Challenges and solutions for antennas in Vehicle-to-Everything services

Katare, Kranti Kumar; Yousaf, Irfan; Lau, Buon Kiong

Published in:
IEEE Communications Magazine

DOI:
10.1109/MCOM.001.2100572

2022

Document Version:
Peer reviewed version (aka post-print)

Accepted for the IEEE Communications Magazine (Special Feature Issue on 5G and Beyond Antennas), Oct. 2021

Challenges and Solutions for Antennas in Vehicle-to-Everything Services

Kranti Kumar Katare, Member, IEEE, Irfan Mehmood Yousaf, Member, IEEE, and Buon Kiong Lau, Senior Member, IEEE

ABSTRACT

Autonomous vehicle is being developed for widespread deployment. Its reliability and safety are critically dependent on advanced wireless technologies, e.g., vehicle-to-everything (V2X) communication. The frontend of a V2X system needs an antenna module that enables the vehicle to reliably connect to all other networks. Designing V2X antenna is challenging due to the complex in-vehicle environment, trend for hidden antenna solution, long simulation time and need for omnidirectional coverage. In this article, we survey these challenges as well as existing V2X antenna solutions. In view of the drawbacks in the existing solutions, we propose an efficient design methodology for V2X antennas to provide the desired coverage. The method utilizes a simple geometrical model of the vehicle that captures the shadowing effects of the vehicle body to obtain candidate antenna locations that offer the best coverage via multi-antenna diversity. Hence, complex full-wave simulation can be avoided. The approach is validated through comprehensive full-wave simulations and pattern measurements on two car models. The results confirm that, at 5.9GHz, line-of-sight shadowing has more dominant effect on the received power than multipath propagation due to the car body. In cases of strong diffraction and surface waves, a simple rule-of-thumb can be devised to improve the accuracy of the method.

INTRODUCTION

Over the last decade, both academia and industry have shown enormous interest in developing autonomous vehicle. Autonomous vehicles excel in safety, traffic efficiency and infrastructure utilization. As a basic requirement, several sensors are currently used to control the vehicle's movement in both longitudinal and lateral directions. However, due to range limitations, these sensors only detect nearby objects. Moreover, these sensors' data are not exchanged with other infrastructures (fixed networks, vehicles) to assure safety, reliability, and coordination.

Recently, numerous approaches are being considered to overcome these limitations. As a potential solution, vehicles with wireless link(s) can circumvent: 1) collisions by exchanging speed/direction information; 2) an unknown deterministic hazard by utilizing speed, route and flow optimization provided by road networks, other vehicles, etc. As an emerging vehicular wireless technology, vehicle-to-everything (V2X) communication is attracting tremendous interest. V2X offers ubiquitous applications, particularly as vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-network (V2N), vehicle-to-road side units (V2R) and vehicle-to-infra-structure (V2I) communication, (see Figure 1). Hence, V2X enhances traffic efficiency, resulting in safe automated driving environments [1].

The frontend of a V2X communication system requires an antenna module to communicate with all other networks. This article overviews various key parameters, challenges and possible solutions of V2X antennas. A simple geometrical model-based multi-antenna diversity scheme is then proposed as a computationally efficient approach to solve the challenging problem of vehicle-body shadowing degrading the antenna coverage. This is achieved by identifying candidate locations for multi-antenna using a geometrical model, without having to resort to time-consuming full-wave simulations over the entire search space of possible antenna locations. The proposed scheme was verified using antenna patterns from both full-wave simulations and measurements for real car models (Volvo S60 and XC90).

To our knowledge, this is the first complete study of antenna diversity scheme in V2X communication, which leverages a geometrical study of line-of-sight (LOS) propagation in a vehicular environment to achieve tremendous saving in computational efforts. In particular, due to the (electrically) large size of vehicles (typically 4m-6m) relative to the wavelength of 51mm at the allocate V2X band at 5.9GHz, many millions of mesh cells are needed in the simulations to solve for the antenna properties accurately, as we have confirmed in measurements. For just one antenna location, the simulation can take many days to complete, even with multiple GPUs or simulation clusters. Therefore, it is prohibitively expensive in time/effort to adopt a brute force approach to locate suitable antenna locations for various vehicle models with different design constraints.

Moreover, the proposed scheme may be even more useful for V2X systems operating at millimeter-wave (mm-wave) frequencies (e.g., 28GHz), since shadowing is more severe due to narrow beamwidth and poor scattering contributing to the lack of multipath propagation. Moreover, simulation complexity will increase by over 100-fold compared to sub-6GHz frequencies, making it impossible to run conventional full-wave simulations even with advanced computers. However, to ensure sufficient link budget as well as coverage at mm-wave frequencies, phased arrays with beam-scanning capability may be needed.

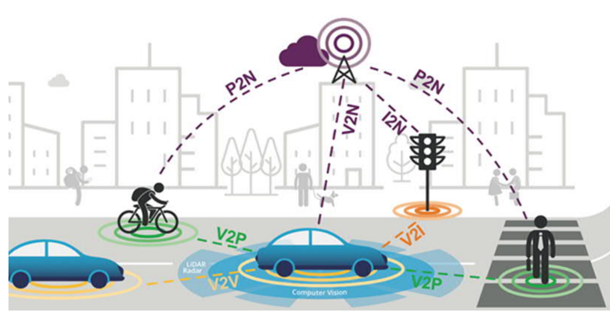


Figure 1. Infrastructure of V2X.

V2X TECHNOLOGY AND ANTENNA CHALLENGES

In this section, we explore the main V2X technologies and design challenges of V2X antennas.

V2X TECHNOLOGIES

In general, many wireless communication technologies (or standards) can be utilized for vehicular communication, including the existing cellular systems like LTE. However, to meet the specific requirements of V2X communication in a connected vehicle ecosystem, two main technologies have been devised: IEEE 802.11p (or Dedicated Short-Range Communications (DSRC)) and the cellular version of V2X (C-V2X). These two technologies are built upon existing standards, with IEEE802.11p belonging to the large IEEE802.11 family of standards and C-V2X defined by 3GPP as part of LTE releases [2]. Both are designed to operate in the dedicated frequency band (5.825-5.925GHz) for V2X application, allocated by the US Federal Communications Commission (FCC) to spur the growth of Intelligent Transport Systems (ITS). The communication environment with either of the enabling technologies (IEEE 802.11p or C-V2X) should be seamless, reliable and smart, e.g., it should support various road safety features such as lane change warning and collision detection. Moreover, antenna design is largely agnostic to the choice of DSRC or/and C-V2X, due to the same 5.9 GHz band being allocated for both ensuring similar propagation channel and antenna simulation effort.

CHALLENGES OF V2X ANTENNAS

As per real-time requirement deduced from the literatures (e.g., [3], [4]) and adopted by Volvo Cars, the V2X antenna module needs to provide radiation coverage for the entire azimuth plane (i.e., azimuth angle ϕ = 0°–360°) within a certain sector in the elevation plane (i.e., elevation angle θ = 75°–105°, with θ = 0° corresponding to the Z-axis). The coverage in the upper hemisphere (θ = 75°–90°) ensures the communication with other infrastructures and networks. On the other hand, to communicate with pedestrians, other vehicles and road-side units, coverage in the lower hemisphere (θ = 90°–105°) is required. As an example, for Volvo S60 and XC90, coverage in the elevation cut θ = 105° facilitates communications with roadside units (e.g., parking sensors) placed at a distance of 5m-6m from the center of the car. Propagation paths from the lower hemisphere of up to θ = 105° were also demonstrated using two-ray model and measurements [3]

This coverage requirement is challenging due to the multiple components/parts inside the vehicle. Moreover, signals from installed antennas inside the vehicle will be blocked and scattered due to the metallic body. To minimize blockage, the antennas should be in the upper half of the vehicle body, if they are under the roof. In this case, the signal blockage is primarily due to the side pillars, which due to their width (typically >100mm, substantially larger than the wavelength) are effective obstacles at 5.9GHz, introducing deep nulls in the corresponding directions. In Figure 2, it is demonstrated that a side pillar (in the -Y direction of a dipole antenna) shadows the electromagnetic waves. As can be seen in the antenna patterns (θ = 105° cuts), the shadowing is negligible at 1GHz, but it becomes increasing severe beyond 2.45GHz. In addition to the side pillars, the roof can also pose obstruction to the radiation (see Figure 2), as will be discussed in the next section. On the other hand, installing the V2X antenna on the roof [5] circumvents signal blockage in the upper portion of the desired coverage region (i.e., θ = 75°– 90°). However, the roof blocks the coverage below the horizontal plane (i.e., θ = 90°–105°). Therefore, the impact of the complex in-vehicle environment on the performance of the relatively high frequency V2X antennas is complicated and warrants a thorough investigation.

Furthermore, finding an appropriate V2X antenna and determining its location in the vehicle are additional challenges. To obtain omnidirectional coverage within θ = 75°−105°, a vertically oriented electric dipole or magnetic loop antenna (as shown in Figure 2) may seem appropriate, although the blockage and multipath problems will mandate more than one antenna to be utilized to provide the required coverage. As for suitable antenna location, it can be found in a brute force manner by simulating the antenna performance at all possible mounting locations inside the vehicle to identify locations that provide the desired radiation patterns. However, this is largely impractical and resource intensive. Such a study may actually be more practical (though still very tedious and costly) using an experimental approach, with the radiation pattern being measured for different antenna locations inside a prototype vehicle. However, prototype vehicles are subject to structural modifications and are increasingly rare due to cost-cutting and shorter development cycle: virtual prototypes are preferred.

RECENT PROGRESS IN V2X ANTENNA DESIGN

Attempts have been made to address some of the above challenges. Placing a V2X antenna in the sharkfin module [5] isolates the antenna from the in-vehicle environment due to the metal roof. However, the protrusion from the car body is unattractive, and the antenna performance can be deteriorated due to mutual coupling with other antennas. To mitigate these issues, a standalone low-profile (3 mm height) antenna solution was proposed in [6] for placement on the car roof. However, the antenna should be hidden in a roof cavity, which will degrade its coverage. Moreover, the metal roof also prevents roof-mounted antennas [5],[6]

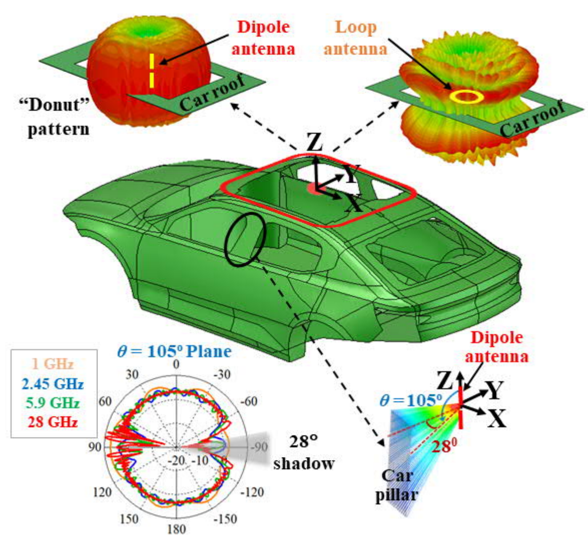


Figure 2. Antenna pattern shadowing due to different vehicle parts: Pillar shadowing at different frequencies (2D patterns for θ = 105°) and roof shadowing at 5.9 GHz (3D patterns), for dipole/loop antenna located at the center of sunroof (marked by red dot).

are based on monopole antenna, which features a "raised radiation pattern" due to the finite ground plane (car roof). This effect, coupled with the curvature of real vehicle roof, further degrade the antenna gain for θ = 90°–105°, rendering these antennas unsuitable for V2X application. Another consideration is the current trend of glass roof, which exposes the antenna to the complex in-vehicle environment. However, this change opens the opportunity to utilize antennas that provide the complete coverage in the range θ = 75°–105°, such as dipole or loop antennas.

In any case, the use of antennas with more suitable radiation patterns does not solve the coverage problem, since metal pillars are needed for structural reasons even for glass-roof designs, and they will cause blockage for the lower sector θ = 90°–105° (see Figure 2). One possible solution is to utilize multiple antennas whose radiation patterns provide complementary coverage to satisfy the requirement. The signals of these antennas are then optimally combined using an antenna diversity scheme to compensate for the coverage holes of any antenna. This approach was studied empirically for antenna locations outside the passenger cabin [4],[7]. However, these studies involved actual drive tests using antennas mounted on two test vehicles, hence limiting the scope to V2V scenario. For example, the coverage of the upper region (θ = 75°–90°) is irrelevant for V2V communication. These tests confirmed that a two-antenna diversity solution is needed, with a roof-mounted antenna together with a bumper antenna being the best combination in [4]. On the other hand, with the more limited V2V scenario of 10-15m distance between two cars in [7], and the antennas positioned on the horizontal surfaces at the front, roof and back of the cars, the best positions correspond to the case when the transmitting and receiving antennas are in LOS. This implies the need for antennas on both the front and back parts of the car. A major drawback of these V2V antenna solutions is the need for long cables to connect the different antennas to the modem. Apart from adding weight, the cable incurs a significant loss (~1.7dB/m) to the RF signals [4]. Moreover, the cables need to fulfill critical requirements such as higher temperature rating, resistance to chemical and water exposure, mechanical robustness to shock and vibrations over the lifetime of the vehicle in hostile environments (e.g., engine compartment, undercarriage).

Regarding the computational aspect, a sparse equivalent source model has been used to speed up full-wave simulation by four times at 5.8GHz [8]. But the antenna is only tested for a metal rooftop location, which has little interaction with the complex in-vehicle environment and hence less sensitive to modeling accuracy. Furthermore, the simple flat-panel car model used significantly reduces the required number of mesh cells for a given accuracy. Another study utilizes the concept of virtual drive to optimize the antenna locations [9]. However, this work focuses on link-level performance, external antennas and the use of ray tracing to account for multipath fading due to objects beyond the vehicle of interest. The coverage of the antenna pattern is not studied. MIMO [10], tri-polarized [11] and phased array [12] antennas have also been utilized for the V2X application; however, due to their large footprint [10] and/or the requirement of additional feed circuitry [11],[12] make them less attractive for the installation over the vehicle. Moreover, although high gain antennas of narrow beamwidth provide more coverage range, omnidirectional antennas are preferred since they provide sufficient gain for the required range [13], and they are simpler/cheaper (no beam-scanning) and more compact.

Therefore, the selection of the antenna elements, their locations in/on the vehicle and the problem with long computational time are largely unresolved challenges that can prevent effective V2X deployment.

OUR CONTRIBUTION

To provide a complete yet practical solution to the challenges of V2X antenna design, we propose the following systematic approach. We begin with determining the antennas that have desirable properties for the problem at hand, for candidate antenna locations that minimize the shadowing problem of individual antenna elements. Then, to overcome the element-wise shadowing problem so to provide the desired coverage in θ = 75°–105°, we utilize multiple antennas in a diversity scheme and optimize their locations to avoid common shadow region(s). The numerical optimization of the antenna locations is based on a simplified geometrical model of the vehicle defined in MATLAB (e.g., see Figure 3), which captures the LOS angular regions of the antenna in the presence of the vehicle body. The candidate set of optimized antenna locations are then verified using full-wave simulations and measurements to provide good diversity gain (i.e., combined antenna gain). Following the successful verification, the geometrical model can be used exclusively in practice to optimize the antenna locations, avoiding altogether time-consuming and resource-expensive simulations or measurements which will otherwise render antenna location optimization impractical for V2X antenna design.

To limit implementation cost and complexity, we focused on a two-antennas diversity scheme, and applied maximum ratio combining (MRC) [4]. A larger number of antennas can be used when the two-antenna scheme does not offer sufficient performance. To study the generality of the approach, the proposed scheme was tested on two structurally different car models: Volvo S60 (a sedan) and Volvo XC90 (a sports utility vehicle).

ANTENNA ELEMENT SELECTION

As stated before, a vertically oriented dipole or loop antenna (Figure 2) may be suitable to offer omnidirectional coverage of θ = 75°–105°. This is because both provide the "donut" pattern in free space, as in Figure 2. However, the vertical dipole antenna (along the Z-axis) radiates mainly θ-polarized electric field ($\mathbf{E}_\theta$), whereas the loop antenna with its axis along the Z-axis offers primarily ϕ-polarized electric field ($\mathbf{E}_\phi$).

As discussed, placing an antenna either on the roof or under the roof are equally problematic. Therefore, placing the antenna at the roof level (e.g., on the glass sunroof) can be an attractive solution. However, the roof interacts with the radiation from the dipole and loop antennas differently, due to their respective polarizations. To show the different interactions, we model the roof of Volvo S60 (see Figure 2) by a sunroof surrounded by metal edges. For the dipole antenna, the electric field $\mathbf{E}_\theta$ can be transmitted through the metal roof edges, supported by surface wave propagation. Hence, its pattern is hardly affected by the roof, as depicted in Figure 2. However, the loop antenna's radiation is effectively blocked by the roof around the XY plane (θ = 90°) (see Figure 2). This is due to the dominance of ϕ-polarization in $\mathbf{E}_\phi$, unsupported by surface wave propagation. Consequently, the vertical dipole antenna is more suitable for sunroof integration. In practice, a shorter variant of the half-wave dipole is preferred for integration on the sunroof. Such miniaturization can be achieved by capacitive loading, for example by adding copper plates at both ends of the dipole.

Although the dipole antenna's pattern is relatively unaffected by the roof, there remains the problem of the supporting pillars (six in the case of Volvo S60 and eight in the case of Volvo XC90) and the lower part of the vehicle body (i.e., below the windscreen, side windows and rear window) shadowing part of the antenna radiation to the

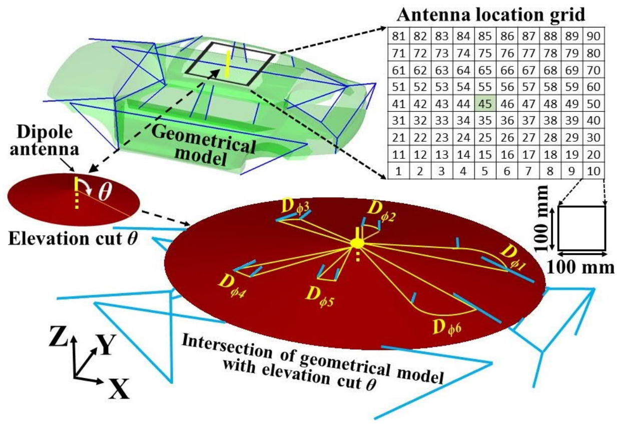


Figure 3. Simulation model and geometrical equivalent of Volvo S60, showing grid of antenna locations and shadowed angular regions for antenna location 45 found from intersection of geometrical model with elevation cut θ.

required coverage in the lower hemisphere (θ = 90°–105°). Fortunately, depending on the antenna location on the sunroof, the angles where the blockage occur can differ substantially. This motivates a multi-antenna diversity solution using two or more antennas at different locations to overcome the shadowing problem. Although multipath propagation due to the vehicle body, including reflection and diffraction, can interfere with LOS propagation, we propose to use a geometrical model to find appropriate antenna locations for a diversity scheme that either avoid altogether or minimize common LOS-shadowed region(s). This simplification is motivated by the relatively high frequency of V2X communication (5.9GHz, with wavelength of 51mm) coupled with the obstructing vehicle body parts being larger than the signal wavelength. Under these conditions, direct (or LOS) propagation often has the dominant effect on the received signal power, as illustrated in Figure 2 for the single-pillar scenario. For proof of concept, we consider a two-antenna diversity scheme.

GEOMETRICAL MODEL

In the diversity antenna solution, the main challenge is to find, with practical computational complexity, proper antenna locations along the sunroof to overcome/minimize shadowing. Even for a two-antenna solution, an exhaustive search involving n possible locations will require n full-wave simulations to obtain the antenna pattern of each location. To determine n, the spacing of the search grid should be fine enough to avoid missing suitable locations, while the grid size should not be too large. Moreover, to keep coupling small between closely spaced cases, we can set the grid spacing to be larger than a wavelength. With this criterion, the patterns from isolated dipoles can be combined in post-processing to obtain diversity gain of a two-antenna setup, with negligible error. But even with moderate spacing (100mm), n is still large (= 90), even for sunroof-only deployment, due to the wavelength of 51mm. To avoid running n full-wave simulations for antenna design, an approximate geometrical approach of finding signal blockage within the desired coverage is proposed based on modeling only the vehicle parts that present obstruction to the LOS path of the antenna radiation.

Here, we elaborate the principle of the proposed scheme with the help of Figure 3, depicting the vehicle body of a Volvo S60. In the proposed geometrical model, the sunroof is first discretized with n = 90 square grid cells, where adjacent cells are separated by a distance of d = 100mm (~2 wavelengths) (see Figure 3). The n antenna locations correspond to the center of the cells. Then, a geometrical model of the car body (Figure 3) is created in MATLAB to capture the edges of the car body parts that can shadow antenna radiation from any given antenna location. The shadow regions for a given location (in angular domain) are then calculated using the directions to the edges of different car parts (e.g., pillars, bonnet, trunk). One simple method is to solve for the intersection points between the conical representation of the elevation cut θ and these edges, shown in Figure 3. As expected, the shadowing increases as the elevation angle increases from θ = 90° to 105° (with ϕ = 0° to 360° for any θ). Therefore, the analysis considers both individual "elevation cones" as well as the complete result over the entire coverage region.

As an example, when the dipole antenna is placed at location 45 (as in Figure 3), all six pillars will shadow the radiation in the horizontal plane in angular sectors, denoted by $D_{\phi 1}$ (due to pillar 1) to $D_{\phi 6}$ (due to pillar 6). Similarly, if location 50 is considered, these metallic pillars will also provide shadow, however with different sectors: $D'_{\phi 1}$ (due to pillar 1) to $D'_{\phi 6}$ (due to pillar 6). To take full advantage of the antenna diversity scheme, these two shadow regions ($D_{\phi 1}$ to $D_{\phi 6}$ for location 45 and $D'_{\phi 1}$ to $D'_{\phi 6}$ for location 50) should not overlap (or with minimum overlap if overlap cannot be avoided).

Based on this concept, the shadow regions for all antenna locations are calculated from the geometrical model, and the common shadow region(s) are then calculated for all possible pairs of n locations. The ranking of the location pairs is based on the pair giving not only no common shadow within the range θ = 90°-105°, but also the closest shadow regions are separated by the greatest amount (in azimuth angle). This is followed by cases of decreasing clearance between closest shadow regions between two antenna locations, and thereafter cases of increasing overlap of the shadow regions.

After the model was used to rank the location pairs for the Volvo S60, the approach is repeated to rank antenna location pairs on the sunroof of a Volvo XC90 (see the simulation model in Table I).

VERIFICATION WITH FULL-WAVE SIMULATION AND MEASUREMENT

To verify the merit of our geometrical results, radiation patterns of a 22mm long half-wavelength dipole antenna at the 90 sunroof locations were simulated in the I-solver of the CST Microwave Studio Suite using a detailed preprocessed meshed model (mesh cell size of wavelength/10) of a Volvo S60 car model that contains all sizable metallic structures except for seat frames and other minor parts (see Figure 2). Non-metallic parts were omitted in this study since they have less influence on wave propagation. The full-wave simulation of antenna over the roof of vehicle for a single location took around 2 days, while using a computer with two Nvidia Quadro-M600 GPUs and 224GB RAM. Then, the radiation patterns in the coverage region (i.e., θ = 75°–105° with ϕ = 0°–360°) are combined at each azimuth and elevation angle using MRC [4] for all location pairs. One possible physical system layout of the proposed V2X scheme is depicted on the car model in Figure 4, where the two dipole antennas at locations 10 and 81 can be integrated onto the glass sunroof and connected to an off-the-shelf electronic control unit (ECU) through coaxial cables. The ECU converts the RF signals to baseband and performs MRC. A similar diversity scheme, but for antennas above the car roof, is elaborated in [13]. Figure 4 also shows the radiation patterns for the

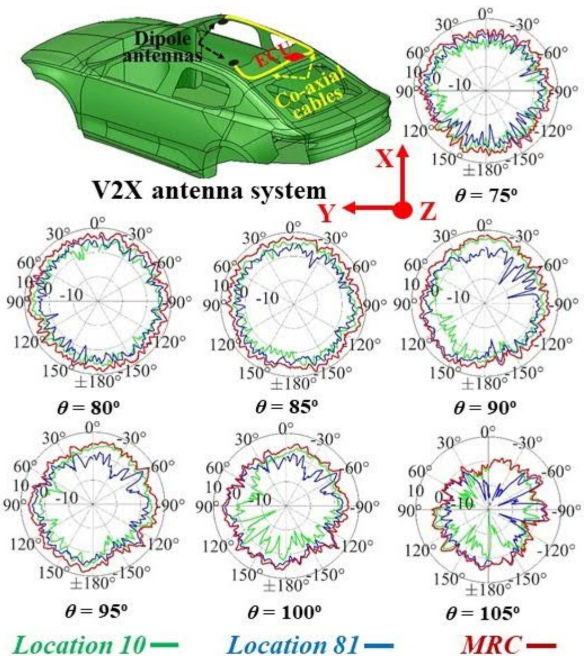
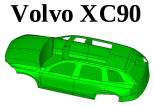


Figure 4. Proposed V2X antenna system with the simulated antenna patterns (at locations 10 and 81 of Volvo S60) and their MRC patterns in different elevation cuts (θ).

Table I. 10 best antenna location pairs (L1, L2) for Volvo S60 and 3 for Volvo XC90 with geo-metrical (Geometrical shadow) and full-wave (Min MRC Gain: G_m) results.

Car Model	L1	L2	Geometrical Shadow (°)	Min MRC Gain: G_m(dB)
Volvo S60 	10	81	0	-3.0
	1	90	0	-2.8
	44	50	0.5	-3.1
	3	30	1.1	-3.0
	83	70	1.1	-3.0
	14	10	4.2	-3.0
	1	60	4.9	-3.3
	74	80	6.1	-3.0
	14	30	6.7	-2.9
	74	70	6.7	-3.0
Volvo XC90 	41	50	5.8	-3.0
	1	10	6.2	-3.9
	81	90	6.2	-3.9

antennas at the two locations and the corresponding MRC patterns over different elevation cuts. Each MRC pattern was calculated from the two radiation patterns [4] by combining the antenna gains with the MRC scheme over the 3D space. It can be observed that MRC provides good signal strength in most of the directions, and the two patterns well complement each other, indicating the effectiveness of the proposed scheme.

Furthermore, since in reality waves are spread in time and angle by multipath propagation, the same signal does not arrive from only one angle. The angular spread in V2X scenarios is found to be 2°-8° and 5°-30° in LOS and non-LOS conditions, respectively [14]. This means that deep nulls (of under -3 dB gain) in the installed antenna pattern over a narrow angular range (of up to 2°) can be filtered out from the MRC-combined pattern in post-processing. The filtered patterns within the coverage range are then ranked according to decreasing minimum antenna gain (over location pairs). This strategy is motivated by the coverage performance being limited by the region with the weakest gain, which likely results from common shadowing by the car body at both antenna locations.

For verification with the geometrical approach, the 10 best antenna pairs (L1+L2) on Volvo S60 were identified based on minimum MRC gain values. Then, the geometrical model was utilized to find the common shadow region for each possible antenna pair, using the procedure described in the previous section. It was found that the best antenna pairs from MRC had common shadow regions from the slopped sections of the car such, as bonnet, trunk and top edges of the four corner pillars. The LOS signal blockage in these regions was alleviated by surface waves that diffract off these surfaces, allowing part of the signal to reach the LOS-shadowed regions. This meant that the geometrical model was pessimistic and could be modified (calibrated) based on the effective blockage. We deduced from simulated antenna patterns that the height of these car sections could be reduced by one wavelength (51mm). With this correction implemented in the geometrical approach, the 10 best antenna pairs from the geometrical model (based on common shadow) match those from the full-wave simulations (based on minimum MRC gain G_m), and they are listed in Table I. To cover the minimum range requirement (~400m) of V2X communication [13] for the best antenna pair (10+81), the average and the minimum MRC gain values are 5.56dB and -3dB, which require -4.2dBm and 12.9dBm of input power to each transmitting antenna, respectively.

An important practical consideration is whether these solutions are robust to small errors in the antenna locations (for real installation). Hence, a sensitivity analysis was performed using full-wave simulations and MRC scheme for the location pair (10+81). Each of the two antennas was displaced in the X and Y directions by up to one wavelength, and the resulting MRC gain varied between -2.6dB and -3.0dB. This indicates a robust solution with <0.5dB performance loss.

The antenna patterns at these locations (10+81) were then verified through pattern measurement at Aalborg University for a real (striped-down) Volvo S60 (Figure 5), to verify the full-wave simulation results. Pattern measurements were carried out by placing a cardboard over the sunroof (with 100mm × 100mm cells printed on its lower side for antenna positioning), as depicted in Figure 5. A 102mm long ANRITSU 2000-1361-R dual-band dipole [15] operating in 2.4-2.5GHz and 5.0-5.9GHz with 3dBi gain was used. The simulated and measured patterns of the dipole antenna at location 10 for the center frequency (5.9GHz) in different elevation cuts (θ = 75° to 105°) are shown in Figure 5. The measured cross-polarization level is better than 10dB in most of the directions. To quantitatively compare the simulated and measured patterns, we

utilized the empirical cumulative distribution function (ECDF). We found that 72% of the gain pattern is within 3dB of each other in the coverage range, indicating reasonable agreement. In general, it is difficult to achieve good agreement due to the car being very large (4.76m in length for Volvo S60) relative to the small wavelength (51mm), resulting in even minor geometrical discrepancies between the actual car and the simulation model to cause substantial variations in the patterns. Tolerance of the

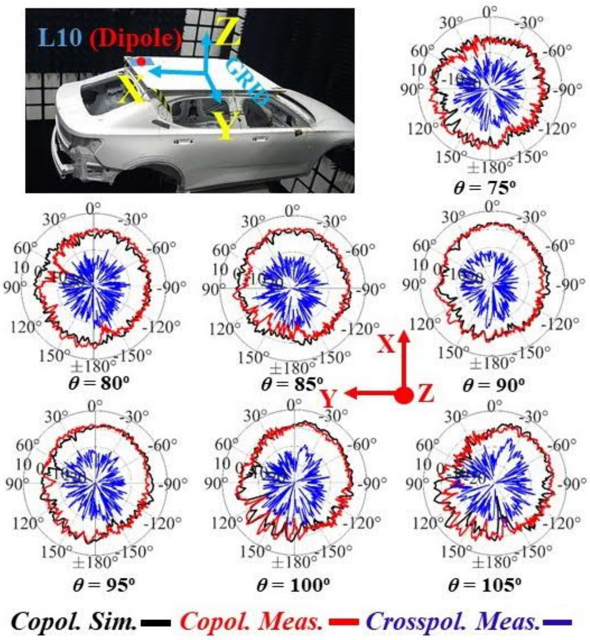


Figure 5. Measurement setup with simulated co-polarized and measured co-polarized & cross-polarized normalized patterns (in different elevation cuts (θ)) of dipole antenna placed at location 10 for Volvo S60.

measurement chamber (0.5dB), non-ideal pattern of the real dipole antenna and cable effects are additional sources of discrepancy. The proposed geometrical based approach was also validated for Volvo XC90 by comparing its results with those from full-wave simulations. As opposed to Volvo S60, the difference to the full-wave simulations was only caused by surface waves along the bonnet, and this was calibrated by lowering the effective height as before. The best three location pairs from the geometrical and full-wave approaches are listed in Table I. The best location pair is 41+50 (along the centerline, i.e., Y = 0 in Figure 3), which is different to the best antenna locations for Volvo S60 (along the diagonal of the sunroof). This is mainly due to different car configuration: Volvo S60 has six pillars, outstretched profile and a large sunroof, whereas Volvo XC90 has eight pillars, elevated profile and a smaller sunroof.

From the above discussion, we have confirmed the usefulness of the geometrical approach in identifying antenna locations that provide the best full-wave simulation results, which allows us to avoid performing time-consuming and resource intensive brute-force optimization using full-wave simulations.

CONCLUSION

In this article, a complete investigation is carried out to address different challenges and solutions for V2X antenna module. Specifically, a simple geometrical model-based diversity antenna approach is proposed to obtain antenna locations that can meet the coverage requirement. This approach optimizes for appropriate antenna locations without the need for time-consuming simulations. The approach was verified by full-wave simulations and pattern measurements. Therefore, the proposed diversity scheme can be a powerful enabler in the ongoing efforts to deploy V2X technology in real applications.

ACKNOWLEDGMENTS

This work is supported by the VINNOVA FFI Programme (Grant no. 2014-01403).

REFERENCES

[1] M. Boban, *et al*., "Connected Roads of the Future: Use Cases, Requirements, and Design Considerations for Vehicle-to-Everything Communications," *IEEE Veh. Technol. Mag*., vol. 13, no. 3, pp. 110-123, Sep. 2018.

[2] B. M. Masini, A. Bazzi, and A. Zanella, "A Survey on the Roadmap to Mandate on Board Connectivity and Enable V2V-Based Vehicular Sensor Networks," *Sensors*, vol. 18, no. 7, 2207, Jul. 2018.

[3] M. G. Nilsson, C. Gustafson, T. Abbas and F. Tufvesson, "A Measurement-Based Multilink Shadowing Model for V2V Network Simulations of Highway Scenarios," *IEEE Trans. Veh. Technol.*, vol. 66, no. 10, pp. 8632-8643, Oct. 2017.

[4] T. Abbas, J. Karedal, and F. Tufvesson, "Measurement-Based Analysis: The Effect of Complementary Antennas and Diversity on Vehicle-to-Vehicle Communication," *IEEE Antennas Wireless Propag. Lett*., vol. 12, pp. 309-312, 2013.

[5] Q. Wu, Y. Zhou, and S. Guo, "An L-Sleeve L-Monopole Antenna Fitting a Shark-Fin Module for Vehicular LTE, WLAN, and Car-to-Car Communications," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7170-7180, Aug. 2018.

[6] H. Wong, K. K. So, and X. Gao, "Bandwidth Enhancement of a Monopolar Patch Antenna With V-Shaped Slot for Car-to-Car and WLAN Communications," *IEEE Trans. Veh. Technol*., vol. 65, no. 3, pp. 1130-1136, Mar. 2016.

[7] N. Adhikari, A. Kumar, and S. Noghanian, "Multiple Antenna Channel Measurements for Car-to-Car Communication," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 674-677, 2016.

[8] H. Zhao, C. Li, Z. Chen, and J. Hu, "Fast Simulation of Vehicular Antennas for V2X Communication Using the Sparse Equivalent Source Model," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 7038-7047, Aug. 2019.

[9] L. Reichardt, J. Maurer, T. Fugen, and T. Zwick, "Virtual Drive: A Complete V2X Communication and Radar System Simulator for Optimization of Multiple Antenna Systems," *Proc. IEEE*, vol. 99, no. 7, pp. 1295-1310, Jul. 2011.

[10] J. K. Che, C. C. Chen and J. F. Locke, "A Compact 4-Channel MIMO 5G Sub-6 GHz/LTE/WLAN/V2X Antenna Design for Modern Vehicles," *IEEE Trans. Antennas Propag*., in press.

[11] B. Feng, J. Chen, S. Yin, C. Y. D. Sim and Z. Zhao, "A Tri-Polarized Antenna With Diverse Radiation Characteristics for 5G and V2X Communications," *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 10115-10126, Sept. 2020.

[12] M. Kamranishfaq et al., "Compact Wide-Angle Scanning Multibeam Antenna Array for V2X Communications," *IEEE Antennas Wireless Propag. Lett., in press.*

[13] https://www.auto-talks.com/wp-content/uploads/2020/06/Cost-efficient-C-V2X-Antenna-Installation-final.pdf.

[14] R. Zhang, *et al*., "Measurement and Modeling of Angular Spreads of Three-Dimensional Urban Street Radio Channels," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 3555-3570, May 2017.

[15] https://www.anritsu.com/en-us/componentsaccessories/products/2000-1361-r

BIOGRAPHY

KRANTI KUMAR KATARE is a Postdoctoral Fellow with both Lund University and Volvo Car Corporation, Sweden.

IRFAN MEHMOOD YOUSAF is the Product Owner for Antenna Systems at Volvo Car Corporation, Sweden.

BUON KIONG LAU is a Professor at the Department of Electrical and Information Technology, Lund University, Sweden.