International Journal of Computing and Digital Systems
ISSN (2210-142X)
Int. J. Com. Dig. Sys. 15, No.1 (Jan-24)

http://dx.doi.org/10.12785/ijcds/150104

Channel Modeling Techniques for Multiband Vehicle to Everything Communications: Challenges and Opportunities

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Received 7 Apr. 2023, Revised 18 Oct. 2023, Accepted 23 Dec. 2023, Published 1 Jan. 2024

Abstract: The joint usage of sub-6 GHz and millimeter wave (mmWave) bands is believed to satisfy the high data rate, low latency, and ultrahigh reliability requirements of the vehicle-to-everything (V2X) communication; thus, its channel modeling has advanced to the state of the art. This paper offers a comprehensive review of existing multiband based V2X communication channel modeling techniques and their associated challenges. To provide an overview of V2X communication, the system layout describing the vehicle to vehicle/infrastructure/pedestrian (V2V/V2I/V2P) links and performance goals is presented. Then, trend of large-scale and small-scale propagation parameters acquisition using deterministic and stochastic channel modeling approaches is described. The received power for various scatterers size is also examined to simulate the real-world scenarios in which a group of scatterers surround a car and observed that size of blockers impacts the receiving power. The 3D non-stationarity issue and lack of a flexible algorithm that can transition between sub-6GHz, mmWave, or combined modes based on the links' traffic inquiry category are challenges that have not yet been overcome. On the other hand, developments in mobile edge computing, integrated signal processing, channel modeling tools, and measurement-driven findings are presented as opportunities to further advance V2X communication. The role of potent technologies in advancing vehicular communication goals by their synergistic relation with mmWave frequency is also illustrated. Specifically, developing flexible algorithm and loading into edge computing enabled roadside units aids to meet dynamic resource scheduling targets which in turn triggers the realistic intelligent transport system. The hybrid sub-6/mmWave mode selection pseudo code is provided as well in this study as an insight to algorithm developers. Therefore, this article serves as a valuable reference for academics who are interested in this field providing an in-depth review of the joint sub-6GHz/mmWave based V2X channel modeling techniques for autonomous driving.

Keywords: Channel Model, Propagation Loss, Millimeter wave, Multiband, Vehicular communication

1. INTRODUCTION

Both academia and industry have been extensively investigating means to exploit the fifth generation (5G) untapped potentials under three application perspectives: enhanced mobile broadband (eMBB), internet of things (IOT), and ultra reliable low latency (URLL). Vehicular communications under URLL application area requires greater connectivity for assuring safety, autonomous driving, and internet based services accessing. An overall real time road situation information is shared among neighboring vehicles, road sharing pedestrians and associated transport infrastructures collectively known as vehicle to everything (V2X) communication. As predicted in [1], implementing V2X technology not only reduces annual accidents and CO_2 footprints significantly, but also saves driving hours.

This technology formally appeared when IEEE 802.11p was deployed at 5.9 GHz frequency by modifying its preceding IEEE 802.11a WiFi technology [2]. Later on, it has been modified and standardized by third generation partnership project (3GPP) as a cellular V2X (C-V2X) in release 14 (Rel.14) guideline documents [3], [4] around 2017. The LTE based V2X communication uses two air interfaces: interface for wide-area networks (LTE-Uu) and interface for direct communications (LTE side-link). The LTE side-link handles communications among vehicles (V2V) and roadside units (V2RSU) that may function without network infrastructure whereas the LTE-Uu handles communication between vehicles and core networks [5]. In Rel.15 advanced V2X features such as, transmit diversity, transport block size scaling for 64-QAM, and carrier aggregation for mode-4 operations were added on top of the prior version [6].

Although V2X communication technology has been developed for many years, there are still significant gaps between what vehicular communication requires and what can actually be achieved. This is due to the fact that the vehicles are expected to host light detection and ranging (LIDAR), automotive radio detection and ranging (RADAR), and ultrasonic sensors to oversee their surrounding. They use terabytes of generated data per driving hour for navigation collaboration, attaining traffic efficiency, and safety of life goals [7]. Currently overcrowded V2X communication technologies, long-term evolution (LTE) and dedicated short range communication (DSRC), are unable to handle this huge volume of data. Moreover, license-exempt transmission at DSRC band causes significant interference, resulting its practical data rates

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below 6 Mbps [8]. Another challenge associated with existing system is high end to end (E2E) latency of about 10ms which is 10 times greater than V2X's requirements [9], unable to meet ultralow latency collision avoidance applications demand [10]. In response to this, foremost technologies which are believed to fill these gaps such as, small cell [11], spectrum sharing [12], novel network architecture [13], and millimeter wave ranging 30-300 GHz frequencies allocation [14], [15], [16] have been proposed by researchers. Particularly, adopting mmWave creates opportunity to incorporate massive MIMO, the forefront enabler of achieving quality of service and data rate in 5G V2X communications. This spectrum has been in the transport avenue for long time in RADAR application at 77GHZ [17], making its adoption simple. In parallel to this, advanced requirements denoting practical situations and how to attain them has been documented in consecutive versions in Rel. 16 [18] and Rel.17 [19]. Cross radio access technology (RAT) and in-device coexistence of LTE V2X and new radio (NR) V2X sidelinks were drafted in Rel.16. The specification of the C-V2X direct communications (PC5) radio interface for automotive based on 5G NR RAT including many additional features, such as shorter symbols enabling even lower latency, feedback channels to increase reliability as well as higher capacity and support of unicast and multicast in addition to broadcast transmissions. From the summary of the three recent guidelines, Rel.15 to Rel. 17, particularly targeted to V2X services realizations combinations of technologies must be dwelled in a single device, in device co-existence, and optimization algorithms are to be embedded to boost the synergy. In Rel.18 focuses on further advancing the preceding version's targets [20]. Among set agendas, enhancements of uplink coverage, supporting up to 500km/h velocity, and vehicle mounted relaying techniques are highly associated with vehicular communication demands' fulfillment [20], [21]. The signal relaying and co-existence of LTE V2X and NR V2X are employed to broaden coverage while trapping spectral resource from higher frequencies. By benchmarking upon V2X requirements, two options are shown as option one, Opt_1, and option two, Opt_2, in Figure 1. Under Opt_1, an efficient spectrum utilization, aggregate of carrier banks, and communication at lower frequencies is described as a possible solution. Whereas, Opt_2 focuses on handling large number of antennas inside the transceivers, bandwidth enhancement, network densification by minimizing user distances and noise reduction techniques. The two alternatives look for possible solutions nearly an independent manner. Opt_1 focuses on utmost level exploitation of the existing lower bands while Opt_2 recommends migration to the higher frequencies where abundant idle band exists. But, for the multiband based operations the two solution schemes should be combined together. This hybridization yields high channel capacity, low latency, and low outage probability. Their comparison for the three V2X communication candidate frequency bands is presented in Table I. While the mmWave-based scheme meets the needs for low latency and high data rates, LTE-A-based operation at sub-6 GHz provides resilient services to users at high speeds but at the expense of high end-to-end latency.

However, aforementioned potentials of multiband based operations are encircled by challenges. The most serious bottleneck is associated with the channel model. A channel model is a mathematical equation that describes the transfer function between the received and transmitted signals and emulates the actual radio waves propagation [25]. The transmission channel alters the signal's amplitude, phase, and time, causing attenuation, incoherence, and delay at the receiving end. Furthermore, due to high velocity movement of its communicating elements, the V2X communication is highly prone to Doppler effect. Unless properly managed, their aggregate effect critically degrades the signal power.

These brings multipath components (MPCs) that are function of complex amplitude, delay from the transmitter to receiver, angle of departure, and angle of arrival signals at receiving end. Based on the nature of time/spatial variations there are two main signal fading: small scale fading where the signal variations that occurs over a short time interval or short spatial distances and large scale fading (i.e. path loss and shadow fading) that occurs when a user moves over a long distances [26].

Before proposing remedial technologies required for compensating the signal weakening, obtaining an instantaneous channel behavior is a prerequisite. Searching for the realistic and demand based customizable channel model that can well describe V2X links in both sub-6 GHz and mmWave frequency ranges is state of the art. In this article, a survey of an existing works on V2X communication channel modeling techniques focusing on multiband based approach is presented to bring a unified document to upcoming researchers by pointing out well addressed issue and the remaining pressing gaps. To the best of authors' knowledge, no previous works have surveyed multiband based 5G V2X communication channel modeling works in details by considering available opportunities and remaining challenges. For instance, survey papers [5], [13], [27], and [28] that appeared similar to this work only considered V2V links. The major concern and corresponding feasible technologies are summarized to assist researchers move forward on problem identification steps and reach upon significant solution. To assist the readers easily track an overall concepts of the article, the contents in the paper is organized as follows: In section 2, V2X communication is described in terms three link types and their corresponding requirements. In section 3, various multiband based channel modeling techniques are discussed. Section-4 discusses the role that key technologies play in satisfying V2X requirements when encompassed in V2X systems. In section 5, summary of challenges and available opportunities are pointed out. Finally, conclusion and the future works are discussed.

Contributions

In this review paper, up-to-date literature focusing on revealing potential in joint utilization of sub-6GHz and mmWave bands are comprehensively surveyed. Acknowledged works in this article focus on combined approach considered hence this paper brings unified comprehensive document on:

- The state of the art and unaddressed gaps yet in multiband based V2X channel modeling tech-

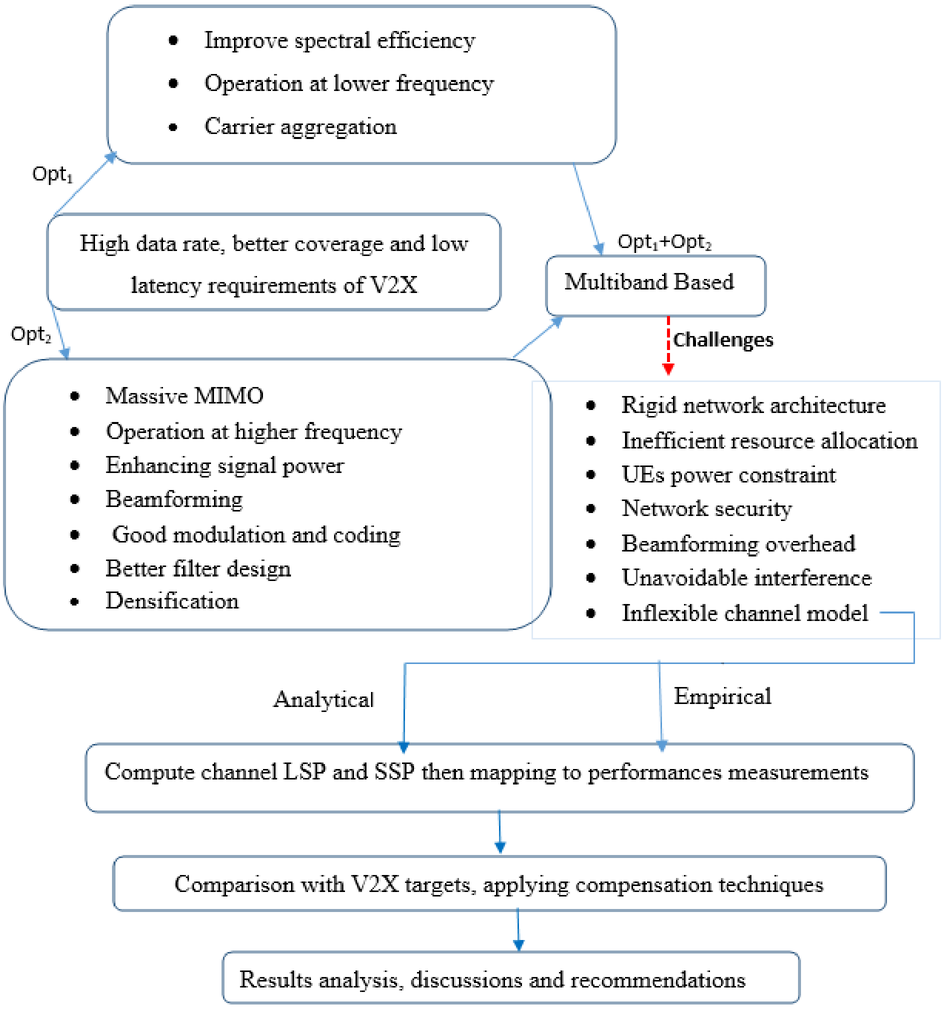

Figure 1. An overview of channel modeling approach

niques.

- Provide an overview of sub-6GHz-mmWave coexisting V2X communication and the complementary technologies.
- Provide network selection steps when both sub-6 and mmWave services are available per region
- Discussion on main challenges and available opportunities for multiband V2X communications channel modeling techniques.
- Recommendations on the future direction of research works for deployment of vehicular communication technology for transport sector.

2. Vehicle to Everything Communications

Vehicle to everything (V2X) communication is an information sharing mechanism where vehicle on the move send (receive) real time data to (from) a neighboring vehicle (V2V), network infrastructure (V2I) and pedestrian (V2P) ultimately to (from) an intelligent transport management centers as shown in Figure 2. This network provides services ranging from basic to sophisticated levels such as, assisting lane change, guiding in navigation and to fully autonomous driving system [29]. As highlighted in section 1, being URLL targeted area of 5G, reliability of the V2X system expressed by outage probability, spectral efficiency (bits/s/Hz), and end-to-end latency (second) are the main performance requirements of V2X as depicted in Figure 3. These parameters are described by vehicle-infrastructure-pedestrian (V-I-P) plane where vehicle positioned at origin forms V2P, V2I, and V2V links. It is observable that focusing on research works that contributes to green shaded region significantly impacts V2X communication realizations. For instance, the multiband V2X operation supplemented by massive MIMO is used for spatial multiplexing and diversity techniques based channel conditions for small cell attains the trinomials. The three interrelated terms robustness, reliability and multiconnectivity were well defined in [30]. The channel robustness measures the links' ability to resist the environment challenges whereas its reliability quantifies percentage of successfully received packets. The latter one is measured by comparing the ratio of the total number of sent network layer packets to packets that were successfully delivered to a communication entity within a time frame specified by that targeted service

TABLE I. Three candidate Access technologies in V2X communications

References	[22]			[23]			[24]	
Parameters	D	L	M	D	L	M	L	M
Frequency[GHz]	5.85–5.925	0.45- 5	28, 38, 60	5.9	2.6	73	6.75	30,73
Bandwidth[MHz]	10	up to 100	>200	10	20	396	20	614
Bit rate	3.27MB/s	1Gb/s	7Gb/s	<500 Mb/s	<500 Mb/s	>10 Gb/s	NA	NA
Latency[ms]	< 10	100-200	< 10	NA	NA	NA	NA	NA
Mobility[km/h]	< 130	< 350	< 100	36	36	36	0	80
(N_T, N_R)	NA	NA	NA	(2,2)	(4,4)	(64,16)	(1,1)	(4,4)
$(\phi^{T}_{3dB}, \phi\cdot^{R}_{3dB})^{0}$	NA	NA	(65, 65)	(65, 65)	(10, 10)	omni	omni	(30,30)

NA = Not Assigned, D = DSRC, L= LTE-A, M = mmWave

[31]. To attain six nines (99.9999%) reliability, gigabits of data rate, and milliseconds of end-to-end latency, vehicular communication definitely needs a range of enabling technologies.

In the perspective of low latency, proper trace on overall transmission control protocol (TCP/IP) layered architecture is required. This is an essential step because round trip time (RTT) budget consists of the air interface, UE processing, baseband processing, transport legs, core function, and connectivity to the server [32]. As a result, significant recommendations from academic and standards groups have been provided:

- Control and user plane segregation allow delay-sensitive applications to access the network without going via remote servers. This is facilitated by a close deployment of computing resources nearby roads.
- Preempting eMBB's uplink transmission upon arrival of URLL services and supporting the use of downlink channel information (DCI) to stop eMBB uplink transmissions and give URLLC traffic a higher priority [33].

To get an accurate channel modeling solution, proper classification of the propagation environment, link nature and instantaneous service demand is mandatory as shown in Figure 2. For example, as V2V and V2P links are located at azimuth plane the impact of the surrounding objects is very high requiring blockage compensation technology whereas for V2I round trip delay is an issue triggering nearby base station deployment. To meet these 5G V2X requirements, enabling technologies discussed in section 4 play prominent role. In V2V, the base station acts as a coordinator while the nearby vehicles communicate in adhoc fashion by beam alignment techniques. Usually, this link is considered as an extended version of device to device (D2D) communications where users' velocity is up to 120 km/h.

The vehicle to infrastructure (V2I) communication link is usually described by one ring scatterer where vehicle's end bounded by collections of obstacles. The signal blockage by human body at vehicle to infrastructure (V2I) scenario needs a serious attention for millimeter wave frequencies. Besides the signal blockage challenges, centralized architecture of existing system V2I communication scenario also face delay constraint. To solve the high latency issue, mmWave V2X is also expected to have cloud edge driving, processing and storage resources are positioned nearby the moving vehicles and pedestrians by means of road side unit (RSU) and on-board units (OBU) Another link type is vehicle to pedestrian (V2P) that shares information with side walking road users. This link can be a duplex channel enabling drivers to get support from residents and pedestrians to upload their small sized data to cloud. Moreover, V2P link creates an sporadic network and contribute to instant vital information collection from agriculture in rural areas and special incidents urban residents.

As highlighted in the previous subsections the coverage range of the mmWave base station is very small, and the user mobility leads to an intermittent connection making it unreliable for V2X communication. On the other hand, good data rate and low latency expectation are among the main reasons to shift to the higher bands. To unleash the synergistic potential for future advanced V2X applications whose targets illustrated in the Figure 3 undoubtedly an orchestra of sub-6GHz and mmWave frequencies is proposed. This necessitates multi-connectivity in frequency that can maintain reliable and stable V2X links while reaping benefits of mmWave bands [34]. The authors in [35], [36], [22], [37], [38] discussed multi-connectivity system advantage in terms of deployment cost, creating opportunity for supplementary technologies like massive MIMO and throughput enhancement. According to [35] following the 3x architecture option for its initial deployment approach, strong service continuity and quick network development in the early stages of 5G deployment by employing 4G as the anchor point of the control plane can be achieved. With this 4G-5G co-site deployment, operators can guarantee continuous coverage and minimize costs associated with infrastructure, network planning, and optimization phases. As shown in Figure 5 this option is described the master eNode B from 4G connectivity followed by 5G secondary Node (i.e. gNode B) forming Evolved-Universal Terrestrial Radio Access (E-UTRA) - NR dual connectivity (EN-DC) where user plane paths are interfaced with eNode B, gNode B and serving gateway (S-GW) [39]. The eNode B remains the master Node and is able to control the selection of the downlink data path from the S-GW. It provides mobility management entity (MME) with the IP address of the gNode B for some evolved packet system (EPS) Bearers, while providing the MME with its own IP address for other EPS bearers.

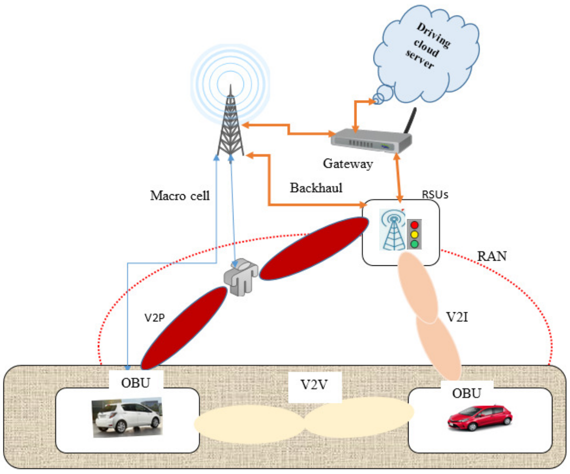

Figure 2. High level V2X communication system layout

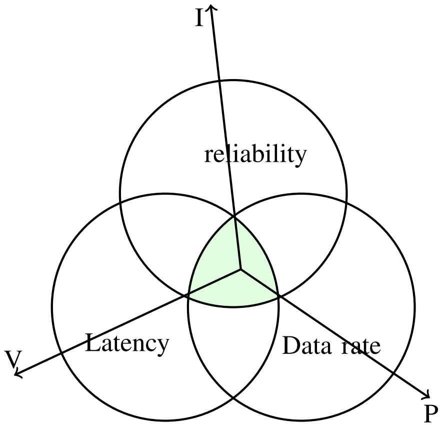

Figure 3. Three main targets in V2X communications

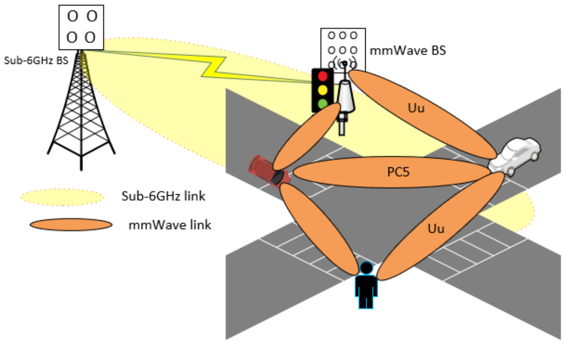

Figure 4. Dual band communication

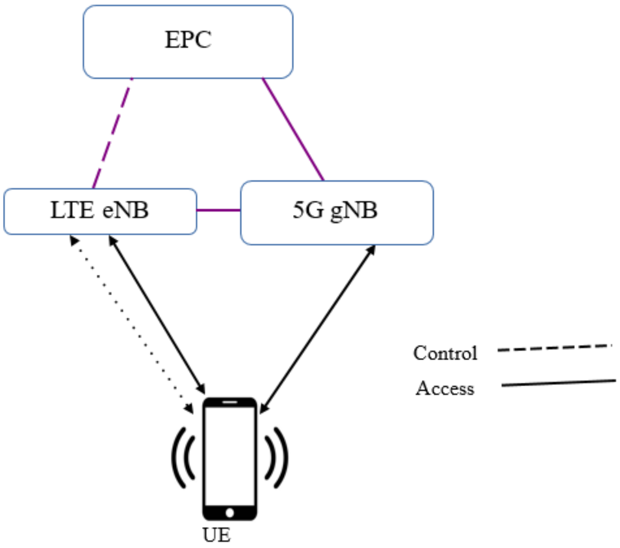

Figure 5. Sub-6 GHz/mmWave dual bands utilization access and control links

If coverage from the gNode B becomes weak then the gNode B can dynamically forward data across the X2 interface towards the eNode B. In [38] from an antenna design perspective for this dual band communication system, from the comparison of dedicated short range communication (DSRC) at 5.9 GHz and mmWave at 28 GHz for V2V communication link achieved array gain improvement at 28 GHz due to the higher order modes generated by 5.9 GHz array. With a low-profile and design simplicity, a single layer shared aperture antenna array for V2V communications also offers increased radiation efficiency and improved port-to-port isolation.

Various enabling technologies are also under investigation to achieve full V2X communication requirements discussed in section 4. For example, mobile edge computing [40] that position computation resources nearby users reduce the round trip propagation time significantly. It is appearing as a resource scheduler loaded into roadside units (RSUs) thereby minimizing system complexity. It also aids the users to intelligently decide whether to dwell only in one of the sub-6GHz/mmWave resources or jointly based on their service requirements. As per [24], V2V communication channel measurement is carried out at carrier frequencies of {6.75, 30, 60, 73} GHz in urban and highway environments to characterize the effects of blockage by vehicle between transmitter and receiver. For urban case three categories were defined: when there is no vehicle blockage case; when blockage is due to small sized personal vehicle positioned in between transmitter and receiver and finally larger blocking vehicle replaced. The researchers in [41] tried to reveal mysteries behind mmWave robustness and connectivity efficiency for high speed mobility users. The analysis is based on three general challenges in mmWave V2X communications: link recovery upon blockage, optimal beam management and complicated multiplexing schemes.To confirm this, they utilized co-sitting mmWave BS with LTE and deploying RSU 20m away from the main road show significant coverage improvement over non-RSU areas.

Interested in filling some of the recommendations in [41], in [42] presented a comparison of the two bands for massive MIMO implemented system in terms of the propagation channel behavior for different link types and use cases. In particular, for applications that requires URLL and high speed mobility mMIMO enhanced sub-6GHz become feasible while mMIMO in mmWave bands yields untapped throughput for LoS link types. The significant amount of band in mmWave achieves per user data rate demand whereas good channel coherence serves multiple users by means of multiplexing. This shows that to accommodate divergent user demands dwelling both frequencies per region with an interplay between instantaneous service inquiries as depicted in Algorithm 1.

In [43], the researchers described propagation measurement results from crowded city environment at 5.2 GHz and 26.4 GHz frequencies for dense urban area scenario stationary transmitter and receiver moving from 8m apart to 70m emulating. The measured frequencies are {0.81, 2.2, 4.7, 26.4, 37.1}GHz. The distance between the base station and the mobile was between 30 and 676m in the LOS case, and between 56 and 959m in the NLOS case. An extra diffraction and path losses of 14 dB and 21 dB respectively observed at 26.4 GHz. The regression analysis is applied on alpha beta gamma (ABG) path loss model and obtained corresponding values {3.47, 25.3, 2.07}dBi and standard variation of shadow fading 6.2 dB at is observed 20 GHz by using antennas with gain 2.4 dBi at transmitter and 19.1 dBi at receiver end. The NLOS close in (CI) propagation model yield comparable path loss exponent and shadow fading variations to that of ABC whereas in LOS these values are approximately equal to the free space model.

For the small scale channel counterpart amplitudes of subcarriers are stored and converted to channel impulse response then to power delay profile (PDP) is calculated at university campus environment for LOS links and the average number of paths, delay spreads (DSs), azimuth spreads (ASDs), and elevation spreads (ESDs) were evaluated found respectively 30, 49.6 ns, 19.7^0 and 2^0. To estimate the number of clusters K-Power-Mean method was used and found its average value 5. From this, it is noticeable that there are often fewer paths and clusters throughout an open outdoor area. Hence, similar measurements must be performed in other locations to verify the obtained results.

In [23], the mmWave vehicular channel was characterized and its performance was compared with the DSRC and LTE-A (sub-6 GHz) vehicular channel for the downlink of mMIMO enhanced V2I. Similarly, in [9], for inter-site distance of 100m small cell has shown about 70% (i.e. 87 to 286 Mbps) and 67% increment in case of combined centimeter wave (10 GHz) and mmWave (73 GHz) cell edge and average throughput respectively. It has been demonstrated that the mmWave technology has an area capacity that is thousands of times greater than that of sub-6 GHz-based systems at different distances of 50, 75, and 100 m. According to [44], mmWave V2X communication channels must take into account the impacts of antenna placement as well as obstruction brought on by neighboring buildings, cars, and people. Taking factors into consideration the researchers in [45] assessed V2I link behavior at 22.1-23.1 GHz mmWave range by using RT simulator by uploading geographic data. To represent on ground situation the dynamics of neighboring vehicles, communicating vehicle, massive MIMO four LSPs (i.e.,received power, Rician K -factor, root-mean-square delay spread, and angular spreads) were investigated.

3. MULTIBAND CHANNEL MODELING APPROACHES

To approach channel modeling problem, the researchers follow both analytical and empirical channel modeling techniques [46] as shown in Figure 1. To validate the models, the investigators have been generating large scale parameters (LSP) as well as small-scale parameters (SSP), and compare with the standardized values. If there is a significant deviation, the necessary modifications are applied.

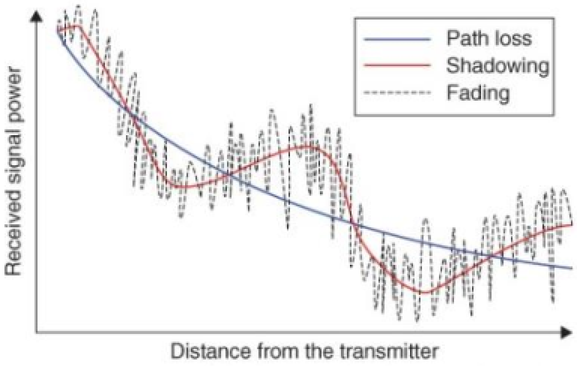

Figure 6. Received power fluctuations over distance [48]

Nowadays, different channel modeling techniques including drive test for representative sites, mathematical models and combination of both approaches are under-investigations to make this vision practical [40], [24], [41]. Once the behavior of the links between V2X entities is known and classified as poor, moderate, and good channel, then it will be augmented by, for example, diversity, a mix of diversity and multiplexing, and exclusively multiplexing schemes of massive MIMO, respectively. This illustrates the necessity of developing a channel model before carrying out the necessary operations on V2V, V2P, and V2I links. By taking this concern into account, researchers have been carrying out multidimensional investigations on V2X communication channel modeling and measurements that contributes to obtaining URLL and high data rate simultaneously.

The measurement driven channel modeling focuses on recording the propagation environment data and apply curve fitting techniques to extract performance metrices while the analysis driven targets on extracting parameters via mathematical analysis. The wireless channel modeling starts from the link budget analysis that computes the difference between gain and losses of power. According to [47], received power in decibel can be expressed as:

$$P_r = P_t + G_t + G_r - (P_l + SF) \tag{1}$$

where P_t, G_r, G_t, P_l, and SF are transmit power, receiver gain, transmitter gain, path loss and shadow fading respectively. The LSPs, P_l and SF, depend monotonically on the distance between transmitter and receiver hence described by deterministic models. Other LSPs such as Ricean K-Factor (KF), RMS delay spread, azimuth(elevation) spread of departure (A(E)SD), azimuth(elevation) spread of arrival (A(E)SA), and cross polarization ratio which are capable of representing the real situations are being investigated [49].

Since the world radio conference 2015 on mmWave adoption, researchers have been taking multitude of contribution to reveal its potentials [50]. The most common concern is an inverse relationship between the carrier frequency and the received power. In fact, moving to the higher frequency obviously incurs path loss and shadow fading. Hence, various path loss models that study mmWave features and sub-6GHz bands in comparative fashion emerged in the last few years. For example, in [51] path losses for LOS and NLOS links for sub-6 GHz and mmWave were separately modeled and compared. From the comparison, 28 GHz LOS path loss values are nearly equal with that of 1.8 GHz NLOS case. Similarly, in [52] used alpha-beta-gamma (ABG) and close in (CI) to compute P$_L$ for urban macro and micro environments at frequencies ranging 2 to 73 GHz. From the comparative study it was verified that CI model yields results very close to measurement data in overall frequencies and coverage of about 1.4 km. Inspired by its closeness to the realistic environment, the researchers in [53] used CI model with a frequency-weighted path (CIF) to study path loss exponent against the two models in [52]. The three models, ABG, CI and CIF, were compared in terms of their accuracy and sensitivity against sufficient recorded data set in 2 to 73 frequency ranges within coverage area about 1.3 km. From this comparison due to its fluctuating behavior for near and far way from transmitting end, ABG model unfits for considered case. Whereas, the two-parameter CI model and three-parameter CIF model offer computational simplicity hence researchers finally proposed candidacy of the later two models capable of representing measurement data. Computations focusing on LSPs are used to predict the mean received signal strength for an arbitrary transceiver separation in (1) and are useful to estimate the radio coverage area. These are central concern during network planning and optimization phases to meet better coverage requirement of V2X. Apart from aforementioned LSPs, signal arriving at receiver can either destruct or support each other depending on their phases are characterized by complex amplitude, delay time from the transmitter to receiver, angle of departure (AOD) from the transmitter, angle of arrival (AOA) at the receiver. These multipath components show small scale fading as the signals' variations occurs over a short time interval or short spatial distances in contrary to that of path loss and shadow fading that occurs when a user moves over a long distances. Furthermore, the small scale propagation is used estimate the rapid fluctuations of the received signal over a short distance or a short time duration.

Therefore, to have full spatial/temporal characteristics of wireless channel, detailed knowledge on both LSPs and small scale parameters (SSPs) is compulsory. Hence, computing channel response involves determining these components and finally channel coefficient generation as outlined in [54]. Authors in [55] presented classifications of MIMO channel models under three main categories: physical, analytical and standard models. The geometry based stochastic channel model under physical approach considers the blockage caused by surrounding environment.

The double directional channel impulse response incorporating temporal and spatial domain can be expressed by superposition of its MPCs [56] as:

$$H = \sqrt{\frac{KA_rA_t}{K+1}}\alpha_0 d_{m_r}(\psi^v_{r_0})d^H_{m_t}(\psi^v_{t_0}) + \sqrt{\frac{A_rA_t}{L_p(K+1)}}\sum_{l=1}^{L_p}\alpha_l d_{m_r}(\psi^v_{r_l})d^H_{m_t}(\psi^v_{t_l})$$

$$h(\tau,\vartheta,\theta) = \mu_H + \sum_{i=1}^{L_p} h_i(t,\tau,\vartheta,\theta) \tag{2}$$

where A_r, A_t, L_p, τ, ϑ, θ, K, $h_i(.)$ denotes number of receive antennas, transmit antennas , MPCs, the propagation delay, DOD, DOA, K-factor, and i^{th} path CIR respectively. As massive MIMO is expected to be indispensable from vehicular communications, its directional beamforming effect needs to be included in channel models and performance evaluation. By considering this, in [57] for sparse mmWave channel with multipath components appearing in a clustered manner, the second component of (2) the downlink channel is formulated as:

$$H_{cluster} = \sqrt{\frac{A_tA_r}{N_cN_L}}\sum_{i=1}^{N_c}\sum_{l=1}^{N_L}\alpha^k_{il}a^k_M(\theta^k_{il})a^k_B(\phi^k_{il})^H \tag{3}$$

where L is total scattered propagation paths in N_C clusters with N_L paths. To reflect the sparsity of the mmWave channel, both N_C and N_L should not be too large. α^k_{il} is channel complex gain of the l^{th} path in the i^{th} cluster with zero mean and σ^2 variance. θ^k_{il} is the k^{th} MS AoA and ϕ^K_{il} is the BS AoD. $a^k_M(\theta^k_{il})$ and $a^k_B(\phi^k_{il})$ are array response vectors of receive and transmit angles, respectively, assuming the angles are taken at azimuth direction only. However, ULA takes into account only azimuth coverage ignoring V2I links, while UPA covers both azimuth and elevation coverage. In [58], eight antennas oriented along vertical and horizontal planes form 64 massive MIMO. By using one-ring model that can emulate V2I where vehicle end is encircled by bundle of scatters with various size as shown in Figure 7. As noted in [58] the more energy is packed into a few strong eigendirections of the channel when small sized scatter with radius of 30m particularly for uniform distributions and it is sparse when the scatter radius is 120 m for Laplacian distribution. From this comparison uniform distribution scatter modeling looks ideal compared to Gaussian and Laplace models.

From (2) the first part, μ_H, is deterministic whereas the second part denotes MPCs of length L_p whose nature is described by stochastic model. These components are discussed in their respective 3-A and 3-B subsections.

A. *Deterministic*

As pointed out in the previous section, deterministic component of channel is dedicated to shadow fading and path loss of LSPs. These are a central concern of mmWave based system particularly in vehicular communication applications. The Ray tracing (RT) algorithms are commonly used in deterministic modeling to compute radio propagation in multipath situations. The accuracy of propagation modeling is substantially higher than that of empirical models, but it comes at the cost of increased computational effort and the requirement for accurate 3D geographic data of the target area [59]. Geometry-based

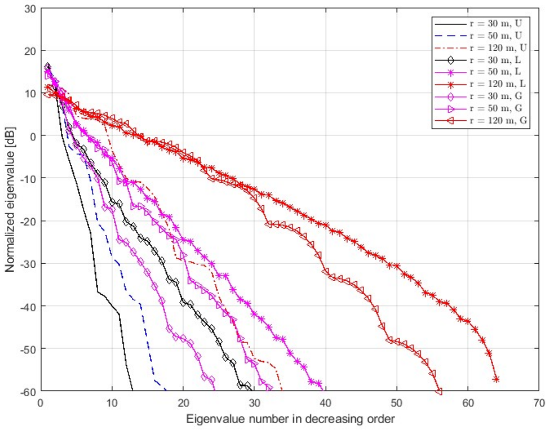

Figure 7. Scatter effect due to different sizes

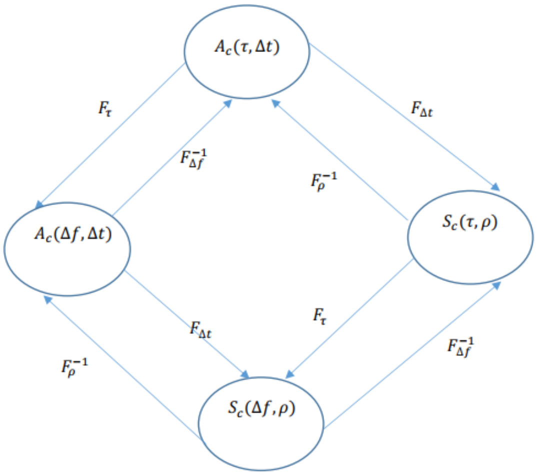

Figure 8. Delay-Doppler representations by Fourier transform

stochastic modeling techniques, for example, address the lack of geospatial data by recreating scatterers using a specified stochastic distribution.

B. Stochastic

Stochastic process modeling is employed to estimate the CIR's unpredictable behavior in spatiotemporal domain. Nowadays, commonly used stochastic channel modeling for mmWave range communication includes correlation based, geometry based and Extended Saleh Valenzuela approaches with main focus on temporal, spatial and clustered channel characteristics study concerns respectively. Motivated by existing wide band models gaps in previous carried works, in [60] studied 2D GBSM modeling performance in terms of space-time correlation function, Doppler spectral power density, envelope level crossing rate and average fade duration. To accommodate both stationary and moving environment factors under the stochastic and deterministic components two-rings around vehicles and a multiple confocal ellipses model was considered for V2V. The rays were categories as LOS, arriving after one bouncing and two bouncing.

In correlation based stochastic channel modeling technique, the statistical characteristics of CIR is fully known from its ensemble averages; mean, autocorrelation and cross-correlation. The power delay profile (PDP), from which delay spread is calculated, is produced by computing an autocorrelation function and applying a Fourier transform. The Fourier transform with respect to either (or both) time and delay results in four different but equivalent denotation [61] shown in Figure 8. Mean delay and Rms delay spread can be expressed respectively according to [47] as:

$$\mu_\tau = \frac{\int \tau A_c(\tau)d\tau}{\int A_c(\tau)d\tau} \tag{4}$$

$$\sigma_\tau = \sqrt{\frac{\int (\tau-\mu_\tau)^2 A_c(\tau)d\tau}{\int A_c(\tau)d\tau}} \tag{5}$$

where is $A_c(\tau)$ power delay Profile

The coherence bandwidth is expressed by:

$$B_c \approx \frac{1}{2\pi\sigma_\tau} \tag{6}$$

From this relationship, it is observable that delay spread vary with the definition of coherence bandwidth.

In [62], for the case where the coherence bandwidth is defined as a bandwidth with correlation 0.9 or above, and with correlation of 0.5 or above the corresponding relationships between coherence bandwidth and RMS delay spread are given by 5 and 6 respectively. In other words, these are points where the channel is decorrelated by 90% and 50%. When transmitted signal bandwidth exceeds beyond 50% of coherence bandwidth the channel behaves as frequency selective hence demand channel equalize.

The small-scale fading characteristics of a channel can be described through frequency selectivity and time selectivity. The former is determined by looking at the power delay profile (PDP), computing the RMS delay spread and comparing with symbol period. The most commonly used methods to describe PDP in existing literature includes Rayleigh, Rician and Nakagami- m distributions. However, presence of Bessel function part in probability density function (pdf) makes the Rician distribution a complex. On the other hand, Rayleigh fading model excludes a non-fading line-of-sight (LOS) component which is very common event at mmWave frequency communications. Due to its tractability and having amidst behavior of Rayleigh and Rice models make Nakagami-m distributions is becoming more preferable. Another stochastic model is Weibull distribution that can express channel impulse response as [63]:

$$f_{|H|}(h) = abh^{b-1}\exp(-ah^b) \quad h,a,b > 0 \tag{7}$$

where a and b are scaling factors

For different values of b the channel behavior changes. From reliability theory if its value is larger the signal power is decreased whereas when it is declined the received signal power is enhanced. When the model parameter b is equal to one the Weibull distribution converges to exponential distribution. At this situation influence of an external environment on the system performance become a major concern. Therefore, studying the characteristics of this parameter b can provide us the channel status thereby enabling to choose either spatial diversity or spatial multiplexing techniques in our data transmission. Once the link's delay spread is determined, PDP takes into account the conditional probabilities of multivariable. An estimate of an event's cause can be determined given its effect by applying Bayes' rule in conjunction with the conditional probability [64]. This distribution paves ground for computing gradient of impulse response to estimate AoA/AoD of signal approach

In [65], [66], statistical channel impulse response was assessed for an urban line of sight (LOS) and non-LOS channels at two representative mmWave frequencies,28 GHz and 73 GHz, from measured power delay profiles and arrival/departure angular power spectra. Compared to the Rayleigh distributions, the Rician distribution and measurement data spatial statistics of the multipath component can produce higher channel capacity when the number of transmit antennas is low [66].

C. *Quasi-Deterministic*

According to [75], in addition to purely deterministic and stochastic models, in mmWave sometimes there are appearing and disappearing features called flashing rays for short periods. Therefore, to represent this component in mmWave link characterization it requires additional statistical descriptions.

The authors in [76] used the measurement data from [75] to compare two well known community validated mmWave simulators, NYUSIM and WinProp to validate measurement data by simulation results in terms of received power as a function of propagation delay at 77 GHz frequency. Both metrices were in alignment with measurement data for WinProp simulator making it feasible for RADAR based communications. Besides, the detailed propagation environment database capability including buildings, vegetation are stored and modified in WallMan suite. It also superimposes the three dimensional car antenna patterns calculated with Feko and analyze the radio waves arriving to/from UE (vehicle, pedestrian, infrastructure) along the selected test route. The two simulators were also compared in terms of usability, simulation time and accuracy with respect to the realistic measurement results. Both simulators support features of frequencies from 0.5–100 GHz.

To examine mmWave propagation mechanisms in real-world non-stationary situations, researchers in [77] conducted measurements aided by ray tracing simulations at two crowded urban street cities. The study considered when both transmitter and receiver are fixed at 25m apart and when receiver only moves towards transmitter cases. From the computed average PDP (APDP) obtained 83ns LOS delay. Besides LOS, other rays as reflections from large static objects and some rays that are randomly appearing and disappearing due to closely located elements of the dynamic street environment were also observed. Then they have classified the rays as deterministic whose appearance probability is greater than 80% with blockage probability less than 4%. The second category is random rays with appearance 40-70% whose reflection is from faraway static objects, weaker and more susceptible to blockage due to longer travel distance. The third ray type is flashing that appeared for short period and needs additional stochastic modeling to account for probability of appearance and duration. Finally, by comparing two-ray model with experimental measurement data at more complex and multipath environments verified suitability of the quasi-deterministic (Q-D) approach to the millimeter wave channel modeling. This combination of deterministic approach to the strongest ray parameters evaluation with the statistical description of the random components is key to achieve mmWave based vehicular communications requirements.

Through these approaches we can compute both LSP such as path loss, shadow fading, and small scale parameters delay spread, Doppler shift. There are sufficient sub-6GHz channel model and measurement results available except its evolutionary features to be added to co-exist with higher frequencies. The 3GPP 3D MIMO channel model valid for carrier frequencies in the range 2–6 GHz and bandwidths of up to 100 MHz is a representative of this model [78]. It is characterized by a deterministic system layout (i.e., BS and UE locations, antenna orientations, field patterns, and carrier frequency) and a set of random parameters (i.e., delay spread, delay values, angular spread, shadow fading, and cluster powers) which are generated from statistical distributions obtained from extensive channel measurements.

On the other hand, mmWave side various attempts are being taken to extract its features in university campuses, mall areas and outdoor environments. For instance, the survey in [79] summarized V2V link channel measurement results for highway, urban street, open area, university campus and parking area at {28, 38, 60, 73, 77} GHz carrier frequencies. Obtained NLOS path loss exponents ranges from 1.9 to 2.7 and resulted path loss beyond 30dB. As a small scale fading counterpart the delay spread, Doppler spread modeled by Rician distribution given the Rician K-factor of about 0–4 dB when the transceivers distance is below 120m. For distance beyond 120m Nakagami distribution is used and its parameter is approximated as 0.4–1.1. Despite a significant findings from measurements, transceivers did not support MIMO system, both vehicles were equipped with only single antenna. This research has to be expanded by using an optimal massive MIMO-based channel measurements for the general V2V communication link.

The authors in [35], [36], [22], [37], [38] discussed advantage of multiband based vehicular communications in terms of deployment cost and creating an opportunity for hosting supplementary technologies. According to [35] by following the 3x architecture that employs 4G as the anchor point of the control plane facilitates a strong service continuity and a quick network development in the early stages of 5G deployment. With this 4G-5G cosite deployment, operators can guarantee continuous coverage and minimize costs associated with infrastructure, network planning, and optimization phases.

In [38], from an antenna design perspective for dual band communication system, from the comparison of dedicated short range communication (DSRC) at 5.9 GHz and mmWave at 28 GHz for V2V communication link achieved array gain improvement at 28 GHz due to the

TABLE II. Survey of related works on vehicular communication aspects

Ref.	Motivation	Performance studied	Proposed solution	Remarks
[22]	Limited survey works in overall mmWave vehicular channels classifications and proposal on full V2X capacity	Overall classification of mmWave aspects and modeling approaches for different scenarios and V2X link types	Inclusion of lower and higher frequency ranges, extending current standard models, and multiband-multi radio access technologies	Summarized techniques to meet V2X requirements in mmWave
[67]	V2X services standardization progress of 3GPP's releases from Rel. 13 to Rel. 16	Reliability, velocity supported, latency at various settings of urban roads	Fast switching between PC5 and Uu interfaces in joint LTE V2X and 5G NR. Flexible resource scheduling schemes in mode 3 and mode 4	Insight from the precommercial onboard and roadside units measurements were verified against 3GPP's V2X requirements
[68]	Limited survey works that provides details on measuring methods and channel models that characterize THz channels	Studied large scale parameters and their corresponding correlations	Considering the 3D nonstationarity issues in dynamic environment channels Recommendation on inclusion of IRS	Compared THz, centimeter, and mmWave channels characteristics
[69]	Verifying matching between existing measurement data with RT simulations	Reference signal received power for short distances at various link conditions	From the comparative results when a queue of cars has shown a significant received power showing the candidacy of 39 Ghz for vehicular communication	Considered for LOS, a single static car is blocking, vehicle obstructing communicating vehicles, and the platooning conditions
[70]	Joint sub-6 GHz and mmWave links utilization to improve the reliability as component of URLL	Analysis of Microwave-mmWave channels reliability for VR by including caching, reliablity, and computation.	Link selection strategy based on the minimum-delay delivery VR probability over hybrid microwave-mmWave links	Details on complexity of selection algorithms is not presented as it matters delays of VR applications
[71]	To propose best technology for V2V from performance comparison of various V2X technologies	IEEE 802.11p better performance next to NR-V2X	Both 11bd and NR-V2X outperforms both in 0.8 and 1.2kbps packet transmissions	Packet size is very small the maximum size of about 12kbps that can not denote realistic data transmission situations
[72]	IEEE 802.11p based existing works for links between moving vehicle and stationary RSU denoting V2I and replacing it by LTE antennas	Verified that 2.6 GHz LTE based system provides better throughput and lower error rate than IEEE 802.11p	Good choices for the considered range in the case of a packet	Assumed single antenna system at both ends which makes this study highly ideal
[73]	Assumptions considered in existing works are missing the realistic situations surrounding V2V	Comparison of realistic human blockage attenuation with standard models by varying blocking person's positions for mmWave frequencies	For high packet transmission NR-V2X is the only choice for higher range	This model missed critical mmWave propagation environment conditions
[74]	Mobility, security, and resource allocation techniques gaps in existing works	Comparative study of V2X communication requirements of all candidate bands	Proposal on future 6G V2X architecture and associated challenges are described	An overall path from the current state to forthcoming 6G V2X has not elaborated in comparative manner

higher order modes generated by 5.9 GHz array. With a low-profile and design simplicity, a single layer shared aperture antenna array for V2V communications also offers increased radiation efficiency and improved port-to-port isolation.

In [24], V2V communication channel measurement at {6.75, 30, 60, 73} GHz carrier frequencies was conducted. The blockage of various sized vehicles obstructing direct link was investigated at urban and highway road situations. From their research both delay spread and received power were computed by varying the blockers size. From the comparative received power of the three bands no significant gaps were observed confirming candidacy of the mmWave frequencies in the presence of obstacles. From this measurement the authors critical recommendations to the future researchers. One, changing the location of antenna location from roof-top to side mirror level to study its impact on V2V communication link blockage loss, delay and angular spreads. The second open issue issue is carrying out measurements at environments where transmitter, receiver and scattering objects are moving at a variable speed

Motivated by the link recovery during blockage, complex beam management, and complicated multiplexing challenges in mmWave V2X communications, by co-sitting mmWave BS, LTE, and deploying road side units (RSU) the authors in [41] brought an improvement. The RSU positioned 20m away from the main road has shown a meaningful coverage improvement over non-RSU areas. Interested in filling some of the recommendations in [41], in [42], comparison of the two bands for massive MIMO implemented system in terms of the propagation channel behavior for different link types and use cases was presented. In particular, for applications that requires URLL and high speed mobility mMIMO enhanced sub-6GHz become feasible while mMIMO in mmWave bands yields untapped throughput for LoS link types. The significant amount of band in mmWave achieves per user data rate demand whereas good channel coherence serves multiple users by means of multiplexing. This shows that to accommodate divergent user demands dwelling both frequencies per region with an interplay between instantaneous service inquiries as depicted in Algorithm 1.

In [43], the propagation measurement results were analyzed at 5.2 GHz and 26.4 GHz frequencies for dense urban area scenario by using stationary transmitter while the receiver is moving apart till 70m emulating V2I link. The measured frequencies are {0.81, 2.2, 4.7, 26.4, 37.1}GHz. The distance between the base station and the mobile was between 30 and 676m in the LOS case, and between 56 and 959m in the NLOS case. An extra diffraction and path losses of 14 dB and 21 dB respectively observed at 26.4 GHz. The regression analysis is applied on alpha beta gamma (ABG) path loss model and obtained corresponding values {3.47, 25.3, 2.07}dBi and standard variation of shadow fading 6.2 dB at is observed 20 GHz by using antennas with gain 2.4 dBi at transmitter and 19.1 dBi at receiver end. The NLOS close in (CI) propagation model yield comparable path loss exponent and shadow fading variations to that of ABC whereas in LOS these values are approximately equal to the free space model.

For the small scale channel counterpart, amplitudes of subcarriers are stored and converted to channel impulse response then to power delay profile (PDP) is calculated at university campus environment for LOS links and the average number of paths, delay spreads (DSs), azimuth spreads (ASDs), and elevation spreads (ESDs) were evaluated and found respectively 30, 49.6 ns, 19.7^0 and 2^0. To estimate the number of clusters, K-Power-Mean method was used and found its average value 5. From this, we can deduce that the number of paths and clusters in an open outdoor space tends to be minimal. Finally, we can conclude that similar measurements must be performed in other locations to verify the obtained results.

In [80], by using ray tracing simulations V2I channel in the urban and highway scenarios were characterized in terms of LSPs for various weather conditions and scenarios. To emulate the real-world situations researchers have been developing mathematical analysis and simulators. For example, the Network York University Simulator (NYUSIM) in [81] contains 49 very important simulation parameters grouped under antenna properties, channel, spatial consistency, and human blockage parameters bravely mimics the realistic situations. This tool based on statistical spatial channel model (SSCM). The channel parameters consist of 19 fundamental input parameters about the propagation channel denoting almost all real-world environment aspects. The scenarios are switchable into the urban microcell, urban macrocell, rural macrocell, and indoor hotspot. Once this condition is predetermined, some of modeling attribute states are dynamically triggered into their corresponding compatible modes.

4. KEY TECHNOLOGIES FOR V2X COMMUNICATIONS

The ”Off the individual and into the family” principle of joint sub-6GHz/mmWave based system induces both its cons and pros into the shared communication platform. The network architecture, switching mechanisms between multiple frequency bands based on instantaneous users’ demand, advanced signal processing schemes, minimizing e2e latency, and overcoming signal blockage are the most common research topics nowadays. Therefore, utilizing massive MIMO [82], deploying intelligent reflecting surfaces (IRS) [83], applying higher order orthogonal time-frequency modulations [84], developing perfect beam tracking algorithms [85], applying dynamic demodulation reference signals (DMRS) [86], mobile edge computing (MEC) [87], and machine learning (ML) [88] are some of the countermeasures to challenges in multiband V2X. In this section, these technologies are discussed in detail to pinpoint their contributions in V2X communication. Beyond the dual sub-6GHz/mmWave connectivity, synergistic technologies like edge computing, beamforming, intelligent reflecting surfaces, and massive MIMO, to mention a few, are crucial to the realization of V2X communication.

Some of aforementioned problems can be resolved with the use of mmWave MIMO beamforming technology, but it is necessary that this technology be able to adapt to dynamic channels as devices move and signals interact with people and moving vehicles in a scene. Ray tracing simulations can forecast the quick fading and Doppler spectra anticipated in an active urban environment and calculate the effect a dynamic channel has on MIMO beamforming in order to assess performance.

Algorithm 1 Pseudo code to select joint sub-6/mmWave

```
1:  Users' enquiry to service provider
2:  if Sufficient resources is available in both bands then
3:      Compare need with available resource and allocate corresponding one, notify associated details
4:      if Allocated from sub-6GHz then
5:          Consider channel model using 3GPP 3D MIMO channel model standard
6:          Compute Path loss, shadow fading and small scale parameters from ray tracing deterministic methods
7:          Find the received power, Signal to noise ratio, data rate
8:          if These values $\geq$ threshold AND Service demand continue then
9:              Repeat steps 5 to 7
10:             if mmWave AND favourable channel condition then
11:                 Consider advanced mmWave channel parameters
12:                 Clustered signals signal arrival,shadow fading, blockage, environmental absorption, AOA/AOD in (3)
13:                 Compute Path loss, shadow fading and small scale parameters from ray tracing deterministic methods
14:                 Find the received power, signal to noise ratio, data rate
15:             else
16:                 Combined Sub-6/mmWave approach with
17:                 Consider partial of services under sub-6GHz and remaining under mmWave Wave based on received power
18:             end if
19:         end if
20:     end if
21: end if
```

A. *Massive MIMO*

The multiconnectivity creates multiple connection at a time improving the system robustness. This is possible by transmitting duplicated data from numerous cells to the same UE, combating shadow fading, blocking effects, and cell failures; a daunting challenge in mmWave. The higher the carrier frequency, the smaller is the array form factor making arrays with a large number of antennas especially attractive at mmWave frequencies. The large-scale antenna arrays are expected to be used for directional beamforming in mmWave systems, in order to overcome the increased path-loss at mmWave frequencies and to provide other-cell interference isolation. Based on the conditions of wireless channel this large number antennas can be used for accomplishing spatial diversity, multiplexing and/or array gain; ultimate goal of massive MIMO. These antennas modify the amplitude or phase settings in response to the channel condition to provide high order spatial multiplexing for increased capacity or high gain adaptive beam formation for increased coverage. In other words, for interference-limited systems those deployed in 6 GHz or frequency range one, high order spatial multiplexing is used, whereas for coverage limited systems above 6 GHz carrier frequency or frequency range two (ranging 24.25- 52.6 GHz), high gain adaptive beam forming is used. When appropriate beamforming techniques are used, massive MIMO for sub-6 GHz bands enables the channel vectors to demonstrate orthogonality to each other, resulting in an interference-free transmission. When number of antennas increases the channel hardening and favorable conditions are met. To achieve this goal arrays of antennas are arranged in different configurations such as, linear, planar and cylindrical. The latter two configurations are capable of identifying users in both azimuth and elevation domains in areas where blockages are very common. Rank of channel matrix determines how many data streams can be multiplexed over a channel, whereas condition number characterize the quality of MIMO channels in the context of wireless communications. The channel condition number is a performance indicator computed as ratio of the largest and smallest eigenvalues of the MIMO channel matrix, with lower condition numbers allowing higher data rate transmissions.

The input-output relationship between transmit signal x(t) and received signal y(t) including corrupting noise can be expressed as [89]:

$$y(t) = \sqrt{\rho} w_c^* H w_p x(t) + w_c^* n(t) \tag{8}$$

where ρ is the average received power, w_c^*, w_p are combining and precoding vectors respectively.

The channel spectral efficiency, C_{SE}, is given by [90]

$$C_{SE} = min(A_t, A_r) \log_2(1 + SNR) \tag{9}$$

where A_t , A_r represent number of transmit and receive antennas respectively.

(9) shows that maximizing spectral efficiency relies upon achieving uncorrelated propagation paths at least $min(A_t, A_r)$ between the transmitting and receiving antennas. Knowledge on Rician K-Factor (KF) and channel condition number provides a clue to decide whether spatial diversity or multiplexing schemes to utlize available resource.

NYUSIM simulation tool developed by NYU-WIRELESS research team models the mmWave channel as a function of time as well as space [92]. In [91], the spectral efficiency of NYUSIM and 3GPP were compared for single and multiple steam transmissions as shown Figure 9. From this comparison, 3GPP achieves higher rate per frequency resource than NYUSIM when SNR is above 0 dB. From [92], while the highest number of clusters offered by the NYUSIM is 6, the 3GPP channel model creates 12 and 19 clusters in LOS and NLOS, respectively. This shows that NYUSIM is highly aligned

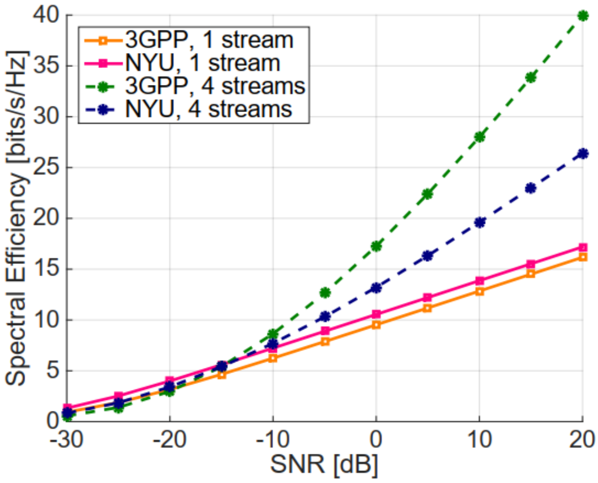

Figure 9. C_{SE} of NYUSIM and 3GPP [91]

with a practical propagation measurement. Besides, at the left side of antenna panel shown in [92] under spatial consistency parameters panel the simulator supports user mobility about 30m/s (i.e. 110km/h) which is vehicular velocity [93]. The most common 5G simulators were discussed in comparative manner in [94]. Another open source 5G simulator is Quasi-Deterministic Radio channel Generator (QuaDRiGa) which is based on MATLAB or octave systems [95] which is compatible with 3GPP TR 38.901 and mmMAGIC models. The dual end mobility allowing V2V and V2I communications are also incorporated in this simulator.

This spatial correlation matrix was studied using eigenvalue for different distributions [58]. The authors have shown that height of a planar antenna array as a function of the carrier frequency for 16 antennas per vertical column and different vertical antenna spacing. The higher the carrier frequency, the smaller is the array form factor making arrays with a large number of antennas especially attractive at mmWave frequencies. The large-scale antenna arrays are expected to be used for directional beamforming in mmWave systems, in order to overcome the increased path-loss at mmWave frequencies and to provide other-cell interference isolation.

Due to the system complexity, space constraint and battery drain the number of antenna at user end is limited whereas at BS it is of order of hundreds, being limited by $M \geq 64$. Based on the conditions of wireless channel this large number antennas can be used for accomplishing spatial diversity, multiplexing and/or array gain; ultimate goal of massive MIMO. Knowing time varying channel characteristics is a prerequisite to realize merits of massive MIMO. The base station antennas modify their gain or phase settings in response to the channel condition to provide high order spatial multiplexing for increased capacity or high gain adaptive beam formation for increased coverage. For interference-limited systems (typically those deployed in 6 GHz or frequency range one (FR1), high order spatial multiplexing is used, whereas for coverage-limited systems typically those deployed above 6 GHz carrier frequency or frequency range two (FR2 ranging 24.25-52.6 GHz), high gain adaptive beam forming is used. The 5G NR massive MIMO technology supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD), i.e. making it duplexing agnostic technology. When appropriate beamforming techniques are used, massive MIMO for sub-6 GHz bands enables the channel vectors to demonstrate orthogonality to each other, resulting in an interference-free transmission.

Therefore, directional beamforming needs to be included in the mathematical modeling and performance evaluation

When number of antennas increases the channel hardening and favorable conditions are met. To achieve this goal arrays of antennas are arranged in different configurations such as, linear, planar and cylindrical. The latter configurations are capable of identifying users in both azimuth and elevation domains in areas where blockages are very common. Rank of channel matrix determines how many data streams can be multiplexed over the channel in the context of MIMO communications whereas condition number characterize the quality of MIMO channels in the context of wireless communications.

B. *Reconfigurable intelligent surfaces*

Reconfigurable intelligent surfaces (RIS) create favorable propagation conditions by controlling the phase shifts of the reflected waves at the surface such that the received signals are reflected towards the receivers without extra power. RISs can act as a passive relay to send signals to users by being placed in areas where the quality-of-services (QoS) of links between users and the BS are unsatisfactory (i.e., dead zone). This increases the coverage areas beyond the present mmWave range [96], which is typically thought to be up to 200m [97]. When a barrier stands between transceivers IRSs modify the phase of signals and redesign channels using reflection avoiding main challenges of signal propagation in mmWave. Close observations of the challenges the mmWave signals are facing in its paths figure outs the contributions of RISs. For example, in [98] the authors measured channel fading caused by walking pedestrian obstruction in dense urban environments at 73 GHz carrier frequency by using 70, 150, and 600 half-power beamwidth antennas at 14.2m distance separations. From th findings as the antennas half power beamwidth (HPBW) increase, the mean signal attenuation decreases since a larger and equal spread of the wavefront impacts the blocker leading to more energy diffracted around the blocker and thus captured by a wider viewing angle at receiver. For very narrow HPBW antennas, which is common for mmWave, the mean signal attenuation was large since the spread of the transmitted wavefront and viewing angle at the receiver were fully blocked by an obstruction, leading to little-diffracted energy observed at receiver. According to [99] smart radio environments are made possible by IRS's ability to reflect signals and alter propagation directions in a highly intelligent and energy-efficient manner. It has gained widespread recognition as a potential technology for ground and aerial vehicular networks to improve signal strength, physical layer security, and location accuracy due to its simple deployment and inexpensive cost. The transmit beamforming at the BS and passive beamforming at the IRS are cooperatively optimized to maximize the received power. According to [100], a novel sensing-assisted communication system is used to improve the performance of sensing and communication by deploying an intelligent Omnisurface (IOS) on the surface of vehicles. By concurrently adjusting the transmit beamforming, the IOS phase shifts, and the duration of the combined sensing and communication stage, the feasible communication rate is maximized to estimate the communication improvement brought about by sensing for sensing coupled vehicular communication.

C. Edge Computing

The round trip time (RTT) budget is made up of the air interface, user equipment (UE) processing, baseband processing, transport legs, core function, and server connectivity delays. Thus, strategy that focus on minimizing latency in either of or combinations of these components can contributes to overall latency reduction. In vehicular communications, fulfilling this target is not optional duty, rather an obligatory. This requires an architecture where the UPF, gNB, and server are present at the same site or near the radio in contrary to classical network architecture in which many functionalities were hosted hundreds of kilometers away. The Xn/X2 interface is defined for a dual connection, either for the 5G-5G scenario or for the 5G-LTE case, connectivity between 5G RAN nodes and 5G RAN or LTE nodes, and mobility between 5G RAN nodes. The user plane and the control plane are parts of the interface. According to [101], [102], a significant reduction in response time and energy consumption can be achieved by moving computing from the faraway servers to the proximity of data source. This decentralization also contributes to privacy of users from the third party called intruders.

D. Beamforming

Beamforming can be defined as an angular domain filtering used in array processing to receive signals emanating from desired direction while suppressing others [103]. Because of the substantial path and penetration losses at millimeter wavelengths, antenna beamforming become a critical step to establish and maintain reliable communication links. By configuring large scale antennas discussed in subsection 4-A in multiple rows, both azimuth and elevation directions beamforming gains denoting V2V and V2I links respectively can be achieved. A hybrid of analog and digital beamforming technique is becoming increasingly popular due to its cheaper hardware cost and numerous beam generating capabilities [104]. In [105], hybrid beamforming combining analog and digital processing to achieve both spatial diversity and beamforming gains are proposed for two-tier heterogeneous networks. The researchers verified that an achievable sum rate of the hybrid beam forming with-cooperation algorithm is higher than those without-cooperation. A codebook is a bank of candidate beams where each beam covers a specific direction in space and its aggregate provide a coverage to users distributed within the region [106]. A column vector of the total beam space matrices contains the weights that steers the beam to a certain direction. Currently, codebook-based beamforming is being proposed as way to strike good balance between complexity and performance while eliminating overheads. In alignment with this optimal choice, in [107] the researchers proposed less complex and almost optimal performance. To characterize the channel behavior clustered manner appearance of rays was taken into account. In mmWave massive MMIMO systems, they also analyzed the ideal analog precoder and analog combiner pair that optimizes the achievable rate. From this it is observable that a codebook-based beamforming approaches for millimeter-wave communications in the context of low-mobility and high-mobility channel situations minimizes complexity of massive MIMO in V2X. Hence, investigations that examine an existing codebook-based beamforming algorithms in terms of their complexity, performance optimal, and association with signal processing is required.

E. Machine Learning

Machine Learning (ML) is a sub disciple of artificial intelligence that is an essential technology for supplementing vehicular communications. The supervised ML category plays channel equalization, decoding, and prediction, path loss and shadowing, localization, sparse coding, filtering, adaptive signal processing,beamforming. Reinforcement ML enables link preservation, channel tracking, on-demand beamforming, secure transmission, power selection, nodes selection, channel access management, modulation mode selection, coverage optimization. These days, as large site specific V2X communication channel measurement data is available from the measurement campaigns, ML can applied understand propagation processes and create the channel models. In [108], by reviewing various channel measurement and model in perspective of broad range six generation (6G) services, described achieved and remaining tasks for vehicular networks. By adopting artificial intelligence and machine learning algorithms as a component of channel models we can forecast the nature of communication hence we can pro-act to counteract ill-effects.

5. CHALLENGES AND OPPORTUNITIES IN MULTIBAND BASED V2X CHANNEL MODELING

This section provides detailed information regarding the recent research challenges for multiband-based V2X channel modeling. In addition, we have also articulated available opportunities that can facilitate fast full-featured realistic channel models for the mystic ITS industry. The research challenges that have not been addressed and opportunities are discussed in subsections 5-A and 5-B respectively. These are major concerns for multiband based V2X practicality hence need more attention while investigating vehicular communication system.

A. Challenges

The near future multiband based V2X communication system is awaited to be embodied by multipurpose sensors including LIDAR, RADAR, GPS, MEC devices, and cameras that can minimize commuting time, facilitate modern toll collection, and enable passengers infotainment. For efficient usage of multi-radio access technologies for V2X, there are still open challenges that requires further investigations particularly on on channel modeling and its performance assessment. Furthermore, lacking an end dose remedy to challenges discussed in subsection 2 till

TABLE III. Summary on key technologies to realize full V2X potentials

Technology	**V2X requirement contribution studied**					State of the art	**Ref.**
	Dr	Re	La	Co	Cv		
AI	✓	✓	✓	✓	X	✓	[108]
Edge computing	✓	X	✓	X	X	✓	[40], [109]
Joint sensing and ranging	X	X	✓	X	X	✓	[17]
Relaying	X	✓	X	X	✓	✓	[110], [111]
IRS	X	✓	X	X	X	✓	[112], [113], [114]
Sub-6GHZ	X	✓	X	X	✓	✓	[58]
mmWave	✓	X	✓	X	X	✓	[22]
Sub-6GHz & mmWave	✓	✓	X	✓	✓	✓	[115], [70], [74], [71]
Massive MIMO	✓	✓	X	X	X	✓	[116], [117], [118], [42]
Beam forming	✓	X	X	✓	X	✓	[119], [120]
UAV	X	✓	X	X	✓	✓	[121]

✓: Addressed, x: unaddressed, Dr: data rate, Re: Reliability, La: Latency, Co: Combined, CV: Coverage

now is indeed hindering realization of the utmost potentials embodied in 5G vehicular communication. These bottlenecks are described in terms of their impact on V2X transmission channel hence aids future channel model developers in their research directions.

1) 3D Non-stationarity issue. The first open issue is associated with 3D non-stationarity modeling: almost all existing researches consider the non-stationarity either model the non-stationarity in a single domain, e.g., in the time/space domain, or model the non-stationarity in a 2D domain, e.g., in the time-space/time-frequency domain. While the modeling of 3D non-stationarity is quite limited, how to properly model 3D non-stationarity is still an open problem.
2) Lack of flexible algorithms. In conventional services ultimate purpose is to transmit a long packet to maximize throughput and when the packet size is small, ultra reliability can be achieved at the expense of the achievable rate reduction. URLL needs to meet two challenging requirements: low latency and ultra-high reliability metrics that are very though to achieve simultaneously. Developing algorithm with low complexity that can fairly interplay among throughput, latency, and reliability unlocks bottlenecks in V2X communication. Moreover, if an algorithm that can map results obtained in one domain into another accurately (i.e. time to spatial or reverse) like Fourier and Laplace have done appear, it will enable us easily compute our desired parameter within selected domain without worrying other domain characterizations.
3) Complexity of Integrated networks. Another forthcoming duty of the scholars is the tight integration of environmental factors, conditions of V2X links, and locations of communicating parties relative to their accessories to emulate realistic communication environment. Most of existing works focus on specific conditions by assuming others in an ideal state which is far apart from the actual situations hence a wholistic models are yet to come.
4) Beamforming Overheads. The mmWave frequency communication needs fast link configuration, beam management, contention-based channel access, sidelink autonomous scheduling, distributed congestion control, and interference management at the MAC layer are major open issues of vehicular communications. Developing an accurate channel model bearing ultra-reliability and low latency in mind is a tricky task. massive number of antennas are tightly packed together with inter element spacing much less than the coherence distance of the channel. Deterministic relationship between the signal arriving at one antenna element and the delayed version of the signal arriving on neighboring one becomes a function of the angle-of-arrival. This results sparsity in the channel. To mitigate this ill-effects, beamforming a central role. This leads complex computations for its wise selection for precoding and combining vectors determinations. Trends of beamforming in terms of computational complexity, advancements, cost and optimizations techniques are among open research issues.
5) Dispersed measurement data. Findings on channel models and its performance assessment are existing in a dispersed manner. The scientific community's efforts are disperse and divergent on the topic hence clustering theme under sub-categories for progressive achievements is required. As a subsection of channel modeling, segmenting drive test and theoretical analysis as a parallel approach. Then, collecting drive test measurements from various topographic regions across the globe in a collaborative manner is required to extrapolate the findings. This could eliminate confineses of the drive test results. Furthermore, this unified effort could enable the researchers properly audit between what has already done and forthcoming duties, saving resources while easily land upon this

fascinating technology. For example, the results from [24] for the multiband V2V link need to be applied to other link types and the V2X scenarios when blocks are placed at different locations.

6) Large Doppler shift. Another challenge in multiband V2X channel modeling is large Doppler shift due to high speed mobility of vehicles and surrounding environment. In [28], [72], researchers have developed channel models LTE based V2I scenario at suburban street, expressway, urban canyon and for 3GPP Extended Vehicular A (EVA) environments. Compared performances of V2I communication channel models for different modulation and coding schemes with respect to the 3GPP EVA channel model (v = 120 km/h). Finally, the authors concluded that better performance within the urban canyon environment can ultimately be explained by dominant direct path and less severe frequency dispersion. From the comparison identified an expressway environment with the largest Doppler frequency shifts as a most challenging scenario and needs further investigations. Moreover, investigations done by [122] needs to extended for vehicular communication to mitigate the effects of Doppler shift.
   Findings discussed in aforementioned sections, provide the following insights for future research: A deeper understanding of the temporal variability of the propagation channel is essential to take user movement, human body obstruction, and moving vehicles into consideration and deploy physical layer technologies when applicable.

B. Opportunities

Despite existence of unconquered problems, we are swiftly approaching to realize green shaded region in Figure 3. Undoubtedly, this progress are due to collaborative efforts of the researchers, standards bodies, automotive industry, and government, etc. In this section, some of opportunities to exploit joint sub-6 GHz and mmWave for intelligent transport system accomplishment are described.

1) Advancements in channel modeling tools. The numerical simulations are commonly used technique for analyzing current communications standards and planning the development of future advanced systems. Nowadays, a significant attempts are being made to develop simulation software that can be used to evaluate link level behavior, ultimately the system level as well. Because of unreserved efforts from the research community, various simulation softwares that consider the behavior of vehicular communication links at both sub-6GHz and higher frequencies are now available. For example, emergence of quasi-deterministic radio channel generator (QuaDRiGa) since 2011 by evolving from low frequency model, WINNER, brought a flexible open source channel simulator [49]. In [123], the MATLAB based 5G link level simulator which is capable of handling all current multicarrier accessing schemes and having flexible numerology is proposed. An extension of this, in [124] Vienna 5G link and system level simulators that can assess an overall performance to academic society free license grant. This simulator supports QuaDRiGa 2.4.0 version that has already included 3GPP clustered delay line and tapped delay line models for TS 36.104 LTE, TR 38.901 NR, TR 37.885 V2X standards and segment by segment basis channel generation. This can facilitate various non-stand alone deployment architecture options such as 3/3a/3x, 4/4a and 7/7a/7x proposed in 3GPP technical report (3GPP TR 38.801 V14.0.0) that can interplay between NR and E-UTRA. This work elaborated a channel measurement result obtained from an urban street environment at 60GHz by using two horn antennas on a moving transmitter vehicle. During the assessment one horn emitted a beam towards the horizon and the second horn emitted an elevated beam at 15-degrees uptilt. From the measurement they concluded that an elevated beam shows fewer MPCs due to spatial filtering of the street level. For both antenna elevations, LOS component with Doppler shift of more than 2.5 kHz is visible at beginning stage. Later when the car approaches the receiver, Doppler shift of the LOS component decreases towards negative frequencies. Through the result shed a significant contribution, a maximum approaching speed of a car is limited and an omnidirectional dipole antenna at receiver has to be extended to a realistic situation of beyond 60km/h speed.
2) Measurement based channel characteristics. Practical measurement based findings on propagation behavior are verifying that the Friis path loss associated can not hinder joint sub-6 GHz/mmWave based vehicular communication realizations. Even though existing progresses are found in dispersed manner, both measurement driven findings at representative crowded cities in Europe, United States of America (e.g. New York), etc verify candidacy of dual band for the sensitive vehicular communications. In addition to the audacious accomplishments made thus far, the fields that are currently being investigated hastens the appearance of joint bands' full potential.
3) Advances in antenna design and signal processing. Evolution in antenna technology is playing a magnificent role in fast forward moving of mmWave based services as the two technologies are highly intertwined together. For example, in [125] developed algorithms that provides fixed coverage to communication and packet-varying scanning beams for sensing part for joint sensing and communication enabled services from a single transmitting array. Likewise, in [126], combination of modulation scheme with other techniques mentioned in section 4 are deployed to achieve less cost hardware and energy efficient modulation. The integrated baseband signal processing, filter design, channel coding, precoding, combining, and beamforming study meet an overall demands of V2X communication. To realize this, expanding

existing achievements is an essential forthcoming research direction.

4) Advances in complementary technologies. Nowadays, different architectural proposal encompassing figurative technologies, some of which described in section 4 are being widely proposed. Particularly, UAV, ML, massive MIMO, and beamforming are Lion-share holders shedding indirect benefits on top of their major role. Thus, to further outshine the gifted potentials in these potent technologies to counteract challenges at wireless channel tremendous efforts need to be employed.

6. Conclusions and Future Work

In this survey article, multiband based V2X communication channel modeling techniques, associated challenges and opportunities are comprehensively summarized to draw attention of the future researchers. An overview of joint sub-6 GHz/mmWave V2X links requirements and the role of potent technologies in meeting these requirements is discussed. Based on received power and delay spreads, the impact of both large scale and small scale modeling factors on V2X communication performance is studied. Existing measurement-based campaigns, analytical efforts, and simulation tool development stages are highlighted as advancements in this study area. From the overall review, URLL is rendered practical via channel modeling supported with cloud servers providing edge computation and distributed core network architecture. This opens chances to load algorithms and models onto mobile edge computing (MEC) capable road side units. As a result, a framework for collaborative data sharing is created, allowing the researchers to focus on the development of multiband based channel models. This survey paper provides important insights for researchers to develop V2X channel models that are fitting for joint sub-6 GHz/mmWave frequencies and select complementing technologies based on instantaneous traffic conditions. Future research should concentrate on unsolved concerns such as dual end high velocity, beam steering overheads, 3D non-stationarity, and rigidity in switching between the sub-6GHz, mmWave, or joint mode in order to meet V2X criteria. The discrepancy between measurement-driven and mathematical models at mmWave frequency emphasizes the necessity of further research accounting for the real-world propagation environment. This gives a clue to generate a corresponding matching between the V2X targets, candidate key technology, and the channel customization.

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