Aakash Bansal [1] and Nicolette Formosa[2]

[1]Affiliation not available
[2]National Highways

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Navigating the Road to Connectivity: Use Cases and Design Considerations for V2X Networks Using Millimeter-Wave 5G Beam-Steering Antennas

Aakash Bansal[1], Nicolette Formosa[2]
[1]Wireless Communications Research Group, Loughborough University, Loughborough, UK
[2]National Highways, UK
a.bansal@lboro.ac.uk, nicolette.formosa@nationalhighways.co.uk

***Abstract*— Connected and autonomous vehicles (CAVs) rely heavily on a suite of perception sensors such as cameras and LIDAR for accurate and robust on-road decision making. However, these sensors have a limitation of line-of-sight (LOS), which can significantly restrict their effectiveness. To overcome this limitation, vehicle-to-everything (V2X) networks are being developed to wirelessly receive non-line-of-sight (nLOS) data from surrounding sources such as road-side units (RSUs). By leveraging nLOS data, V2X networks can significantly enhance the situational awareness of CAVs, improving traffic efficiency and road safety. In this paper, we present selected use-cases of V2X networks such as vehicle-to-vehicle (V2V) communication, vehicle platooning and cooperative perception using a beam-steering antenna that offers a wide bandwidth and fast beam-steering.**

Keywords— Millimeter-wave Antenna, Use Case, V2X Network, Beam-steering.

I. Introduction

Connected and autonomous vehicles (CAVs) have brought a paradigm shift in the world of transport, promising improved road safety and transportation efficiency. The UK market for CAVs is projected to grow to £28 billion in the coming decade [1]. To achieve this transformation, integrating multiple state-of-the-art technologies focused on perception, planning, and control is required for efficient and safe CAV navigation [2][3]. CAVs operate by collecting data about their surrounding environment from highly advanced sensors such as cameras, light detection and ranging (LIDAR). However, these sensors have the inherent limitation of operating on a line-of-sight (LOS) basis, which can be disrupted by various factors such as obstacles, proximity to other vehicles, or inclement weather conditions like rain or fog [4][5]. This limits their effectiveness in certain situations. To compensate for this limitation, the key technology that underpins the success of CAVs is a reliable and high-speed communication system [5][6]. Such a system provides safer and more dynamic trajectories by gathering wireless information from their surroundings and neighbouring vehicles enabling CAVs to operate effectively in a variety of real-world scenarios such as in adverse conditions.

Communication systems are increasingly recognized as essential for the future of CAVs and as a complement to existing onboard sensors. A vehicle-to-everything (V2X) network can wirelessly collect information that may be missed by the vehicle's onboard sensors from other sources such as roadside units (RSU) or nearby vehicles [7]. Current state-of-the-art V2X communication technology, such as Bluetooth, Zigbee, Wi-Fi, 4G cellular network, dedicated short-range communication (DSRC), etc. [8]-[10], has limitations such as a small bandwidth of 10 to 20 MHz and low-gain antennas. This makes it impractical to share large sensor data such as 3D-maps, LIDAR data, and high-resolution camera images. Moreover, the sub-3 GHz frequency band used by DSRC can be crowded, leading to interference and reduced communication range [11].

To address these limitations, 5G communication technology is being explored for its potential in V2X networks [5],[12]-[14]. The new 3GPP standards for 5G are already considering millimeter-wave frequency bands, such as 24-30 GHz, 35-40 GHz, and 58-62 GHz, for V2X implementation with highly directional beams [15], [16]. This allows for the use of small form-factor antennas that can be easily implemented in vehicles or on infrastructure. However, the use of high-frequency millimeter-wave bands for V2X communication may result in limited coverage areas and reduced system capacity due to signal blockages caused by buildings and other obstacles. This problem can be mitigated using antennas' beamforming/beam-steering capabilities [12][15]. Several millimeter-wave antennas have been demonstrated in the literature that provide highly directional beams with electronic steering for implementation in 5G [17]-[19],[31]-[35]. The use of beam-steering 5G networks in V2X has the potential to create new use cases to establish a novel communication method, allowing vehicles to gain more appropriate and real-time data about their surroundings for advanced driving, vehicle platooning, and cooperative perception [20]-[22].

As a result, this paper examines the potential of 5G technology in enabling a full-fledge V2X network by creating new proposed techniques for traditional use cases such as vehicle platooning, cooperative perception, and advanced driving. These use cases have been examined from a millimeter wave 5G network perspective that uses a beam-steering antenna. 5G networks and millimeter-wave communication have their own set of challenges such as low diffraction rate, high path loss, etc. New solutions have been presented in this paper to mitigate such challenges while establishing V2X use cases using beam-steering antennas, dynamic channel allocation, and efficient resource management. By overcoming these limitations, it is anticipated that the deployment of 5G-enabled V2X networks will provide a more efficient, reliable, and safer transportation system for both drivers and pedestrians alike. The findings of this article are useful for policy-makers, industrial experts and other stakeholders involved in establishing a V2X network in next decade. This would also serve as an introduction to the telecommunications industry to take vehicular networks as a potential service market for the future.

II. V2X Use Cases With Beamforming 5G Network

The development of millimeter-wave 5G networks is underway, with a focus on frequency bands above 20 GHz. In comparison to present DSRC and Bluetooth technology, a 10% bandwidth at 30 GHz would offer a bandwidth that is 30 times wider, making it highly suitable for large data throughput and accommodating a greater number of vehicles, roadside units, and network users. This high data-throughput V2X network, which includes vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), vehicle-to-vehicle (V2V), and vehicle-to-network (V2N) communication, offers a range of new use cases when augmented with advanced beamforming techniques, as illustrated in Fig. 1. This section provides an in-depth discussion of these use cases, with a specific focus on 5G beam-steering technology.

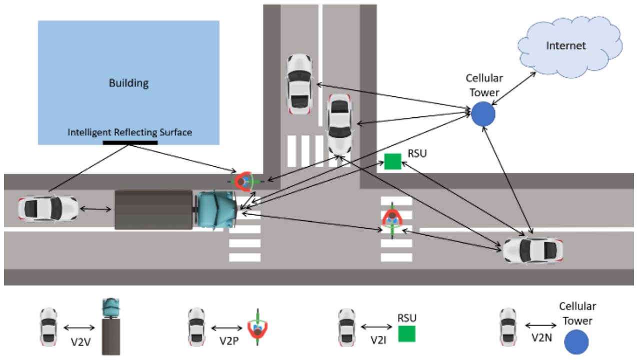

Figure 1: A real-time scenario layout for V2X network on the road, illustrating the various links such as vehicle-to-vehicle (V2V), vehicle-to-people (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N).

A. Vehicle-to-Vehicle Communication

Previous literature has explored various V2V networks that rely on traditional cellular networks and IEEE 802.11 DSRC networks operating at sub-3 GHz bands. However, these networks utilize low-gain omni-directional antennas with limited bandwidth, resulting in communication speeds as low as 9.6 kbps. These speeds are insufficient for vehicular ad-hoc networks that require fast data-throughput. In contrast, the 5G millimeter-wave network operates at frequencies greater than 20 GHz, allowing for a greater number of vehicles within the network and providing a large bandwidth for fast data-throughput.

The beam-steering capabilities of antennas used in millimeter-wave 5G networks enable the creation of an extremely directional network between two vehicles in close proximity, as illustrated in Fig. 2. This directional network can be used passively to detect a vehicle's movements, identify lane changes, and other relevant information, which can greatly facilitate the decision-making process for drivers and vehicles based on the behavior of other vehicles in the surrounding area. Additionally, the beam-steering capability allows a vehicle to communicate with multiple vehicles simultaneously using different beams at different angles, operating at different frequency bands. Moreover, the steered beams tend to have an overlap of less than 3 dB and with different channel selection for different beam pointing angles, the interference is reduced significantly. It establishes a multi-node network, allowing data reception from multiple sources and broadcasting to multiple nodes simultaneously, as demonstrated in Fig. 3. This capability enables the network to support the communication needs of a greater number of vehicles, roadside units, and network users simultaneously while maintaining a high-quality signal with minimal interference. Thus, the use of beam-steering technology in millimeter-wave 5G networks represents a significant step forward in the development of V2V networks, enabling more efficient and effective communication between vehicles, pedestrians, infrastructure, and the wider network.

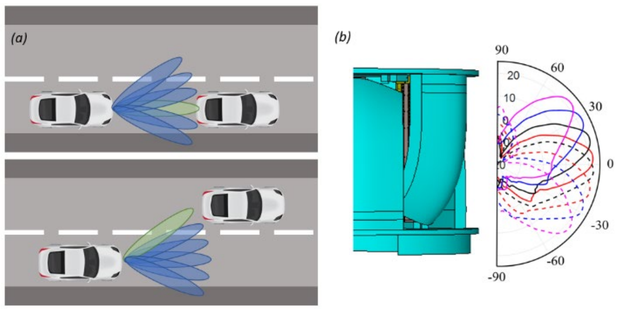

Figure 2: (a) Easy lane-change detection using beam-steering antenna; (b) beam-steering layout of an antenna made at Loughborough University [18].

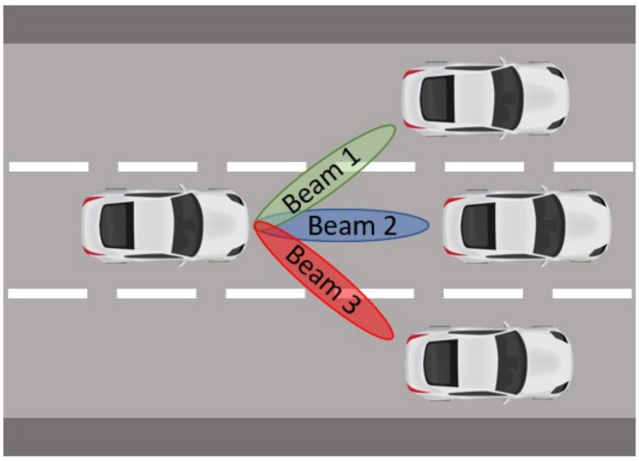

Figure 3: Multi-node V2V network using beam-steering antenna architecture.

B. Vehicle Platooning

Platooning on the road enables the formation of interconnected groups of vehicles in a virtual chain that can travel together, as depicted in Figure 4. This arrangement allows for the exchange of data and information between vehicles, enabling the headway between them to be reduced to less than a second. This reduction in headway saves fuel and reduces the number of drivers required for the journey.

To enable V2X communication in platooning, messaging is required to assign a platoon leader for vehicles to join or leave, as well as to announce or warn other vehicles of any obstructions or other hazards. Additionally, information such as braking, acceleration, and notification of a new platoon leader must be exchanged between vehicles within the platoon. Effective communication between platoon members is essential to maintain the stability of the platoon and ensure that all vehicles are able to travel safely and efficiently [26]. The use of V2X technology in platooning represents a significant step forward in the development of intelligent transportation systems, enabling more efficient and effective communication between vehicles and the surrounding infrastructure.

In the present state-of-the-art, a single leader is appointed to lead a platoon of vehicles [29]. The leader governs the behavior of the entire vehicular cluster with respect to platoon formation and dissolution. However, with the new beamforming 5G technology coupled with beam-steering capabilities, a chain leader model is proposed where the preceding vehicle acts as a leader for the following vehicle.

This proposed model remedies the issue of a single leader being responsible for multiple vehicles and offers a more reliable communication model. By allowing the preceding vehicle to act as the leader for the following vehicle, less strain is placed on each leader to communicate with multiple vehicles, as shown in Fig. 4. This approach also allows for an overlap between different platoon groups, creating a decentralized model that enables vehicles to easily leave one group and join another.

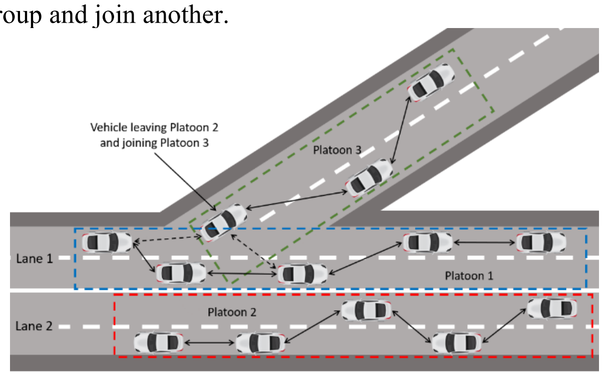

Figure 4: Proposed chain leader model for 5G-V2X based vehicle platooning, showcasing a decentralized network with the preceding vehicle acting as the leader for the following vehicle, allowing for an overlap between different platoon groups.

By being the leader of a much smaller set with a minimum threshold of just one vehicle, the stress on the main leader is significantly reduced, improving network efficiency. This, in turn, reduces the communication latency between vehicles while compensating for the shorter communication range. The chain leader sequence is maintained throughout the platoon, ensuring that the vehicles remain connected and coordinated in their movements.

The proposed chain leader model represents a significant step forward in the development of platooning systems, enabling more efficient and effective communication between vehicles, and improving the safety and reliability of the platoon as a whole.

In addition to reducing complexity, the single node-to-node communication within a platoon also enables better coordination among the vehicles. By receiving information about the road conditions, traffic, vehicle breakdowns, and emergencies well in advance, the following vehicles can adjust their speed and trajectory, accordingly, avoiding sudden braking or lane changes that could disrupt the platoon's flow. This can significantly reduce the likelihood of accidents and enhance road safety.

To further improve the communication network, Roadside Units (RSUs) can be used as a repeater station, storing, and relaying important information to other vehicles within the platoon. This allows for a decentralized network that is resilient to failures and easier to manage. Additionally, the messages exchanged within a platoon must be encrypted with a platoon-specific key to ensure the network's security.

The beam-steering capabilities of the 5G beamforming antenna also play a crucial role in ensuring network security. By creating a highly directional communication link between the two nodes, the risk of eavesdropping and interception by unauthorized parties is significantly reduced. This enhances the privacy and confidentiality of the platoon's communication, making it suitable for sensitive applications such as military convoys and emergency response teams.

C. Cooperative Perception

Cooperative perception is an important feature that can help overcome the limitations of individual sensors in vehicles [23][24]. By sharing sensor data with other vehicles and infrastructure in the network, the overall situational awareness can be enhanced, and vehicles can make more informed decisions. This can significantly reduce the risk of accidents, particularly in critical situations such as lane changes, merging, or navigating through blind spots.

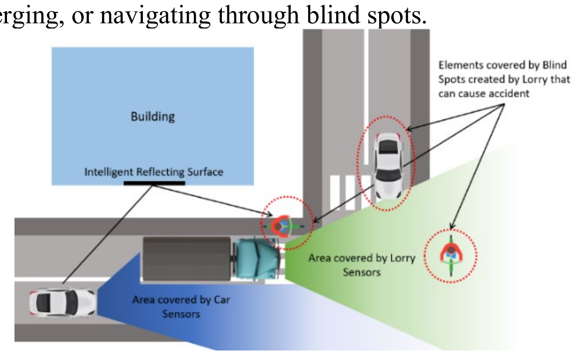

Figure 5: A demonstration of the blind spots created by a lorry and how the data collected from its visibility can compensate for these blind spots. Intelligent reflecting surfaces on buildings can increase vehicles' perception, creating new vehicular infrastructure.

One of the challenges in cooperative perception is the need for a fast and reliable network to transmit the large amount of data generated by sensors [20]. The traditional DSRC network is not capable of providing high data rates, which limits its effectiveness in this scenario. However, the new 5G V2X network can provide the necessary bandwidth up to 500 MHz per channel and almost zero latency communication required for cooperative perception to work effectively.

Moreover, the use of intelligent reflecting surfaces can further enhance the reliability of the communication link. These surfaces can manipulate the propagation of electromagnetic waves, allowing vehicles to look around obstacles and communicate even in non-line-of-sight scenarios [28]. This helps in avoiding the creation of blind spots, thereby improving the safety of the vehicle network.

In addition, the cooperative perception approach can also enable the creation of detailed 3D maps that can be used to fill in the blind spots for individual vehicles. By sharing the sensor data from multiple vehicles, it is possible to create a more comprehensive and accurate map of the environment, which can be used to improve the decision-making of vehicles. This can also help reduce the space between vehicles, enabling more vehicles on the road while maintaining or reducing travel time.

The use of cooperative perception, coupled with the new 5G V2X network and intelligent reflecting surfaces, offers a promising solution for enhancing the safety and efficiency of vehicle networks. It provides a reliable and secure communication link, enables real-time sharing of sensor data, and helps fill in the blind spots, thereby improving the situational awareness of vehicles on the road.

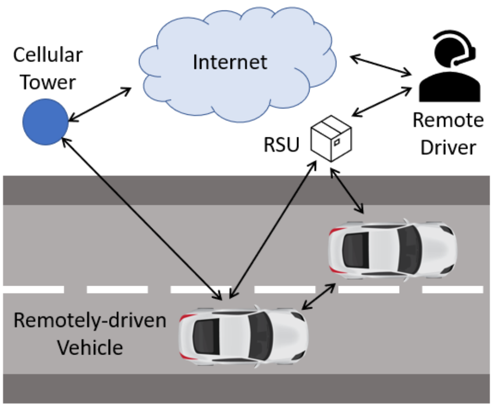

Figure 6: Different possibilities of remote driving within a V2X network via cellular network, RSU, and other vehicles.

D. Remote Driving

Remote driving is a promising application of V2X networks, which requires a high data rate, low latency, and reliable communication between vehicles and the infrastructure [20]. The 5G millimeter-wave band with its new antenna system can provide a channel width of up to 400 MHz, which is 20 times higher than the current DSRC based channel width. This high bandwidth ensures the required bit rate and high data throughput for real-time data transmission, making it possible to support remote driving applications. Cloud computing is also an essential part of this application [20], [30], as it enables the processing and storage of large amounts of data generated by the vehicles and other nodes in the V2X network.

The proposed antenna system for remote driving using 5G can support up to 1 Mbps data rate at downlink and 25 Mbps at uplink for vehicle speeds of up to 250 km/hr. The network can transmit command messages and live video streams with almost zero latency, ensuring a safe and reliable remote driving experience. The network can be established either with the existing 5G cellular network or by using different nodes within the V2X network, such as vehicles and RSUs. As shown in Fig. 6, the remote driving system can be supported with either the existing 5G cellular network, or with the help of different nodes (such as vehicles and RSUs) within a V2X network.

III. Challenges And Recommendations For 5G-V2X Network

The implementation of V2X network faces a number of challenges that need to be addressed for its successful deployment. The introduction of a 5G millimeter-wave network with beam-steering adds new technical challenges to the problem statement. This section discusses these design challenges and offers new recommendations for implementation of a successful V2X network.

The main challenge is the limitation of the current state-of-the-art communication systems such as DSRC, Wi-Fi, and LTE-V2X to the sub-6 GHz frequency band. This frequency band offers a limited channel capacity and does not allow for large data sharing, which is essential for V2X within CAVs. To address this issue, the 5G NR is being proposed for the V2X network at higher frequencies (24, 28, 38, 42 and 60 GHz), which offers a channel bandwidth as high as 400 MHz, allowing for higher data-throughput and fast data-rates.

However, the implementation of 5G in the V2X network is still limited due to a number of challenges. One of the major challenges is the high path loss, low diffraction rates, atmospheric losses due to rain, and multi-path delay spread at millimeter-wave bands. For instance, the 28 GHz frequency band is severely affected due to rain and can cause a loss of up to 6 dB/km, while the presence of foliage and other man-made obstacles can cause a path loss of up to 17 dB/km [25]. To mitigate these issues, beamforming techniques in antennas are used to focus the energy in one direction, allowing for electronic beam-steering, which enables the same antenna to cater to multiple users. Furthermore, a smaller cell size of 200 m is considered as a viable solution to reduce path loss and atmospheric losses [12][15][25]. These solutions can be incorporated into the implementation of the V2X network.

The chained model proposed for vehicle platooning allows for short-range communication to achieve a large size platooning, reducing the strain and need for processing power on a single leader, and allowing the vehicle to communicate only with other vehicles in the immediate vicinity. The direct link between two vehicles with a focused beam also ensures a secure network. However, low diffraction rate at high frequencies makes small obstacles even more significant and hence affects the quality of communication. Intelligent reflecting surfaces (IRS) [27][28] are proposed to be placed on buildings that can manipulate electromagnetic waves in open space and improve the efficacy of a V2X network. Furthermore, 5G enabled RSUs assisted with 5G cellular network can back the V2X network for emergency situations.

Beamforming allows for extremely directional beams with half power beamwidth as low as 5°, which mitigates most of the problems of establishing a long distance V2X network.

However, an extremely focused beam can be very sensitive to motion, making it unsuitable for vehicular networks with high speed, heavy mobility, and quick maneuvers. Antennas offering electronic beam-steering need to have fast beam-switching (in the order of micro-seconds) to align the beam with other nodes as quickly as possible. With the advanced computing system and pre-planned route of the vehicle, the onboard sensors can provide feedback to antenna modules to predict changes in direction, so that the beam can be switched accordingly. Such sensor-aided beam tracking can allow for the vehicles to maintain a strong link between nodes without any break in the signal.

In summary, the implementation of a V2X network faces several challenges such as limited frequency bands, high path loss, low diffraction rates, atmospheric losses, and multi-path delay spread. To overcome these challenges, various solutions such as beamforming techniques, a smaller cell size, chained model for vehicle platooning, intelligent reflecting surfaces, and fast beam-switching antennas can be incorporated. These solutions can enhance the efficiency and reliability of the V2X network and ensure its successful deployment.

IV. Conclusion

Transport has gradually been moving towards more connectivity and autonomy and has been building up a new set of requirements to support different scenarios and use cases. An ultra-reliable and seamless wireless network of vehicles is believed to be a must at present to ensure a faster deployment of emergent transport systems and services (e.g., CAVs). A series of developments in the state-of-the-art of telecommunication systems have been observed in literature as well as in the real-world. The current communication system is limited to sub-3 GHz, with most of the communication happening at 0.9 – 2.5 GHz, in much smaller channel width of roughly 20 MHz to facilitate large number of devices, that are multiplying every day.

The present state-of-the-art vehicular network includes DSRC and cellular-V2X. DSRC operates at the same 2.4 GHz with extremely limited bandwidth of 100 MHz, which is further divided into much smaller channel width, limiting the network speed, and increasing latency. Cellular-V2X is dependent on the development of cellular communication industry and its standards. The current LTE network operates at the sub-3 GHz band, which faces the same problems as DSRC. The new 5G technology is being tested in several parts of the world and it uses a higher frequency band of 28 and 38 GHz for telecommunication applications.

The extent of the new 5G mmWave communication system has been explored here for its applications in V2X network. New communication techniques such as beamforming and beam-steering are required to enable 5G mmWave system. Beamforming allows the wireless system to focus the beam in one direction and hence increasing the reliability of the network and making it more secure. Beam-steering allows the wireless system to use this focused beam and point it in different direction to cover a larger area. Such beam-steering 5G systems have shown the potential to offer additional advantages such as accurate lane detection and precise localization of vehicles in the surrounding.

It improves network reliability drastically and makes the network highly secure from external threats. Furthermore, the proposed new techniques such as chain-leader model complimented with a decentralized vehicular network allows for a much larger range coverage of the network, providing all the vehicles an extended local vision of the area, more accurate shared sensor data with almost zero blind spots, shared processing power for big data and enables advanced remote driving. Such a network benefits all the stakeholders including road and network operators, drivers, vehicle manufacturers, original equipment manufacturers, etc.

The mmWave network comes with a limitation of reduced range compared to the existing communication systems. The network is shown to have an approximate range of 200 m at 28 and 38 GHz in the literature. However, this issue of reduced range is shown to be resolved with the help of chain-leader model, where each vehicle behaves as a leader for the farthest vehicles in the network and at the same time controlling the overall latency, while allowing a faster communication speed and extended field of view.

In conclusion, the proposed 5G mmWave network with the help of smart beam-steering antenna system can be classed as a reliable and a more efficient system for on-road V2X communication in real-time. This paper describes new potential use cases such as vehicle platooning, remote driving, and cooperative perception. The paper discusses the new opportunities in V2X networks with 5G and describes different challenges that will be faced in implementation of V2X networks with beam-steering systems.

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