21]. In IoV environment, vehicles are equipped with sensors and produce big data to the cloud [22]. For this communication to be possible, it is imperative to enable high speed mmWave links for IoV. The mmWave communication can also be used for V2V and Vehicle to Infrastructure (V2I). Vehicles can share raw sensor data with nearby vehicles using mmWave links whereas mmWave V2I links are used to send data to the cloud. To achieve this goal, several bands (such as 5G bands of 28 GHz and 38 GHz) can be used to enable mmWave communication for IoV. Moreover, frequency bands of 24 GHz and 76 GHz can be used for positioning of vehicles [23].

In the mmWave communication environment, the signal wavelength is very short. A high directive gain can be achieved when both the transmitter and the receiver are embedded with a large array of antennas. These antenna arrays are significant for beamforming and increases the network capacity by improving the Signal to Noise Ratio (SNR) of the wireless link. Besides increasing network capacity, complex beamforming is needed for all antennas [24] embedded in vehicles. To this end, an efficient hybrid beamforming approach is required to support high mobility as in vehicular networks.

Various telecommunication standardization organizations [25], [26] have made efforts to propose specific mmWave frequency bands for the 5G cellular system. Similarly, it is significant to propose unique wireless access standard and allocate channel spectra for vehicular mmWave communication. This important step requires more efforts to manufacture mmWave-enabled V2X devices. On the other hand, since the 5G cellular system provides a high data transmission rate, it can be used to support mmWave based vehicular network. More Specifically, 5G eNB can be used to support I2V whereas V2V leverages Device-to-Device (D2D) of 5G to provide communication among vehicles. In a joint effort, SK Telecom, Ericsson and BMW in South Korea deployed the first 5G supported vehicular network wherein the 28 GHz band was used to stream video from camera that is equipped by vehicles [27].

B. Communication Protocols for Vehicular Networks

The history of vehicular communication dates back to three decades ago. In 1997, the National highway automated systems consortium demonstrated the technical feasibility of vehicle platooning. They could implement automatic steering, and maintain a space of 5.5 meters and perform speed control. Switching of positions among each other along with lane changing are also two important features that were considered. Each of those cars was simulated on a Pentium 166 MHz computer. The slotted ALOHA protocol and 900 MHz frequency band were used for communication [33]. Since that time, we have witnessed significant progress in wireless communications that enable vehicle automation. In the Advanced Transportation Technology (PATH) program, IEEE 802.11b has been used for automated merging control, cooperative collision warnings and truck platooning [34]. Efforts have been made to standardize V2V communication under the regulations of federal motor safety standards such as Dedicated Short-range Communications (DSRC) [35].

In order to fulfil the requirements of Intelligent Transportation System (ITS), several communication standards such as DSRC [36], LTE and LTE V2V are developed. DSRC is a technology that provides short range communication among vehicles and cars will be embedded with Wireless Access for Vehicular Environment (WAVE) [35]. In US and Europe, 5.9 GHz frequency band is used for V2X system while Japan use 760 MHz. Recently, NXP Semiconductors developed a single Chip modem for vehicular safety services by promoting communication among vehicles and vehicle to infrastructure. In their design, common device is employed in different countries, but the software configuration needs to be modified in order to tune the frequency range for specified region [37]. Following this evolution, in December, 2016, US National Highway Traffic Safety Administration (NHTSA) issued a proposal to all autocar companies in order to embed DSRC in new vehicles. The plan is speculated to have 50 % of vehicles with equipped DSRC radio by 2021, 75 % by 2022 and 100 % by 2023 [38]. Moreover, DSRC based V2V communication is utilized in [39] and the concept of moving zone is used to improve the efficiency of data exchange and processing. This

traffic efficiency is also achieved through cooperation among vehicles. Incentive mechanism is used to stimulate vehicle participants for cooperative communication [40].

In the past few years, mmWave communication has emerged as promising technology to fulfil the requirements of fast increasing data traffic. Kong et al. in [41] developed vehicular mmWave system based on Internet of Things (IoT) and cloud computing for vehicular environment. Further research works are applied to combine communication technologies as LTE and mmWave for vehicular network environment [42]. In MiWEBA project, LTE and wireless LAN aggregation protocol of 3GPP Release 13 has been used to integrate LTE and 60 GHz WiGig wireless system [43].

Moreover, there are research works on the integration of LTE and DSRC technologies. For instance, the authors in [44] developed a scheduler to stimulate cooperation among vehicles in hybrid infrastructure to vehicles and V2V environment. In such hybrid scenarios, few vehicles are acting as gateway to provide internet service and hence improve the efficiency wireless access utilization. The authors in [45] used clustering mechanism to integrate the IEEE 802.11p with LTE. In their design, they considered vehicular mobility and the cost of cluster formation and maintenance. Following the trend of cluster formation in vehicular networks, in [46] Hu et al. uses clustering mechanism based on fuzzy logic to select an efficient vehicle as gateway in order to integrate licensed sub-6 GHz and mmWave communication and hence achieving high network throughput. IEEE 802.11p based V2V communication has been used to boost handshaking among vehicles for efficient clustering.

C. Related Works and Contributions

In the existing state-of-the-arts, there are many surveys and tutorials that are tailored to the emergence of vehicular networks. These publications range from more general works to particular technical reports and explications in the area. For instance, the surveys in [31] are focused on general aspects in vehicular networks. There are also surveys focused on specific topic such as [28] reviewed routing protocols, [47] focused on static and adaptive beaconing approaches, [29] focused on vehicular social networking and [48] MAC layer algorithms in vehicular environment. On the other hand, there are surveys on mmWave enabled 5G [30]. Meanwhile, the authors in [8] surveyed state of the arts solutions of vehicular mmWave communication. However, their survey is not comprehensive and limited in considering context-aware based beam alignment, link blockage at MAC layer, handover process and technical requirements of promising applications.

In essence, this survey is different from those exist in the literature. This is because of its focus on link blockage, handover process at the MAC level and connectivity and radio coverage issues in vehicular mmWave communication. Table I illustrates published surveys in the domain of vehicular communications. We summarize the main contributions of this survey as follows:

- We compare wireless access technologies for connected vehicles and sensing technologies that are embedded in vehicles.

TABLE I
EXISTING SURVEYS: A COMPARATIVE SUMMARY.

| Ref. | Publication year | MmWave vehicular communications | Technical requirements of vehicular communication applications | Context-aware beam alignment | Link blockage at MAC layer | Handover process | mmWave communications in 5G communication systems |
|-----------------|------------------|---------------------------------|--|------------------------------|----------------------------|------------------|---|
| [28] | 2010 | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| [29] | 2015 | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| [30] | 2015 | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| [31] | 2016 | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| [8] | 2016 | ✓ | ✗ | ✗ | ✗ | ✓ | ✗ |
| [32] | 2018 | ✓ | ✗ | ✗ | ✗ | ✗ | ✓ |
| Proposed survey | - | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |

- We evaluate the effect of beamwidth size, handover techniques at the MAC layer, positional information aware beam alignment on the performance of vehicular mmWave communication.
- We identify crucial applications and their technical requirements, such as Map generation system, sensor data sharing and vehicle to road user data communications.
- We identify research challenges on handover decision making, sensing-aware protocols, beam re-pointing when radio blockage is detected and beamwidth adaptation.

This survey can be used as a useful resource for future research directions in vehicular mmWave communication and connected vehicles. It can also serve as a reference for wireless mmWave access system, mmWave communication challenges, vehicular mmWave communication and comparison between wireless technologies for application in fully connected vehicles.

D. Vehicular Sensing System

This section presents the functions and features of sensors for next generation connected vehicles. Radar sensor is an important component that improve traffic efficiency. The frequency bands for radar operation are 24, 77, 79 and 81 GHz [13], [49]. There are several types of radar based on the range of communication each radar type can provide. Short/medium range radar can support cross traffic alert and blind spot detection for connected vehicles whereas the adaptive cruise control system is a crucial application of long range radar. Radar detects the location and velocity of nearby vehicles by sending a special modulated continuous signal. In contrast to standard communication systems, the signal parameters of radar are different for different vendors. As pointed out in [24], a radar is not appropriate to recognize and categorize different materials and objects without the support of machine learning and signal processing.

An automotive camera extends the frequency band from 400 GHz to 430 THz. It helps drivers extend their perception. For instance, a side visual camera is used for surround view while a rear camera is used for parking assistance. A front camera is

used for sign recognition and lane departure warning. Efficient computing vision algorithms must be embedded into visual cameras for safety applications. A high data transfer rate is required for data transmission from a visual camera. For instance, a data rate of 100 Mbps is required for low-resolution while 700 Mbps is needed for high-resolution visual information [24]. For automated highway driving, visual cameras have been used by Tesla vehicles.

Light Detection and Radar (LiDAR) is a technology that consists of 64 lasers that send microwave pulses of light to its surroundings. Then, it measures the distance based on the speed of the reflected light signal. Millions of data points are generated every second and this data needs even more computing resources to process real time 3D map of cars' environment. The generated information is used by a vehicle to make smart decisions on what to do next. There are several applications of Lidar such as pedestrian detection, emergency braking and collision avoidance [24]. Further, self-driving cars will be deployed in the near future and the number of equipped sensors into these vehicles will increase 10 times [50]. Sensors that are used by current and next generation autonomous vehicles are LiDAR systems, visual camera and automotive radar. Automotive industries such as BMW have been testing a system called remote valet parking assistant. In this system, cars could find a parking slot and park the car by using laser scanners. Table II shows the drawbacks and the data rates to support each type of technology.

III. MMWAVE ENABLED VEHICULAR COMMUNICATION

This section reviews recent research efforts on vehicular mmWave communication. In particular, we analyze radio coverage and connectivity of mmWave wireless access, and context-information based beam alignment, and handover process in mmWave-enabled vehicular context. Table III summarizes recent research works conducted in the area of mmWave vehicular communication.

A. Radio Coverage and Connectivity

In the previous sections, we highlighted that the mmWave communications are completely directional [56]. The high

TABLE II
COMPARISON OF VEHICULAR SENSING TECHNOLOGIES

| Sensing technology | Application | Drawback | Wave source | Data rate |
|--------------------|--|---|--|------------------|
| LIDAR | Object detection and recognition by generating 3D image of an object | Expensive and not efficient in cloudy weather | It uses specific optics and laser to transmit and receive data | 10-100 Mbps |
| Camera | Virtual mirror | Advanced computer vision technique is needed to process massive amount of generated data by cameras | Radio signal | 100-700 Mbps |
| Radar | Easily detect objects in foggy weather and at night | Due to short wavelength, it is hard to detect small objects and precise object image | It use antenna to send radio signals | Less than 1 Mbps |

value of the carrier frequency leads to high path loss which can be compensated by using a large number of antenna arrays and a technique called beamforming. Channel tracking has been used to align antenna beams of a transmitter and a receiver [57]. One of the most popular channel tracking techniques is Beam searching [58] that was developed to address mobility. With this technique, mobile nodes continuously track the signal quality (Signal to Noise Ratio (SNR)) of the wireless channel in order to tune their beams to stabilise link quality [59]. Therefore, beam tracking has a significant effect on the link connectivity and radio coverage [60]. However, frequent monitoring of a directional link (beam tracking) by a vehicle introduces overhead and latency which ultimately became a barrier to offering a reliable service for varying link quality [61], [62].

In [53], the authors derived a formula for beam design in mmWave-enabled vehicular networks. The aim of the beam design is to optimally maximize throughput. The design considers equal coverage of beam design, i.e., the beamwidth has an optimal solution when its strength increases from the edge to the center. This optimal beam design maximizes the throughput. Moreover, since beam sweeping is considered to be a high beam training overhead technique, the authors used the beam switching mechanism to allow vehicles to hop from one beam to the neighboring one [53], [63]. To achieve beam switching, prediction of a vehicle's next position is used for switching to the upcoming beam. Fig. 2 shows the beam switching procedure. At $t=t_0$, the vehicle aligns its beam to the blue active beam and sends its positional information to the RSU. Then, based on the initial position and velocity, the vehicle path can be predicted and switching to the new active beam is performed as illustrated in Fig. 2(b).

To confirm the optimality of equal coverage beam design, outage probability and average data rate have been used as performance metrics. The overlap ratio, which is the ratio of overlap size to the whole beam size, is used to show its effect on the aforementioned performance metrics. When the overlap ratio increases the link outage decreases but link outage increases, when the number of beams increases. In contrast, for average data rate, it increases when the number

of beams increases.

In another effort, the authors in [52] developed a mathematical model to show the percentage of time slots used in the communication between a mobile and an infrastructure node that remain active and the beam pair is aligned. For this purpose, at the beginning of each time slot a report on the link quality is exchanged between the mobile and infrastructure nodes. This information is helpful to find the best beam direction between a pair of nodes. As illustrated in Fig. 3, when communication is lost in the middle of a time slot, the connectivity can be restored only at the beginning of the next time slot when beam tracking is applied. To determine connectivity, the communication duration ratio is defined as a portion of the time slot a mobile device uses to communicate with the infrastructure node and its beam is perfectly aligned. After extensive analysis, the authors have shown that the communication duration ratio increases when the traffic density is low because of the sparse distribution of devices. Hence the mobile node needs more time to pass by the infrastructure node. Moreover, the authors have also shown that the regular update of beam pair and low movement of vehicles would maintain the communication.

Another important performance measure is throughput in V2X scenarios. As shown in Fig. 4, a large distance between mmWave based infrastructure nodes will lead to higher throughput. This is because the beamwidth becomes wider with longer distances and this will preserve communication for a longer time slot duration. For urban vehicular environment in which vehicles are traveling with low/moderate speed, beam direction between nodes is consistently maintained due to the reliable connectivity in the corresponding time slot. Similarly, throughput increases when the time slot duration decreases due to frequent beam tracking which reduces the disconnection time [52].

B. Context Information-based Beam Alignment

Advances in wireless technologies have paved the way for the incorporation of mmWave into Wireless Local Area Networks (WLANs). IEEE 802.11ad is considered as the first mmWave-enabled WLAN in the IEEE family that works in the

TABLE III
COMPARISON OF ALGORITHMS DEVELOPED FOR VEHICULAR MMWAVE COMMUNICATION

| Ref. | Objective | Frequency | Application | Evaluation | Weakness | Strength |
|------|--|-------------------------------|---|--|--|--|
| [51] | Showed the relationship between coherence time and receive beamwidth | 60 GHz | All V2I related applications are possible | Math modelling and simulation | Practical test-bed is not considered to show directional reception will reduce Doppler spread | Have shown coherence time is increased with decreasing the beamwidth |
| [52] | Analyzed the connectivity and coverage for vehicular mmWave scenario | 28 GHz | V2I applications are applicable | Math modelling and simulation | Used channel model which is not specifically tailored for V2I scenarios | Performance improvement of existing beam tracking technique |
| [53] | Optimal beam design and beam switching based on switching among beams | 60 GHz | V2I applications are applicable | Math modelling and simulation | The position prediction would not be accurate due to speed sensing errors | Reduced overhead due to beamforming mechanism by switching from one beam to the next |
| [54] | Developed location-aware beamforming scheme for very fast initial access | The frequency band is not set | Video streaming between Vehicle and infrastructure | Numerical simulation | Assumed there is no blockage of radio link which is unrealistic in a vehicular network | Channel estimation time is reduced significantly and SNR is improved |
| [24] | Developed a technique for beam alignment | 60 GHz | Sharing raw sensor data to enable see-through (embedding camera on the front of a truck and connect it to video displays on the back), adaptive platooning and cloud-driven fully automated driving | Numerical simulation with Ray-tracing simulator | A beam alignment has been used which is specifically not designed for V2X | Beam alignment overhead is reduced |
| [55] | Effect of heavy vehicles on SINR outage and rate coverage probability | 28 GHz | Traffic and driving update, video streaming from infrastructure to vehicles | SINR outage probability and rate coverage probability are used to characterize the effect of heavy obstacles on mmWave communication | Road layout is not realistic because curvature is not considered and Road Side Unit (RSU) follows a Poisson distribution which is unrealistic because NLOS obstacles | Proposed theoretical framework is suitable to model different road layouts |

frequency band of 60 GHz. The aim is to provide multi-Gigabit data rate with a coverage of 10 meters. Amendments of IEEE 802.11 is carried out to adapt the PHY and MAC layers to the mmWave wireless environment. For instance, beamforming is tailored to 802.11ad in order to find the beamwidth and the direction of the beam. Moreover, IEEE 802.11 may also be used as a basis to build PHY layer of mmWave-enabled vehicular communication. In [64], the authors proposed a scheme to find best beamwidth for efficient channel utilization. The simulation results show high channel utilization with low number of collisions. Similarly, the problem of optimal beamforming has been studied in ad hoc networks [65]–[67]. The solutions either tuning the beamforming between the transmitter and the receiver through a control channel of omnidirectional coverage or beam pointing to a neighbor through a complete scan of angular space.

Besides, nowadays GPS receivers are embedded in mobile devices and in the near future will be equipped to the vehi-

cles [24], [68], [69]. Context Information-based (CI) mechanisms exploit position information of mobile user/vehicle and Base Station (BS) to improve the performance of mmWave communication. More precisely, new technologies such as 5G/LTE leverage CI-based solutions to optimize cell search and reduce time delay [70], [71]. In [72], the authors proposed a solution that deploys an anchor-booster eNB in mmWave-enabled Heterogeneous Network (HetNet). Booster eNB, is based on mmWave, works under coverage of the anchor eNB (which is based on 4G). The anchor eNB provides location information about Mobile Nodes (MN) to the booster BS. With this cooperation, the booster BS can direct its beam toward the specified user. However, cell discovery might be suboptimal due to inaccurate position information. For this purpose, the authors in [73] investigated the effect of position error on the performance of cell discovery especially when a new user joins a specific cell. Moreover, researchers use CI-based Initial Access (IA) of the cell search phase which

TABLE IV
CONTEXT-AWARE BEAM ALIGNMENT IN VEHICULAR MMWAVE ENVIRONMENT

| Ref. | Objective | Frequency | Application | Testing | Weakness | Strength |
|------|---|-------------------------------|---|--|---|---|
| [51] | Show the relationship between coherence time and receive beamwidth | 60 GHz | All V2I-related applications are possible | Math modeling and simulation | Practical test-bed is not considered to show directional reception will reduce Doppler spread | They have shown coherence time is increased with decreasing the beamwidth |
| [52] | Analyze the connectivity and coverage | 28 GHz | V2I applications are applicable | Math modeling and simulation | They used channel model which is not specifically tailored for V2I scenarios | Performance improvement of existing beam tracking technique |
| [53] | Optimal beam design and beam switching based on switching among beams | 60 GHz | V2I applications are applicable | Math modeling and simulation | The position prediction would not be accurate due to speed sensing errors | Reducing overhead due to beamforming mechanism by switching from one beam to the next one |
| [54] | Location-aware beamforming scheme is developed for very fast initial access | The frequency band is not set | Video streaming between vehicles and infrastructure | Numerical simulation | They assumed there is no blockage of radio link which is unrealistic in a vehicular network | Channel estimation time is significantly reduced and SNR is improved |
| [24] | Beam alignment | 60 GHz | Sharing raw sensor data to enable see-through, adaptive platooning and cloud-driven fully automated driving | Numerical simulation with Ray-tracing simulator | A beam alignment has been used which is specifically not designed for V2X | Beam alignment overhead is reduced |
| [55] | Effect of heavy vehicles on SINR outage probability and rate coverage probability and rate coverage probability | 28 GHz | Traffic and driving update, supports video streaming from the infrastructure to vehicles | SINR outage probability and rate coverage probability are used to characterize the effect of heavy obstacles on the mmWave communication | Road layout is not realistic as curvature is not considered and RSU deployment follows Poisson distribution, which is unrealistic because of NLOS obstacles | The proposed theoretical framework is suitable to model different road layouts |

allows MN to establish a physical link with a BS in mmWave 5G networks.

The authors in [61] compared CI-based search, exhaustive and iterative techniques in mmWave 5G networks. The aforementioned solutions are all about the capability of BS to determine specific MN by determining the exact beam pointing direction and beamwidth. The authors conducted a performance evaluation and the results shown that an exhaustive search performs the best in providing good coverage and serves edge users in large radio cells. In contrast, an iterative search is most suitable for small radio cells. The type of beamforming is also important for the BS to direct its beam to the MN. For instance, Analog Beamforming (AB)

is superior in terms of low energy consumption as compared to digital and hybrid techniques. In [74], exhaustive approach has been used with AB in order to increase gain at the MN. The availability of CI at the MN is exploited to restrict the MN to specific direction alignment rather than angular cell search. This will significantly result in reducing the initial cell searching delay. However, the accuracy of CI significantly affects the performance of the cell discovery mechanism [70].

Nevertheless, to accurately use the CI of a user by mmWave, the BS needs to reduce the time needed for beam alignment and optimal beamwidth [75]. The authors in [70] proposed an enhanced cell searching mechanism. When a new MN intends to associate with a cell, the BS exploits the CI of

a MN to find the appropriate beamwidth and beam alignment. This is because the cell search mechanism is affected by the beamwidth. In particular, a larger beamwidth would lead to very fast cell scanning with less beam switches. However, only edge users can be reached [70]. To serve far end users, narrow beamwidth should be considered.

The feedback of position information is important for accurate and low overhead beam alignment in vehicular mmWave network. In a vehicle to infrastructure scenario, when a vehicle drives toward a RSU, it uses IEEE 802.11p to send position information. This CI is useful for a RSU to refine beam re-pointing especially at the initial stage when there might be position inaccuracy. It is not recommended to use mmWave communication to send feedback about the position and speed of vehicles to the RSU because Doppler spread could hinder beam sweeping and hence, cause communication failures [76]. Furthermore, in low speed/static wireless scenarios, beam-forming needs to be completed in a short period of time. In high mobile scenarios such as vehicular networks the time needed for beamforming should be very low. The authors in [54] proposed a location-aware beamforming scheme for very fast initial access of a vehicle to the RSU mmWave channel. The received SNR and the average duration time for channel estimation are used to evaluate the proposed scheme. Numerical simulation results show that the time needed for channel estimation is substantially reduced and the channel quality is improved when position information is provided over 80 m distance or more. Moreover, in [?], the authors developed a correlation function between coherence time and the received beamwidth. More precisely, they have shown that the Doppler spread decreases with a decrease in beamwidth. In the scenario modeled, despite embedding beam pointing error and vehicular mobility in the developed

equation, the optimal beam alignment between the transmitter and the receiver is considered. This alignment is necessary in mobile networks due to very narrow beamwidth which causes high signal attenuation. Similarly, in [77], Vu et al. utilized the learning-to-rank machine learning approach to determine the most appropriate pointing direction that can mitigate the required beam training. For this beam direction ranking, the proposed approach uses position coordinates and past beam measurements. Table IV presents positional information-aware beam alignment in vehicular networks.

C. Transient Link Blockage in V2X context

In the past few years, mmWave has significantly contributed to the development indoor Wireless Local Area Network (WLAN) and 5G networks. WirelessHD is an example of mmWave enabled WLAN [78]. In a cellular system, it is used to provide high bandwidth and a dense network [79]–[82]. With the advances in vehicular sensing and perception capability, multi-Gb wireless network is becoming an important requirement for intelligent vehicular networks [24], [83]. The high bandwidth provided by mmWave technology enables efficient communication of raw sensor data among vehicles and RSUs. As a matter of fact, mmWave technology has long been used in vehicles [13]. For example, embedded radar system used in automotive vehicles is based on mmWave. Mmwave-enabled vehicular communication has been studied by Kato et al. in [84]. This technology is even standardized for vehicle-to-vehicle communication by International Organization for Standardization (ISO) [85] and recently gained further interest for the V2X environment [86].

The modeling of highway vehicular scenario in terms of base station deployment is performed by varying time and landscape of the region. For this type of modeling, M. Haenggi et al. in [37] used the stochastic geometry technique and assumed a Poisson Distribution (PD) of RSUs in the highway environment. This assumption is realistic for wireless networks working under 6 GHz frequency band [91]. However, the deployment of mmWave-enabled RSUs along the highway does not follow PD because the Non-Line of Sight (NLOS) link obstructs communication [55], [82]. In an attempt to address this NLOS issue, in [82], the authors considered the existence of radio obstacles in urban mmWave-enabled 5G network. The deployment of RSUs follows a Poisson Distribution and static obstacles are used to block the radio. As shown in Table V, either Boolean Germ Grain (BGG) is

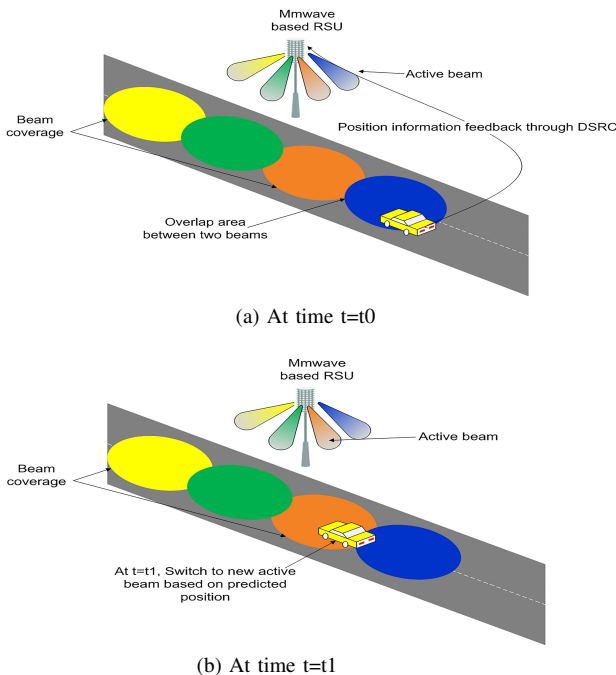


Fig. 2. Beam switching based on positional information

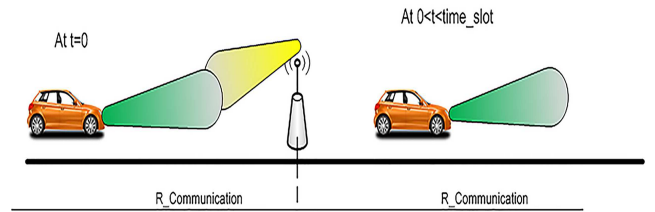


Fig. 3. Connectivity of a vehicle to infrastructure in mmWave-enabled vehicular network. Initially, the vehicle is connected to the infrastructure at $t=0$. When it overtakes at the same time slot, the connection will be down.

TABLE V
LINK BLOCKAGE IN MMWAVE ENABLED VEHICULAR NETWORKS

| Ref. | Wireless | Channel model | Radio obstacle | Network scenario |
|------|----------|--|--|--|
| [87] | 802.11p | Rayleigh small-scale fading | Moving obstacle (vehicles) | V2V |
| [88] | 802.11p | Shadowing propagation model | Existence of buildings increase signal attenuation | V2V |
| [89] | 802.11p | Computing additional attenuation due to vehicles | Vehicles | V2V |
| [90] | 802.11p | Obstacle-based radio blockage | Moving obstacle (Vehicles) | V2V |
| [75] | mmWave | Ray-tracing model | Obstacles not experimented | V2I and V2V |
| [78] | mmWave | Measurements | Buildings | Cellular networks |
| [79] | mmWave | Constant small scale fading | No obstacle modelling | Network backhauling |
| [91] | mmWave | Boolean Germ Grain (BGG) model | Buildings | Cellular network with self backhauling |
| [81] | mmWave | Measurements | Indoor objects | Cellular network with self backhauling |
| [82] | mmWave | Nakagami propagation model; BGG model | Buildings | Dense cellular network |
| [92] | mmWave | Heavy obstacle based radio blockage | Heavy vehicles | V2I |

used wherein the MN can only communicate with BS within the Line of Sight (LOS) range, or the probability of the BS in LOS/NLOS is used to model the path loss propagation.

Obstacle and path loss models that have been specifically developed for vehicular highway/urban network are important to characterize the physical propagation of the environment. In particular, in [88], the authors used a shadowing model [93] to represent the wireless medium erasure channel. They considered a radio range 400 meters with a probability of 80 % of transmission success. The aforementioned parameters have been selected based on real life channel measurements between vehicles [94]. In contrast to [88], in [89], the authors developed a model that considers vehicles as 3D obstacles and how they obstruct the LOS communication, thereby affecting the packet delivery ratio and link quality among vehicles. The IEEE 802.11p standard has been adopted for the MAC/PHY layer. The simulation results obtained by the authors of [89] show that moving obstacles substantially deteriorate the link quality and lead to significant packet losses. In a similar attempt, the authors of [90] developed a model for moving obstacles such as surrounding vehicles and trucks in order to demonstrate the effect of signal blockage on the communication link. They used IEEE 802.11p as the MAC/PHY layer for vehicles. The authors in [87] proposed a routing algorithm for multi-hop vehicular ad hoc communication for highway scenarios. The models developed by efforts in [87]–[90] are best suited for the DSRC frequency band, i.e., they cannot be applied to the mmWave-enabled vehicular context because of its different propagation characteristics. In the mmWave environment, antenna arrays are significant for beamforming. Considering beamforming and highway scenarios, in [92], the authors proposed a mathematical model for the highway V2I scenario where trucks acts as obstacles for vehicles in the fast lane. In vehicular networks, vehicles can be equipped with multiple antenna arrays. However, the signals between antenna arrays need to be precisely synchronized for efficient communication [95].

IV. HANDOVER IN MMWAVE ENABLED VEHICULAR CONTEXT

The high propagation path loss at 60 GHz mmWave technology results in small cell sizes and overlapping configured areas for communication among MNs. As a consequence, frequent handover occurs to switch the point of attachment from one

cell to the next one. Most of the ongoing studies have been focusing on grouping several RSUs into a single virtual cell in a Radio-over-Fiber (RoF) network [96], [97]. Recently, RoF has become a promising field of study and has attracted the attention of many researchers because it combines the mobility capability of mmWave technology with fixed fiber optics [98], [99]. The RoF network addresses several fundamental issues of 60 GHz frequency band in order to achieve fast mobile communications [100]. Many efforts have been made to adopt RoF at 60 GHz frequency band because it provides high bandwidth for indoor [101], [102] and outdoor [100], [103] environments.

In outdoor environment, radio communication range of cells in the 60 GHz frequency band is in the range of 15-20 m with an overlapping region of 4-5 m [104]. As shown in Fig. 5, when a MN needs to change its point of attachment from RSU_1 to RSU_2 , the handover procedure is triggered when the MN senses a beacon message. When the MN is within the coverage of RSU_2 then it receives the beacon message [47]. Thereafter, the MN triggers handover and an association to RSU_2 . In order to support real time applications, this process should be very fast [105], [106]. In other words, the handover process initiation and completion should be done while the MN is within the overlapping region. Therefore, the MN moving at low speed could be served well without connectivity failure [103].

The handover process is more challenging in indoor environment because the time elapsed to trigger and complete the procedure is very short. This is due to harsh signal attenuation induced by indoor components such as walls, doors and windows. In buildings not only produce high attenuation, but squeezes the overlap area between cells [102]. Another obstacle of communication is the existence of corners in buildings, which obstructs signal and hinders the triggering of handover or its completion.

Media access schemes developed in RoF are all based on connecting multiple local base stations to work as a single large virtual cell [97]. As shown in Fig. 6 the authors in [97] proposed an access protocol based on reservation that uses slotted ALOHA for RoF context. This access protocol could significantly reduce handover latency by connecting multiple RSUs to a Central Base Station (CBS) through optical fiber and those RSUs transmit the same information over the same frequency band. One important feature is absent in the work

of [97] wherein the vehicles running on the roads could not recognize the RSU that they are within its radio coverage. Therefore, vehicles could not make handover decision in advance. In [107], [108] similar approaches to [97] have been used for reducing handover latency in RoF technology. However, in the virtual cell, only one RSU is active for transmitting and receiving data. This will effectively reduce co-channel interference between adjacent RSUs. Another significant improvement is that vehicles can recognize which RSU they currently belong to. An RSU broadcast beacons in which its ID is included and with this information vehicles can prepare for advance handover process. For example, when a vehicle wants to move from one RSU of CBS1 to another RSU within CBS2, both CBSs exchange signals to prepare the handover process. Then, actual handover can be triggered while the vehicle is in the overlapping area.

Additionally, three handover techniques namely Moving Extended Cell (MEC), Virtual Cellular Zone (VCZ) and Moving Cell (MC) are reviewed and compared in [104]. An extended cell is used in indoor environment to address corner effects and achieve seamless handover. The idea of MEC extends the EC concept in order to support indoor and outdoor environments. A vehicle receives data from the extended cell coverage since all RSUs transmit the same information over the same frequency band. A vehicle can leave the current serving cell in all directions. When a user joins a new RSU, a new extended cell needs to be reconfigured. Once a vehicle receives a beacon message from a RSU, dynamic formation of a new extended cell will be triggered. This technique significantly reduces the handover latency. However, co-channel interference remains a main concern because RSUs within the same MEC works on the same frequency band. Furthermore, the concept of VCZ is to manage the handover process of N cells in a centralized location. These cells are divided into subgroups called VCZ in such a way that they work on different frequency channels. This will address co-channel interference between VCZs. Time Division Multiple Access (TDMA) is used to slice the

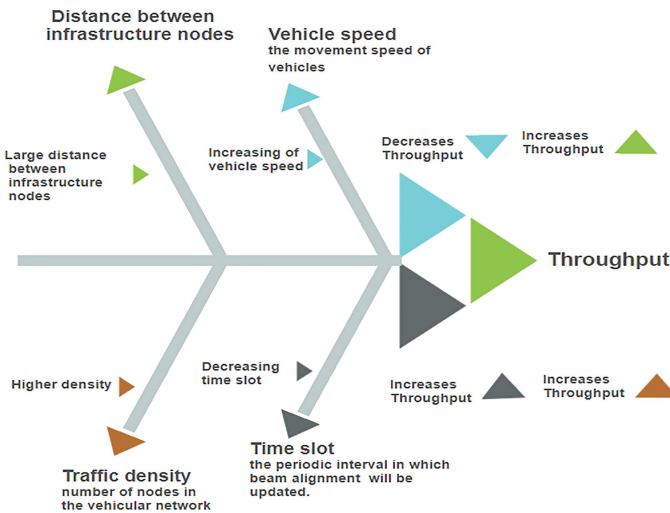


Fig. 4. Effect of distance between infrastructure nodes, vehicle speed, periodic update of beam alignment and traffic density on throughput

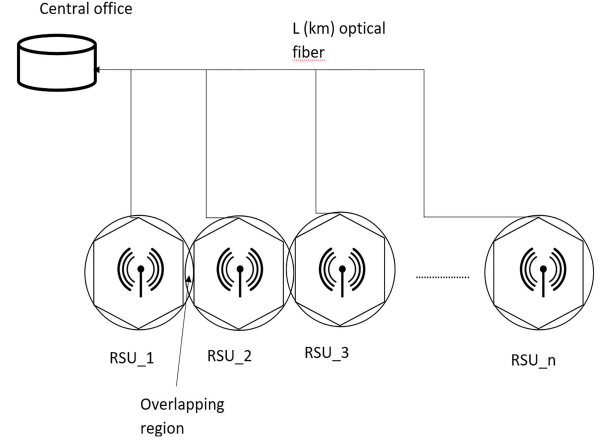


Fig. 5. Handover process between adjacent cells in 60 GHz RoF networks

frequency channel into several constant time frames and each of them is further divided into time slots. Several time slots are assigned to specific VCZ in order to support efficient channel access within VCZ. This type of handover technique is considered as the static clustering method.

Experiments have been conducted to compare the performance of the aforementioned handover algorithms. The results show the superiority of MEC as compared to the rest in terms of delivering more packets and reducing packet loss. This is due to the large overlapping area in MEC, which makes handover process more efficient. However, MEC incurs a higher complexity as compared to the VCZ technique. This is because of the need to track the movement of vehicles in all directions. Table VI illustrates wireless access methods for RoF-based vehicular scenarios.

V. APPLICATIONS OF VEHICULAR MMWAVE COMMUNICATION

The Gbps vehicular communication is a promising field that will support a wide range of applications. In this section, we present some examples to establish the basic requirements

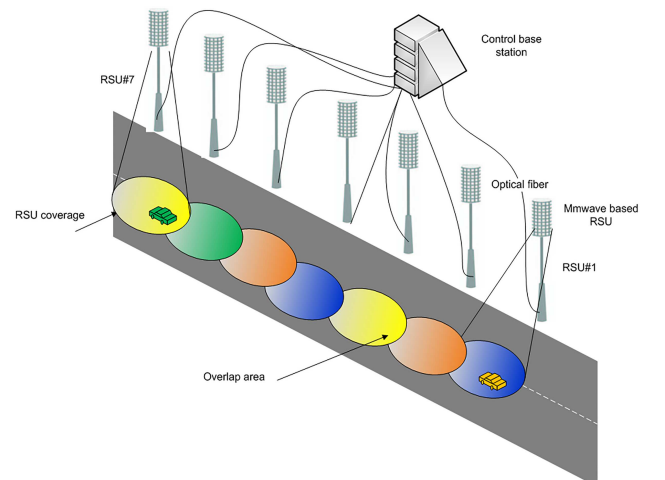


Fig. 6. RoF combined with mmWave in the connected vehicular context

TABLE VI
WIRELESS MEDIUM ACCESS METHODS FOR ROF BASED VEHICULAR NETWORK

| Ref. | Channel access method | Advanced handover | Radio obstacle |
|-------|---------------------------|-------------------|--|
| [97] | Reservation slotted ALOHA | Not supported | Blockage not considered |
| [107] | TDMA | Supported | Blockage not considered |
| [108] | TDMA | Supported | Blockage and fading are not considered |
| [104] | TDMA | Supported | Radio obstacle is not considered |

of the communication links. The following sections presents potential applications. In each of the prospective applications, different sub-categories are derived as follows: (traffic safety and flow management, comfort related applications). In the following sections, we also describe the required data rate, reliability and latency for each use case [109].

A. Cooperative Perception

In a cooperative driving application, perceptual data which include LIDAR, radar, or camera images are shared. The work presented in [110] demonstrated how perceptual data from neighboring vehicles can be integrated with the use of image processing to create a satellite view of the surrounding traffic to expose hidden objects (e.g., at curvature roads) and handle blind spots. Another application developed by the researchers [111] provides see-through vision in a situation such as when one's car is behind a truck (as depicted in Fig. 7). As shown in Fig. 7, the company Samsung developed the viable safety track concept [111] in order to make overtaking heavy vehicles more safer. Moreover, if a pedestrian suddenly crosses the road in front of the truck, the truck's camera should be able to detect the situation and share the image of the pedestrian with the car following behind the truck and by using virtual reality technology, the pedestrian is shown on the windshield board [110]. Automated cars and human drivers can make use of this extended perception range. This application helps to avoid collisions because hidden objects can be easily visualized by drivers while ensuring smoother traffic flow (e.g. a complete view of surrounding traffic helps a driver to make wise decisions for lane-change). Furthermore, to leverage such perceptual data support, the high bandwidth requirement becomes even more important. Since the application needs real-time integration of such data, low latency is needed [112].



Fig. 7. See-through vision for a vehicle following a truck [111]

B. Bird's Eye View at the Intersection/merge on the Highway

Traffic safety and efficiency can be assured at road intersections if a RSU broadcasts images of the crossing roads to approaching cars. For instance, at the intersection in urban or highway scenarios, sensors such as radars or cameras can be used to provide information for approaching vehicles. The streamed data is used by vehicles to identify ultimate pedestrians or free parking slots that cannot be detected with the sensors attached to the vehicles. As a result, drivers can receive guidance on future optimal trajectories such as when joining the highway or navigating through an intersection. All the data streams need to be received with low delays to enable vehicles to make timely decisions in conjunction with data provided by on-board sensors [113], [114].

C. Video Surveillance

In recent years, many nations have witnesses an increase in illegal activities including theft, crimes, robbery, public nuisance, and terrorism. To deter such activities, real time video surveillance inside/outside of vehicular objects can be very helpful. In vehicular video surveillance, a vehicle transmits coded video to the infrastructure network. The content of the video could be a call for help due to some traffic accident or some safety condition of passengers inside vehicles involved in an accident. The video streaming generated from public transportation is sent to the traffic management center to prevent any crimes [115], [116]. Nonetheless, video communication for surveillance purposes remains a challenge with vehicular mmWave communication because of its quality of service requirement.

D. Video Communication

In addition to classical services (e.g., web browsing, file transfers, email, online games, and so on) the Internet can provide, user demands for high-streaming and sharing keep increasing. To meet such demands, higher image resolutions (e.g., 4K standard) will need to be supported [117]. In this case, the required throughput is high along with stringent latency. MmWave based vehicular communication can provide high data rate and fulfil the aforementioned requirements. The amount of multimedia data generated from rich sensor devices such as camera and LIDAR depends on the resolution of images produced and the compression ratio of the image. For instance, a low resolution image generated from LIDAR requires a data rate [110] of 60 kbps whereas high resolution multimedia data requires approximately 33 Mbps [118]. The aforementioned data rates only support data generated from the perception sensors. However, there are many sensors and

actuators embedded inside today's vehicles for positioning and checking the condition of a car [22], [119]. Therefore, the network bandwidth that can support the generated data from many sensors should be high (Mbps to Gbps link rates). This required data rate does not consider the fact that the wireless medium is shared among users and can be accessed through contention based protocols. In a realistic vehicular scenario, we expect hundreds of vehicles to join a shared wireless medium, and therefore, an even higher link data rate is likely to be needed to support multi-gigabit per second data transfer rates of multiple vehicles. Furthermore, latency for safety-related applications should be very low. As a result, we need to develop low latency physical layer and robust MAC layer so that vehicles can efficiently communicate and disseminate information [120]–[122]

E. Map Generation System

Connected vehicles provide many applications ranging from in-vehicle infotainment to traffic safety services. These applications will be more perceptual when vehicles send images and positional information to the cloud. The required data rates and tolerable delay depend on the type of multimedia processing [123]. An accurate map can be produced by using generated data from a large number of vehicles and GPS devices. Recently, Toyota Motor Corporation developed such a system to generate a precise map of urban environments [123]. In particular, vehicles send images of the roads and vehicle's positional information to a data center where image matching technologies are used to combine and correct road images collected from multiple vehicles. This integration results in the creation of an accurate map of a region. Such a map along with traffic rules (such as street signs, speed limits and traffic light signs) are very useful for future automated cars.

F. Sharing of Sensor Data

The sharing of raw sensor data among vehicles can help improve sensing accuracy and ultimately improves vehicular safety. For instance, by sharing raw GPS data and by applying real-time kinematic methodology, the relative positioning accuracy can be improved to less than one meter as presented in [124]. The data rate required to share raw sensor data depends on the sensor type and the number of shareable sensors. To improve sensing accuracy for safety applications, real time processing is needed with minimal latency. MmWave communication is a best candidate to support vehicular communication for sharing such high raw data among vehicles.

G. Cooperative Obstacle Avoidance

In connected vehicles, early lane changing for obstacle avoidance is important. For instance, a driverless vehicle could, in an emergency situation, avoid obstacles by changing lanes early with the support of a cooperative perception system. In [110], the developed system could trigger automatic early lane changing if forward collision has occurred on the road and the lane-changing opportunity is available.

As illustrated in Fig. 8, (a) the obstacle can be detected by the leader vehicle. The ego vehicle cannot not detect the

obstacle due to NLOS limitation whereas the leader vehicle may stop due to the unusual object. In Fig. 8 (b), both vehicles could stop promptly to avoid a front collision because of the obstacle. The ego vehicle takes another lane to overtake the leader. However, it is a challenging task to re-plan the route by the ego vehicle as both vehicles are very close to each other and the front vehicle may come to a sudden stop. In Fig. 8 (c) by leveraging the support of cooperative perception, early lane changing can be activated on time.

H. Vehicle to Road User Communication

Vehicles frequently broadcast their existence and position. Road users include pedestrians, cyclists, or people carrying a mobile device discover vehicles in the vicinity and begin broadcasting themselves. In situations where there is a close danger, the mobile user can trigger a loud warning sound, vibration and/or light flashing. The nearby vehicles receive the information from the announcing road user and possibly informs the driver of the car concerned and the nearby user if any unusual condition is detected. Reliability and accuracy of the location service for this application is crucial. Cooperative positioning [125] and the combination of several localization mechanisms such as Time of Arrival (ToA), satellite and Global Navigation Satellite System (GNSS) [126], [127] are used to improve location accuracy. This hybrid technique could improve the localization accuracy of vehicles in urban and highway vehicular scenarios. Table VIII presents some technical requirements for promising applications of vehicular mmWave networks. As Table VII shows, there are several application scenarios for IoV. In most applications, rich content is shared among vehicles to improve their driving experiences. Most of the applications need high bandwidth and low latency due to sharing of coarse information among vehicles.

VI. PERFORMANCE METRICS OF APPLICATIONS FOR VEHICULAR MMWAVE NETWORKS

This section presents the technical requirements of the aforementioned mmWave enabled vehicular applications:

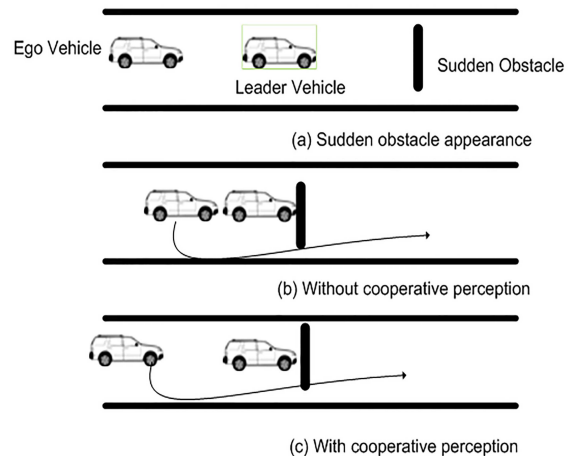


Fig. 8. Automated lane changing for cooperative forward collision avoidance

TABLE VII
PERFORMANCE REQUIREMENTS FOR LOW LATENCY AND HIGH RELIABILITY SCENARIOS [128]

| Scenario | Data plane latency | Reliability | Payload size |
|-------------------------------|--------------------|-------------|---------------------------------|
| General URLLC | 1 ms | 99.999 % | 32 bytes |
| Enhanced V2X | 3–10 ms | 99.999 % | 300 bytes |
| Discrete automation | 10 ms | 99.99 % | Small(≤ 256 bytes) to big |
| Intelligent transport systems | 10 ms | 99.9999 % | Small to big |
| Tactile interaction | 0.5 ms | 99.999 % | Small |

TABLE VIII
TECHNICAL REQUIREMENTS FOR VEHICULAR MMWAVE NETWORKS

| Application | Technical requirements | Background | Network topology |
|-------------------------------------|---|---|---------------------------|
| Cooperative perception | Location accuracy: 0.4 m, High data rate, and low delay (up to 100 ms) | This use case shares perceptual data such as camera images, LIDAR and radar. It requires high rate, low delay accurate position information | Vehicle-to-vehicle |
| Bird's eye view at the intersection | Data rate: 10 Mbps*n n: is number of cameras at the intersection, delay: 50 ms | In this application, four cameras are fixed at the intersection and share traffic of the surrounding area to vehicles approaching the intersection | Infrastructure to vehicle |
| Media download | Data rate depends on content type, delay: in the order of minutes | The required data rate to download data/software update from internet depends on the content type. This application can tolerate delay | Infrastructure to vehicle |
| Map generation system | Location precision: 0.1 m, High data rate | The idea behind map generation is to send image of the road layout by massive number of vehicles and GPS data to the cloud. This requires high data rate and high precision positional information | Vehicle to cloud |
| Sharing of sensor data | Low delay, High data rate | For safety application, real-time sensor data sharing is required. Thus, it needs low delay. High data rate is required to share sensor data | Vehicle-to-vehicle |
| Cooperative obstacle avoidance | Location accuracy: 0.4 m, Reliability: 1/1000, Status update: 100 ms | In multilane roads, cooperation is significant between vehicles to build necessary gap on the lanes to avoid collision. To achieve this objective, vehicle status need to be updated in 100 ms with a packet loss rate 1/1000 | Vehicle-to-vehicle |
| Vehicle to road user communication | Location accuracy: 0.1 m | This application requires ultra-low positioning error | Vehicle to road user |
| Pre-crash sensing | Ultra low latency of 0.01 s | This application requires ultra latency in order to enable a vehicle near an accident scene inform other vehicles that there is an accident | Vehicle-to-vehicle |

- **Location accuracy:** This is defined as maximum error in which a specified application can tolerate. This parameter can be derived for each specific application based on the road layout and the width of a vehicle. For instance, the standard width of a vehicle is 2.5 m [129] while the width of a lane is 3.7 m [130]. Taking 2.5 m from the total lane width 3.7 m, 0.6 m remains on each side of a vehicle. To position a car and still remain inside the lane, the accuracy of 0.4 m is still feasible [131]. It is worth noting that the same procedure can be derived for a vehicle to road user application. **Moreover, vehicular communication permits more accurate navigation by using imaging services to perform 3D positioning based on camera and radar. Furthermore, vehicles are communicating with other vehicles in the vicinity, this communication would be more accurate if absolute and relative position information of vehicles are precise and timely. To achieve this precise positioning, the 5G mobile communication system is expected to provide a suitable environment because of its high**

bandwidth and large antenna arrays which enable accurate Time of Arrival (ToA) and Direction of Arrival (DoA) estimation especially in LoS scenarios. Therefore, different types of location-based services and applications such as intelligent traffic system (ITS) and connected autonomous vehicles, vehicles, will benefit from such a positioning system in 5G.

- **Data rate (Mbps):** This is the required throughput for an application to work efficiently. For sharing traffic images at an intersection, 10 Mbps data rate and 50 ms of delay can be tolerated (MPEG 720p video at 30 frame/s) [116], [132], [133]. **More precisely, the applications of V2X communication include fully automated driving, cloud assisted driving, cooperative collision avoidance, mobile entertainment, and intelligent driving. In automated driving, vehicles act independently and communicate with one another, share what they learn and see [134]. Each of the aforementioned applications has its own set of requirements, but V2X typically requires low latency and medium to high data rates. In**

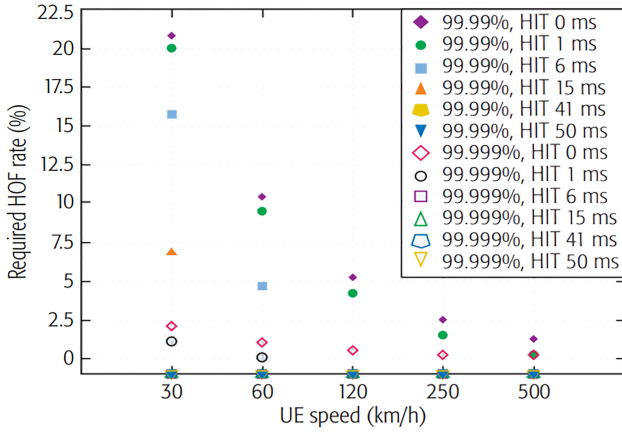


Fig. 9. Required HOF rate to achieve $1-10^{-4}$ and $1-10^{-5}$ reliability with different values of HIT and UE speed [137].

the extreme case of sharing raw sensor data between vehicles, it requires Gbps data rates. Moreover, jointly controlling multiple vehicles and coordinating them in a platoon requires high data rates. In a nutshell, mmWave communication can provide high data rate per user because of its high bandwidth. As shown in equation 1, the data rate per user is defined as follows [135]:

$$\text{Data rate / user} = \frac{\text{Bandwidth} * \text{MIMO} * \text{SE}}{\text{No. of users}} \quad (1)$$

where SE is the Spectral Efficiency and the data rate per user is measured in bit/s. Thus, bandwidth is key for higher data rates. On the other hand, MIMO spatial multiplexing gain requires supporting more antenna in both transmitter and receiver sides. SE Depends on signal, noise and interference power. It is difficult to increase the spectral efficiency because of the limitations in allowable power transmission. In particular, increasing the transmission power also leads to an increase of interference power. Furthermore, in equation 1, the number of users share network resources. Thus, in connected vehicular mmWave scenarios, bandwidth is an important and more flexible factor that could be increased because it will significantly improve capacity, thereby affecting the SE and mmWave antenna beamforming reduces interference experienced by other users [135]. Table IX shows the data rate of current LTE and 5G cellular systems.

- Ultra Reliability:

Reliability is defined as number of packets lost (a packet is lost when it has been transmitted from the source but has not been received by the destination) that an application can tolerate. In other words, the reliability of a communication system can be evaluated by the success probability of transmitting X bytes within a certain delay. There are many reasons for packet loss and these include: unreliable wireless channel, fast channel

variation, high mobility of vehicles and excessive delays. The channel state varies because multiple paths constructively and destructively interfere to each other. Thus, one of the key communication challenges is matching the transmission rate of the source to the quality of wireless channel. However, the quality of wireless channel is not known to the source vehicle. Thus, there are two options. First, the transmitter transmits at a high data rate, possibly leading to transmission failures and the transmitter performs retransmission. Second, the transmitter sends at a low rate which leads to channel underutilization. To achieve reliable transmission, channel coding and partial re-transmission of corrupted transport blocks called Hybrid Automatic Repeat Request (HARQ) is considered in current mobile communications systems. In fact, ultra reliability services require high reliable transmission which is in the range of 0.99999 [128]. Moreover, sensitive use cases, such as connected autonomous vehicle, factory automation and tele-surgery, require highly reliable communication up to $1 - 10^{-7}$ [138]. Table VII presents typical Ultra Reliability and Low-Latency Communication (URLLC) use cases and their performance demand for latency and reliability with payload sizes. Table VII shows that the general URLLC reliability requirement is $1-10^{-5}$ with 32 bytes and a data plane latency of 1 ms. Another important indicator to achieve reliable communication is mobility management in next generation communication scenarios. As stated in [128], mobility is defined as the maximum speed of users at which communication systems can achieve good Quality of Service (QoS). Another metric which affects the reliability of communication systems is the Mobility Interruption Time (MIT). MIT is the shortest time period which is acceptable by the system during which a vehicle cannot exchange data plane packets with any base station during the handover process. Fig. 9 illustrates the importance of the handover process and mobility management on required HandOver Failure (HOF) rate to achieve $1-10^{-4}$ and $1-10^{-5}$ reliability with different values of HO Interruption Time (HIT) and vehicle speed. In particular, the authors in [137] show the impact of user mobility on the reliability of communication (in Fig. 9) by setting the speed to 120 km/h and HIT to 0 ms. With this configuration, the required HOF rate to achieve $1-10^{-4}$ reliability is 5.2 percent whereas when the value of HIT is increased to 1 ms, the required HOF rate to achieve $1-10^{-4}$ reliability is 4.24 percent. Thus, handover failure significantly affects the reliability of communication systems.

- Latency (ms): There are four important components of latency which include propagation, transmission, processing, and queueing delays. All these delay components should be considered in V2X communication systems. For IoV, mmWave can significantly reduce latency because it provides a high data rate and

TABLE IX
DATA RATE OF 4G AND 5G COMMUNICATION SYSTEMS [136]

| System antenna | Duplex BW | fc (GHz) | Antenna | Cell throughput (Mbps/cell) |
|----------------|---------------|----------|-----------------------------------|-------------------------------------|
| mmWave | 1 GHz TDD | 28 | 4*4 User & 8*8 eNB | 1514 for Downlink & 1468 for Uplink |
| mmWave | 1 GHz TDD | 73 | 8*8 User & 8*8 eNB | 1435 for Downlink & 1465 for Uplink |
| Current LTE | 20+20 MHz FDD | 2.5 | 2*2 for Downlink & 2*4 for Uplink | 1435 for Downlink & 1465 for Uplink |

TABLE X
CONTROL AND DATA PLANE LATENCY FOR 4G AND TARGET 5G

| Item | Air link RTT measurement | Current LTE | Target for 5G |
|-----------------------|--------------------------|-------------|---------------|
| Data plane latency | UE in connected mode | 22 ms | 1 ms (URLLC) |
| Control plane latency | UE begins in idle mode | 80 ms | 20 ms |

spectral efficiency. In some IoV scenarios, such as pre-crash sensing, only mmWave can provide low latency in the range of 20 ms for a pre-crash active safety service. The IoV scenarios promise to enable vehicles to promptly detect critical traffic situations by alerting vehicles in vicinity of the hazardous scene. 5G technology provides ultra-low latency to minimize the reaction time of autonomous driving cars. However, the existing LTE system has a few fundamental limitations preventing it from supporting autonomous vehicle scenarios and critical IoV services. The first limitation of LTE is the Transmission Time Interval (TTI) of 1 ms for radio transport block of subframes. To make the underlying communication system more responsive, 5G is using a scalable Orthogonal Frequency-Division Multiplexing (OFDM) framework wherein within 1 ms time duration, six separate slot configurations are available. With this method, the TTI of a transport block could be dramatically reduced. Table X shows the control and data plane latency of LTE and 5G communication system. As the table shows, in current LTE systems the data plane latency, where a user is in connected mode with a base station, is 22 ms while the latency target between a user and a base station in 5G system is 1 ms. In 5G, reducing latency requires careful consideration of all protocol layers including the Radio layer (MAC and physical layers), Mobile Core networks and edge cloud. For example, in 5G radio link there are several techniques to reduce latency and these include redesigning the coding, developing efficient error correcting code and the use of shorter MAC frames.

VII. RESEARCH CHALLENGES

Despite preliminary advances in incorporating mmWave technology into vehicular networks, several important research still need to be addressed before the ubiquitous deployment of mmWave technology in vehicular communications. mmWave networks will promote and support novel services for vehicular communications. To be able to deploy these novel services in practice, several research challenges should be addressed. Next, we discuss some of the challenges that we have identified and they include: deafness and blockage issues, handover, vehicular mobility for mmWave links, adaptation

of beamwidth size, sensing-aware smart protocol and beam management.

A. Deafness and Blockage

Deafness and blockage could obstruct the communication in the mmWave environment. These phenomena are even worse in vehicular networks. Deafness occurs when there is a misalignment of the transmitted beam toward the receiver device whereas blockage refers to the phenomena where high penetration loss occurs due to obstacles or any other external causes [139]. Although solutions such as increasing the transmission power could increase radio coverage, it does not improve performance in these aforementioned cases. Therefore, in order to address these problems, it is necessary to identify the causes (deafness or blockage) of the performance degradation. Next, an efficient solution is needed to alleviate the problem. For instance, an adaptive technique that can re-pointing the beams in case of access failure due to beam misalignment would be worth investigating.

In vehicular networks, the network topology is changing at a fast pace. Deafness and blockage occur frequently and differentiating between them becomes even more challenging. In high mobility, it is a daunting task to frequently update the neighbor table, which includes the positional information. If this is the case, vehicles could not get precise location of their neighbors. This causes beam misalignment and hence leads to deafness between the transmitter and the receiver [140]. A possible solution to this problem is to perform cooperation among vehicles in V2I and V2V scenarios so that accurate positional information can be obtained from DSRC links.

Directional transmission of data and blockage in vehicular mmWave network are two important characteristics. However, current state-of-the-art research results do not address them in realistic scenarios. In vehicular mmWave networks, not only heavy vehicles can obstruct packet transmission but small cars could also deteriorate channel quality [141]. This deterioration is due to multipath fading and signal shadowing. Therefore, adaptive beamwidth is important to address multipath fading and achieve fairness especially in urban vehicular scenarios. Narrow beams could ease multipath fading. However, very narrow beamwidth (10° [142]) is costly due to its high overheads. **The authors of [143] addressed the link blockage issue by enabling the base stations to predict if a certain link will be susceptible to blockage. For this purpose, they**

used past beamforming vectors. Moreover, blockage events can be reduced by deploying more RSUs, but this will lead to a less system responsive. Another possible solution is to make the handover to sub-6 GHz during the link blockage period [144].

B. Handover Process

In mmWave networks, the feasibility of directional antenna depends on efficient beam alignment and tracking. This necessity is confirmed by existing mmWave based wireless technology standards such as IEEE 802.11ad. In a vehicular environment, beam alignment is even more challenging because it should be complete in a very short period of time. Very fast beam alignment techniques need to be developed to meet the vehicle's mobility requirements [145], [146]. Thereafter, beam tracking is required to maintain the alignment of beams between the transmitter and the receiver.

Efficient beam tracking could enhance the performance of vehicular communication. In particular, advanced beam tracking can be adopted by considering the direction of movement of the vehicles, position and load on the access point rather than selecting the optimal access point based solely on the SINR. By using a combination of these aforementioned parameters, more efficient handover decisions can be made since the interaction time between a vehicle and the infrastructure node will be higher and hence number of handovers will be significantly reduced. Fig 10 depicts the fuzzy logic [147], [148] system for advanced handovers when selecting the optimal mmWave enabled access point. The fuzzy logic consists of three main components which include fuzzification, inference engine and defuzzification. To precisely design the fuzzy logic, it is required to find the number of inputs, the range of inputs, the knowledge base and the output variable with its ranges. The inputs that can be used by a vehicle to make a decision are the distance to the infrastructure node, the relative direction between the vehicle and the infrastructure node and the channel quality (SINR).

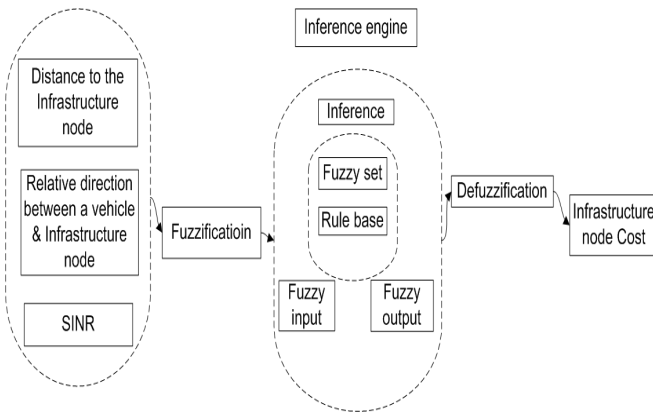


Fig. 10. Fuzzy inference system for advanced handover in mmWave vehicular environment

In the existing literature, researchers have been focusing on the distributed antenna mechanism (formation of large virtual cell), where all of the connected infrastructure nodes transmit

the same information to all nodes within the radio coverage. This mechanism could significantly reduce the frequency of handover. However, this approach is at the expense of poor frequency reuse wherein the same frequency can be re-utilized in different cells [149]. Thus, the trade-off between spatial reuse and frequency handover should be studied.

C. Vehicular Mobility Model

Realistic simulation studies of vehicular communication can have a significant impact on the credibility of simulation results. Mobility models represent the realistic movement of vehicles and vehicular urban scenarios. Thus, mobility models should incorporate efficient vehicular interactions such as a car following a trajectory, lane changing model and gap acceptance. Several mobility models exist in the literature that generate mobility traces using vehicular network simulators such as SUMO or STRAW [150]–[152]. Despite the importance of vehicular mobility model in generating road traces, microscopic modeling of vehicular movement has not been fully explored [153]. This is because the SUMO road traffic simulator assumes a constant speed of vehicles whereas STRAW supports random way-point vehicular movements. Thus, microscopic vehicular movement should be further studies in order to evaluate mmWave beam misalignment.

D. Adaptation of Beamwidth Size

Most of the existing works relate to the directionality of beam transmission are based on large beamwidth (60°). However, large beamwidth degrades the transmission rate. Moreover, mmWave communication utilizes narrower beamwidth in order to provide higher directivity and hence large throughput. This is at the expense of significant overhead due to beam searching in many directions. As a result, this process incurs alignment overheads, which is defined as the time taken to find the best beam. Further, channel access requests from nearby vehicles to a specified infrastructure node may lead to high packet loss. This is because a smaller cell size increases congestion on the channel access. Thus, it is necessary to consider cooperation among vehicles based on DSRC short range communication among cars [154]. It is also required to adapt beamwidth from large to small sizes in order to strike tradeoff between overhead and throughput. More efficient beamforming algorithms are required because traffic conditions change rapidly with high vehicle movements.

E. Sensing-aware Smart Protocol

Today, many types of sensors are embedded into a vehicle in order to increase its sensing capability. Sensors and V2X technology can complement each other. Different functionalities can be achieved by several types of sensors such as long and short range radar, LIDAR, ubiquitous cameras and ultra sound sensor. These diverse sensors can improve the robustness of driving assistance systems and make the car more autonomous. The proliferation of embedded sensors will make Intelligent Transportation System (ITS) more efficient and feasible. After obtaining information from various sensors, optimised sensor

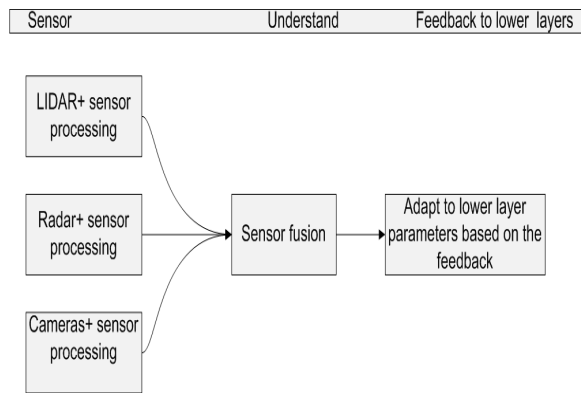


Fig. 11. Multiple sensors generate data about the environments

fusion engines required to understand multiple modalities and then make a decision in terms of warning, assisting or controlling the car [68]. Fig. 11 shows the process of merging the outputs of multiple sensors and then constructing intelligent information that can be used to make the vehicle better understand its surrounding environments. Thereafter, this information is fed back to the lower layer for the decision of beam forming, beam alignment and several other relevant processes. Protocols at the lower layers (i.e., physical and MAC layers), should take advantage of the vehicle's awareness about its surrounding environment. The sensing capability can make lower layer protocols act intelligently. For instance, a transmitter that supports a sensing-aware MAC protocol can detect obstacles in advance and start to search for another best beam aligned with the receiver. This method is much more efficient than transmitting data and waiting for time-out. To this end, there is a strong need to exploit such sensing information in order to improve the design and implementation of lower layer protocols aimed at vehicular mmWave networks.

F. Beam Management

Beam management plays an important role in assuring a high quality wireless channel between a transmitter and a receiver. Beam management consists of beam sweeping, steering and selection. With beam steering, vehicles continuously access the SNR of the channel to tune their beam direction accordingly. We need to develop efficient and reliable beam steering techniques during wireless access and we need to be able to perform fast beam tracking for a vehicle when the wireless channel is changing due to shadowing and vehicles' movements. Moreover, maintaining vehicular communication based on beam recovery despite poor communication links or blockage is also crucial for vehicular mmWave networks.

In vehicular networks, utilizing beam tracking to distinguish link failure due to vehicular mobility or radio blockage is still an open research issue. There are ongoing works [24], [52], [155] that aim to reduce the complexity of beam sweeping. However, they fail to address the reasons behind link failures, i.e., whether they have been caused by blockage or mobility. Utilizing lower frequency bands (i.e., 2.4 GHz) will be useful to estimate the direction of the receiver and then perform

smart beam steering. In this way, transceivers perform better diagnostics and trouble shooting functions.

G. Impact of Mmwave Communication on Security Issues

Vehicular ad hoc networks are susceptible to many types of security threats that not only deteriorate the performance of the network, but also could lead to the traffic accidents. The possible security threats include eavesdropping [156], [157], sybil attack [158], message spoofing and falsification [159], [160] and many other types of attacks [161], [162].

Directional antenna and the high data rate of mmWave communication are increasingly being considered as efficient methods for increasing link capacity. But, there are very few research works that have investigated security enhancements in mmWave enabled vehicular networks [163]–[165]. Therefore, more research should be undertaken to investigate the impact of beam directionality and steering on security issues.

VIII. CONCLUSION

Smart cities cannot be achieved without efficient smart transportation. That depends on the convergence of communication, computer and sensing technologies with a consolidated framework that can provide support for reliable intelligent transport systems. For the communication part, we argue that the mmWave spectrum is a promising candidate that can partially address the data rate and end-to-end delay challenges of existing wireless technologies. Eventually, living cost, environment protection and quality of life will also improve. In this paper, we have reviewed vehicular mmWave communication protocols and algorithms for urban/highway transportation along with various applications and services.

We focused on mmWave-enabled connected vehicles that require efficient directional MAC and robust physical layers. We have thoroughly discussed the protocols and algorithms related to MAC and physical layers for vehicular mmWave networks. In particular, we discussed link quality and radio coverage as well as how beam tracking improves the throughput of directional MAC. Then, context-information is used to provide feedback information to RSUs to reduce overheads and achieve accurate beam alignment. As the vehicular environment is highly heterogeneous, many types of obstacles such as moving vehicles, buildings and trees exist. The current literature does not have many published works on the design of efficient MAC/physical layers that actually take into consideration various types of obstacles. We also extensively discussed handover techniques in vehicular mmWave communication and we highlighted the challenge of small cell size in high frequency band. In order to demonstrate the weaknesses and strengths of state-of-the-art solutions, we have compared schemes that been developed for vehicular mmWave communication.

In the end, we identified a few application and research challenges that still need to be addressed for vehicular mmWave networks. Existing and emerging research challenges include cooperative perception, extending driver's vision at road bends, media download and cooperative obstacle and hazard avoidance. We also discussed some of the technical requirements

for vehicular mmWave networks applications which include data rate, latency and positioning accuracy. In order to fully integrate mmWave into a vehicular network, we identified several future research challenges which include link blockage, beamwidth adaptation, security issues, the deafness problem, roaming among mmWave cells and beam tracking.

To conclude, there is a lack of standard protocols for reliable communications in smart transportation. Standard directional MAC and physical layer protocols are needed to operate at mmWave spectrum in vehicular scenarios. When multiple radios mounted on vehicles, accurate synchronizations are required among multiple mmWave enabled radios. Another barrier for conducting research in this area at the moment is a lack of appropriate mobility models and vehicular simulation tools as we discussed earlier. In fact, at present there is no simulation framework that exists for vehicular mmWave communications but we hope that this survey will help motivate researchers, designers, and application developers to investigate innovative solutions in the field of vehicular mmWave networks.

ACKNOWLEDGMENTS

We thank the anonymous reviewers for their valuable comments which helped us improve the content and presentation of this paper.

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