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Research Article

Analysis of C-V2X Antenna Performance on Vehicular Panoramic Glass

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This paper presents an analysis of a cellular vehicle-to-everything (C-V2X) quarter-wavelength monopole antenna performance when mounted on full glass roof. Antenna gain measurements performed on a full glass roof exhibited a performance degradation in a linear average gain (LAG) of 8 dB compared to when the same antenna is mounted on a metallic ground plane. In addition, the antenna radiation pattern on the glass roof had deep nulls. Due to a lack of information about the electrical material properties and architecture of the full glass roof sample from the glass supplier for proprietary reasons, a series of gain measurements were performed for the C-V2X monopole when mounted on different glass material samples. The measurement findings suggested the existence of a metal layer in the glass roof sample. Based on this information, the antenna was simulated using a full-wave, three-dimensional electromagnetic field solver on the full glass sample with a low-emissivity (low-E) coating on the edges of the full glass roof. The simulation results showed acceptable agreement with the measurements. A practical solution is suggested to improve the C-V2X antenna performance on the full glass roof. Specific absorption ratio (SAR) analysis is conducted for the passengers in the front and rear seats due to the passenger radiation exposure from the C-V2X monopole antenna mounted on the glass roof. The SAR study showed that the effect of the roof-top C-V2X monopole antenna radiation on the passengers is negligible.

1. Introduction

Cellular vehicle-to-everything (C-V2X) communication is crucial for autonomous driving and intelligent transportation systems. It leverages the evolution in the cellular systems from 4G to 5G cellular networks to enable reliable communication with low latency for vehicular networks. C-V2X has four applications which are vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N) communications. By exchanging messages between vehicles, pedestrians, and infrastructure, C-V2X can support many use cases such as forward collision warning, vehicle platooning, and remote driving [1].

Antenna placement on vehicles significantly impacts the antenna performance, so most antennas are placed on the vehicle's roof to avoid signal blockage by the vehicle's metallic parts [2]. The continuous evolution of car aesthetic designs led to the introduction of many car roof types, such as sunroofs and panoramic roofs, to allow light and air inside the car [3]. Lately, the automakers have introduced a new roof type, the full glass roof, to present a new experience and view for the passengers. However, introducing glass and plastic parts on the vehicle's roof affects the roof-mounted antenna performance [4].

The goal of this paper is to analyze the performance of a C-V2X quarter-wavelength monopole antenna when mounted on a vehicle's glass roof through a series of measurements and simulations. Currently, there are no studies on the antenna performance when mounted on a vehicle's full glass roof in any frequency band. Few references discuss the C-V2X antenna performance when mounted on a metal behind a panoramic roof [4–7]. Although the C-V2X antenna is mounted on the metallic portion of the vehicle's roof, the antenna performance is degraded to the front of the vehicle which is the direction of the panoramic roof area [4–7].

In this work, the performance degradation of the C-V2X roof-top antenna when mounted on vehicle's glass roof is investigated. The measurements setup and the C-V2X monopole antenna measurements on the glass roof are presented in Section 2. Section 3 shows the C-V2X half-wavelength dipole antenna measurements. Section 4 discusses the C-V2X monopole antenna measurements when mounted on four different glass types. Section 5 presents the C-V2X monopole antenna simulation results. The SAR study for the passengers inside the vehicle is presented in Section 6, and Section 7 concludes this paper.

2. C-V2X Monopole Antenna Performance on Vehicle's Glass Roof

Figure 1 shows a vehicle's glass roof section provided by an automotive original equipment manufacturer (OEM) with its computer-aided design (CAD) files. No other information is provided by the OEM or the glass supplier about the construction of the glass roof or the layers stacked inside the glass. The glass roof section consisted of a metal frame underneath the glass and the rear mirror on which the antenna was mounted, as shown in Figure 1. The glass size ($L \times W \times H$) is $982 \times 620 \times 3.85\,\text{mm}^3$ with the antenna mounting hole located 125 mm from the back end of the glass. Due to the curvature of the glass roof, the antenna is tilted by an angle of 8.3° in the *yz* plane as the front of the glass roof is higher than the back of the glass roof. Also, the sides of the glass roof are curved in the *xz* plane as shown in Figure 1. The quarter-wavelength C-V2X monopole antenna is used in this study as the monopole is the most used C-V2X antenna in the automotive industry. The monopole antenna has a height of 13 mm and a width of 2 mm as shown in Figure 2. The antenna is soldered to a printed circuit board (PCB) with an FR4 material which has a dielectric constant of 4.4. A small green cable with an SMA connector is then soldered to the antenna to act as the antenna feed. The antenna and the PCB were mounted on a small shark-fin chassis with a size (LxW) of $117 \times 67\,\text{mm}^2$, as shown in Figure 2.

The C-V2X antenna gain measurements are conducted at Oakland University's Outdoor Automotive Antenna Range in Michigan, USA. First, the C-V2X monopole antenna is measured when mounted on the 1-meter rounded metallic ground plane and then when mounted on the vehicle's glass roof, as shown in Figure 3. The far-field measurement data are analyzed and expressed in two parameters, i.e., radiation pattern (RP) and linear average gain (LAG). The RP is measured at three elevation angles of (10, 0, and −6), corresponding to theta angles of 80°, 90°, and 96°, respectively, at 5.9 GHz. These elevation angles are chosen to represent above-horizon (80°), horizon (90°), and below-horizon (96°) angles. LAG is calculated by converting the measured gain values in dBi to linear values at each elevation angle between $\Theta = 80^\circ$ and $\Theta = 96^\circ$, at each of the 360 azimuth points per elevation. The linear values are then averaged and converted back to dBi to determine the LAG value for each frequency. For the antenna measurements, the angular resolution is 1° and 2° for theta and phi resulting in 16 theta points and 181 phi points per elevation point.

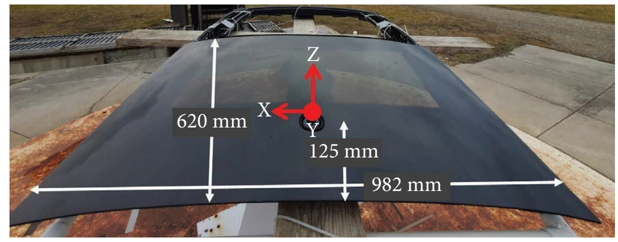


Figure 1: Vehicle's glass roof section dimensions.

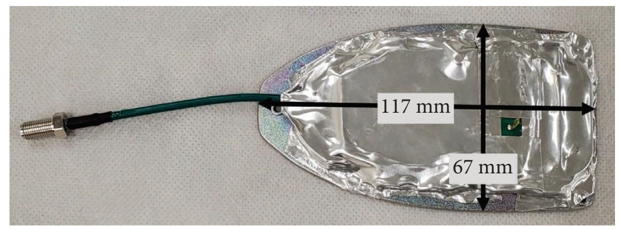


Figure 2: C-V2X monopole antenna prototype used in the study.

Figure 4 shows the performance comparison for the C-V2X monopole antenna when mounted on the metallic ground (GND) plane vs. mounted on the vehicle's glass roof. When mounted on metal, the antenna has an omnidirectional radiation pattern without nulls at all three elevation angles. In contrast, when the monopole was mounted on the glass roof, the radiation pattern had deep nulls on the sides at $\varnothing = 90^\circ$ and 270°. The front and back directions of the radiation pattern do not show deep nulls like the side directions; however, the gain is significantly less than the metallic ground plane placement. The antenna performance degradation when mounted on the vehicle's glass roof is evident in the LAG as shown in Figure 5, as the LAG for the monopole mounted on metal is about −1 dBi compared to −9 dBi when mounted on the glass roof.

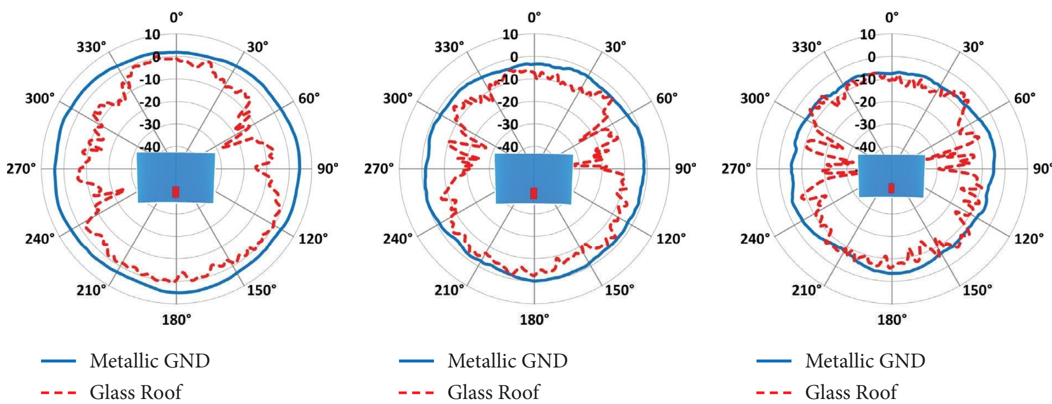
To better understand the results in Figures 4 and 5, simulations of the C-V2X monopole antenna on the full glass roof were performed to investigate the reasons behind the performance degradation. The Ansys high-frequency structure simulator (HFSS)' finite element method (FEM) was used for the simulation with the glass roof CAD files (Figure 6). Glass material was assigned a dielectric constant of 7 and a dielectric loss tangent of 0.009 [7]. The simulation results do not match the measurements shown in Figure 7 as the simulated RP shows void of deep nulls, which are missing in measured results, and simulated LAG shown in Figure 8 is more than eight dBi higher than the measurements, which indicates that there are materials other than the glass causing the antenna performance degradation on the full glass roof.

3. C-V2X Dipole Antenna Performance on Vehicle's Glass Roof

Although the C-V2X monopole antenna is the most used antenna in the automotive industry, a half-wavelength C-V2X dipole antenna is also added to the measurements campaign

(a) (b)

FIGURE 3: C-V2X monopole antenna when mounted on (a) vehicle's glass roof and (b) 1-meter rounded metallic ground plane (GND).



(a) (b) (c)

FIGURE 4: C-V2X monopole antenna measured radiation pattern on the full glass roof and metallic GND at (a) theta = 80°, (b) theta = 90°, and (c) theta = 96°.

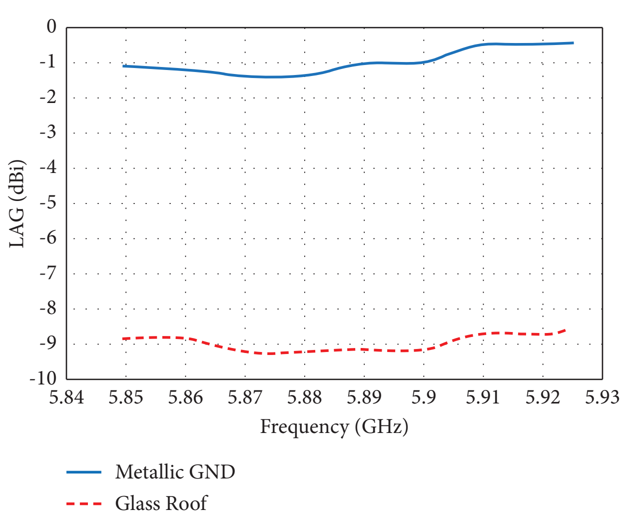


FIGURE 5: C-V2X monopole antenna measured LAG on the full glass roof and metallic GND.

to study the effect of the vehicle glass roof on different antenna types. The dipole antenna is suitable to be investigated as it is less dependent on the ground plane than the monopole antenna. The C-V2X dipole antenna is measured when the dipole antenna is mounted on1-meter rounded metallic ground plane and then when mounted on vehicle's glass roof as shown inFigure 9. The far-field measurement data are analyzed and expressed in two parameters, i.e., radiation pattern (RP) and linear average gain (LAG) as in the monopole antenna case which was discussed earlier.

Figure 10 shows the performance comparison for the C-V2X dipole antenna radiation pattern when mounted on the metallic ground plane vs. when mounted on the vehicle's glass roof. When mounted on metal, the antenna has an omnidirectional radiation pattern without nulls at all three elevation angles. In contrast, when the dipole antenna was mounted on the glass roof, the radiation pattern had deep nulls. The front and back directions of the radiation pattern do not show deep nulls like the side directions; however, the gain is less than the metallic ground plane placement. The antenna performance degradation when mounted on the vehicle's glass roof is evident in the LAG shown in Figure 11, as the LAG for the dipole mounted on metal is about 1 dBi compared to −6.5 dBi when mounted on the glass roof. The C-V2X dipole antenna followed the same trend as the C-V2X monopole antenna when mounted on the vehicle's glass roof which indicates that the antenna performance degradation when mounted on the vehicle's glass roof is not related to the antenna type.

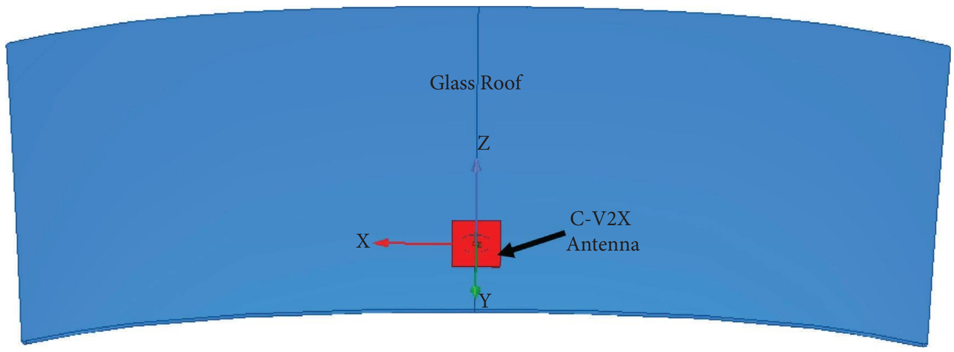


Figure 6: C-V2X monopole simulation on the clear glass roof.

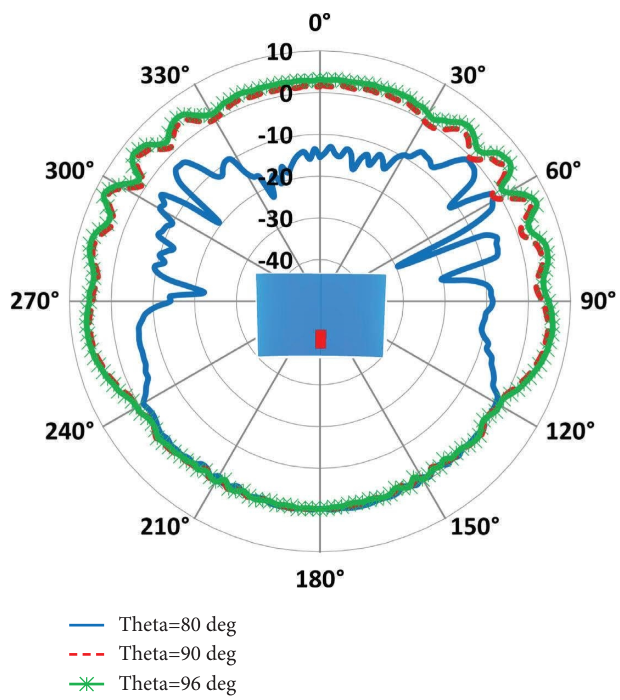


Figure 7: C-V2X monopole antenna simulated radiation pattern on the glass roof.

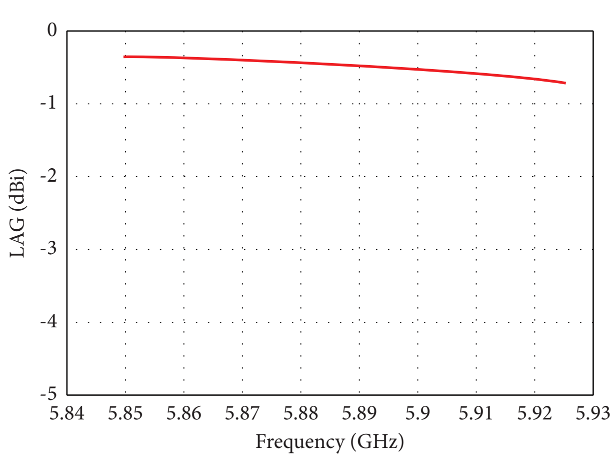


Figure 8: C-V2X monopole antenna simulated LAG on the glass roof.

4. C-V2X Monopole Antenna Measurements on Different Glass Types

As it is quite clear that the glass properties affect the antenna performance, different studies were performed and presented in this section to learn further the effect of roof material properties on antenna performance. The C-V2X monopole antenna was measured on four different glass types which are as follows:

(i) Clear glass sheet with the size of $508 \times 508 \times 3.2\ mm^3$

(ii) Low-emissivity (low-E) glass sheet with the size of $508 \times 508 \times 3.2\ mm^3$

(iii) Metal wire-reinforced glass sheet with the size of $585 \times 585 \times 6.35\ mm^3$

(iv) Vehicle's glass roof sample

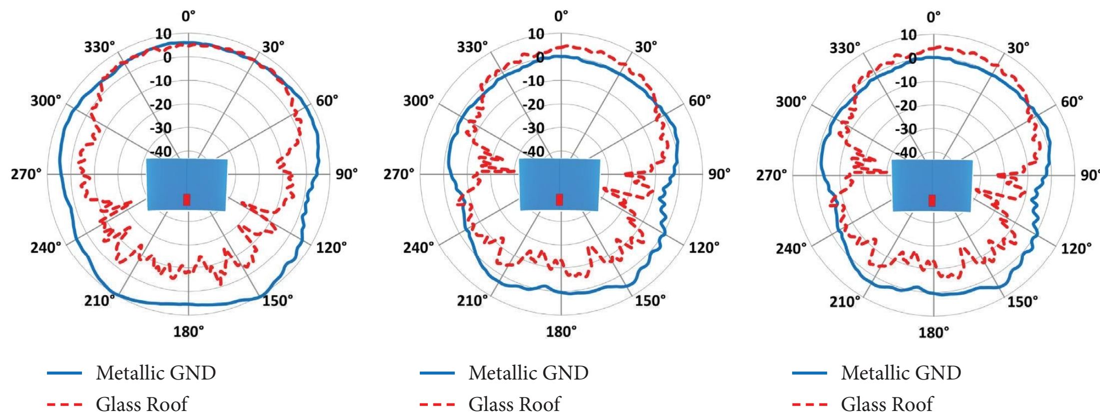
Figure 12 shows the measurement setup for the C-V2X monopole antenna when mounted on the four types of glass. Figures 13 and 14 show the radiation pattern and LAG for the C-V2X monopole when mounted on the four glass materials, respectively. When the antenna was mounted on clear glass, it had an omnidirectional radiation pattern, while the wire-reinforced glass and the vehicle's glass roof showed deep nulls in the radiation pattern, especially at $\ominus = 90^{\circ}$ and 96°. The antenna showed an omnidirectional pattern for the low-E glass case but with a gain less than the clear glass antenna mounting. The antenna LAG shown in Figure 14 proves that when the antenna is mounted on clear glass, it performs well, like when mounted on metal. The antenna mounted on wire-reinforced glass and glass roof exhibited the worst LAG performance due to the nulls in their radiation patterns.

Figure 15 shows the average gain over elevation angles for the C-V2X monopole antenna mounted on the four glass materials. For the antenna mounted on clear glass and low-E glass, the gain for elevation angles above the horizon ($\ominus < 90^{\circ}$) and below the horizon has comparable values, while the wire-reinforced glass and the glass roof showed better gain values in the above-horizon angles compared to the below-horizon angles.

These measurements conclude that the glass material is not the reason for the C-V2X monopole antenna

(a) (b)

Figure 9: C-V2X dipole antenna when mounted on (a) 1-meter rounded metallic ground plane (GND) and (b) vehicle's glass roof.



(a) (b) (c)

Figure 10: C-V2X dipole antenna measured radiation pattern on the full glass roof and metallic GND at 5.9 GHz: (a) theta = 80°, (b) theta = 90°, and (c) theta = 96°.

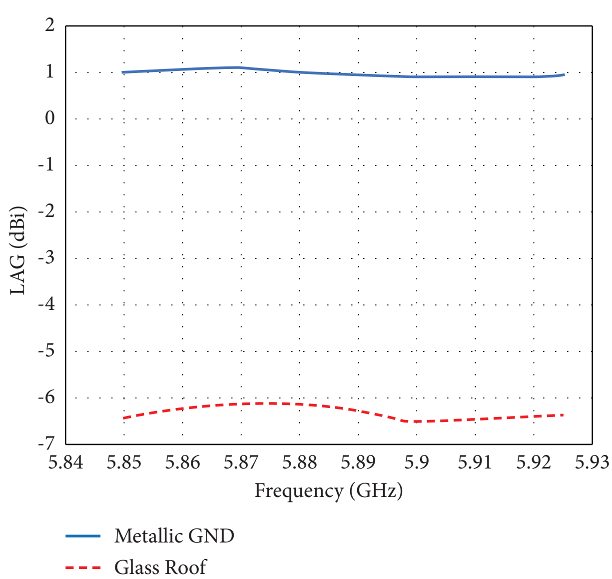


Figure 11: C-V2X dipole antenna measured LAG on the full glass roof and metallic GND.

performance degradation since the clear glass shows a good performance. However, the antenna mounted on wire-reinforced glass shows a trend similar to that of when the antenna is mounted on a glass roof, indicating that there may be some metallic coating or metallic particles in the construction of the vehicle's glass roof.

5. C-V2X Monopole Antenna Simulation on a Full Glass Roof

The objective of this section was to get simulation results that matched the measurements for the C-V2X monopole on a glass roof. The antenna measurements on the four glass materials showed the possibility of a metal layer in the glass roof sample, so the best assumption was that there is a low-E coating underneath the glass roof to protect the vehicle interior and passengers from the heat of the sun. The glass roof CAD files contained opaque areas at the edges of the glass roof while the middle of the glass roof sample was transparent, so we assumed that the low-E coating layer was in the opaque area at the edges while the transparent area was just pure glass. The low-E coating is a thin transparent coating that is put on the glass to prevent heat and allow the passage of the visible light. One of the low-E coating simplest layer stacks is as follows: glass-SnO_2(40 nm)-silver(10 nm)-SnO_2(40 nm) [8, 9]. The tin-oxide (SnO_2) layer is a high refractive layer which has a dielectric constant of 24 and a conductivity of 2 S/m [10, 11]. Figure 16 shows the layer stack used for the simulation. The antenna is mounted on the glass layer, and the low-E coating is underneath the glass,

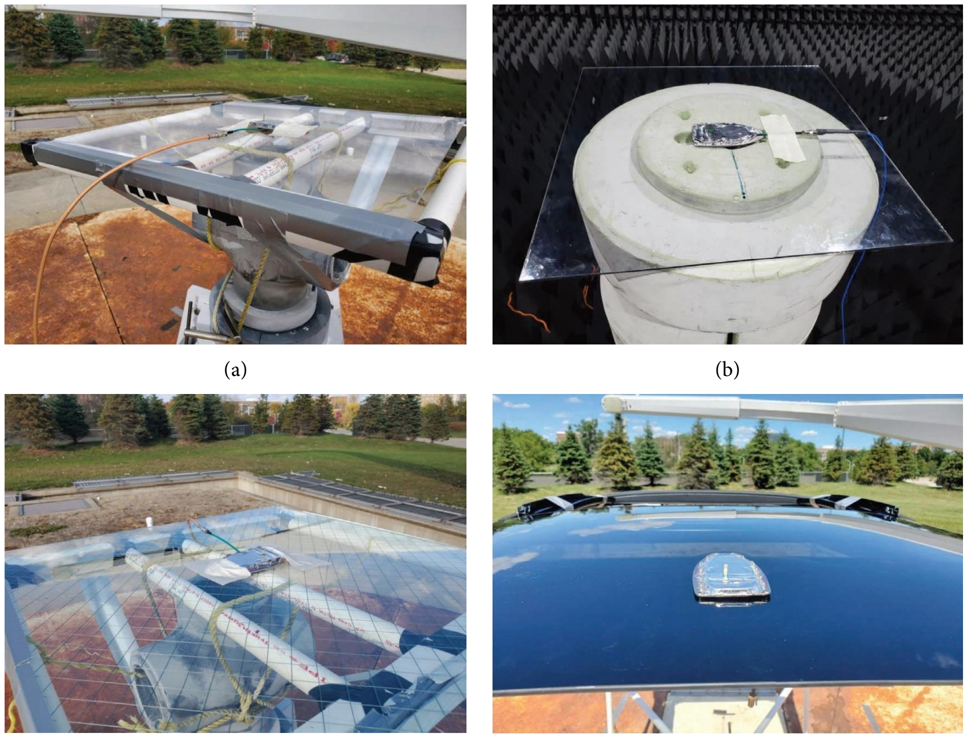
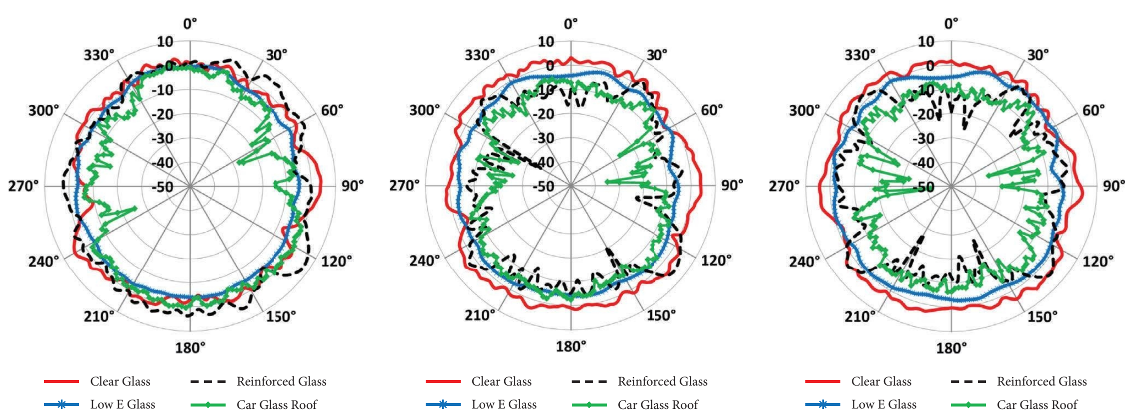


FIGURE 12: C-V2X monopole antenna when measured on (a) clear glass, (b) low-E glass, (c) wire-reinforced glass, and (d) vehicle's glass roof.



(a) (b) (c)

FIGURE 13: C-V2X monopole antenna measured radiation pattern on different glass materials at (a) theta = 80°, (b) theta = 90°, and (c) theta = 96°.

with each layer having a thickness of 1 μm to avoid meshing errors during the simulation when lower thickness values are used.

Figure 17 compares the measured and simulated radiation pattern for the C-V2X monopole when mounted on the full glass roof sample. A good agreement is achieved between the simulation and measured radiation pattern, as the simulated radiation pattern shows deep nulls with slight differences from the measurements. For $\ominus = 96^\circ$, the simulated radiation pattern had more reflections in the front direction compared to the measurements. The LAG shown in Figure 18 also agreed well with values of −10 dBi and −9dBi, for the simulations and measurements, respectively. Figure 19 shows the simulated and measured average gain over elevation angles for the C-V2X monopole mounted on the glass roof sample. For the elevation angles above the horizon ($\ominus < 90^\circ$), a good agreement was achieved between measurements and simulation. However, for the below-horizon elevation angles, a difference of more than 1.5 dBi is observed

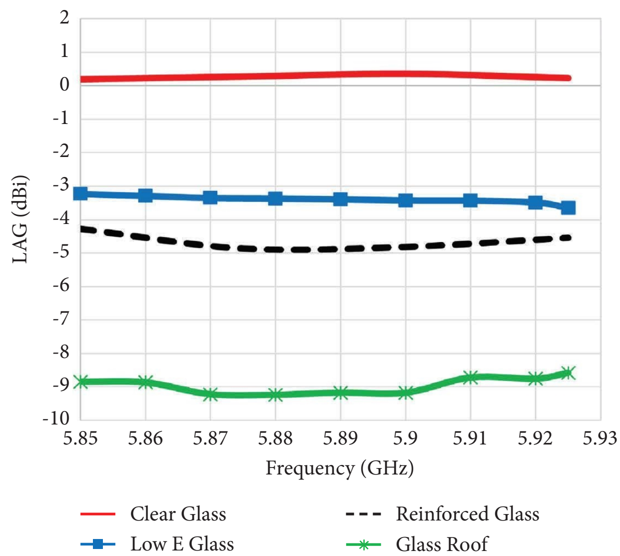


Figure 14: C-V2X monopole antenna measured LAG on different glass materials.

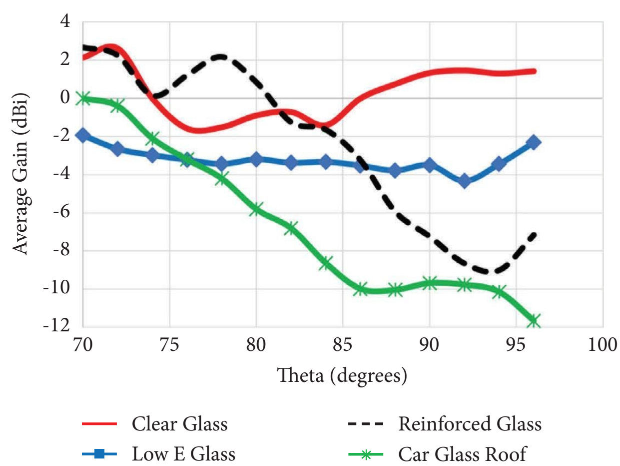


Figure 15: C-V2X monopole antenna average gain vs. elevation angles on four different mounting glass types.

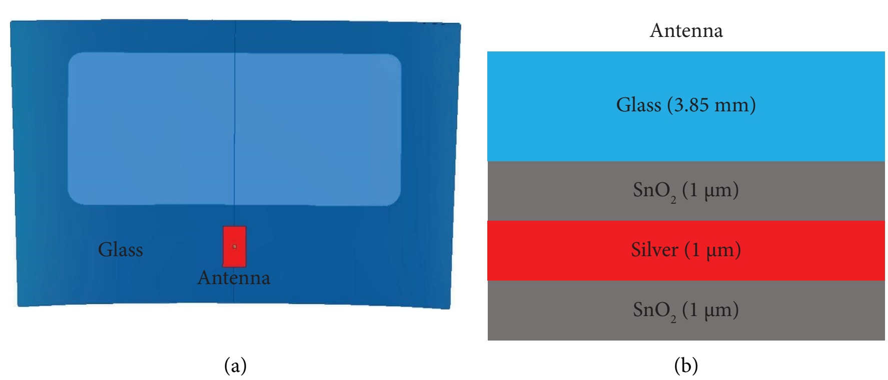
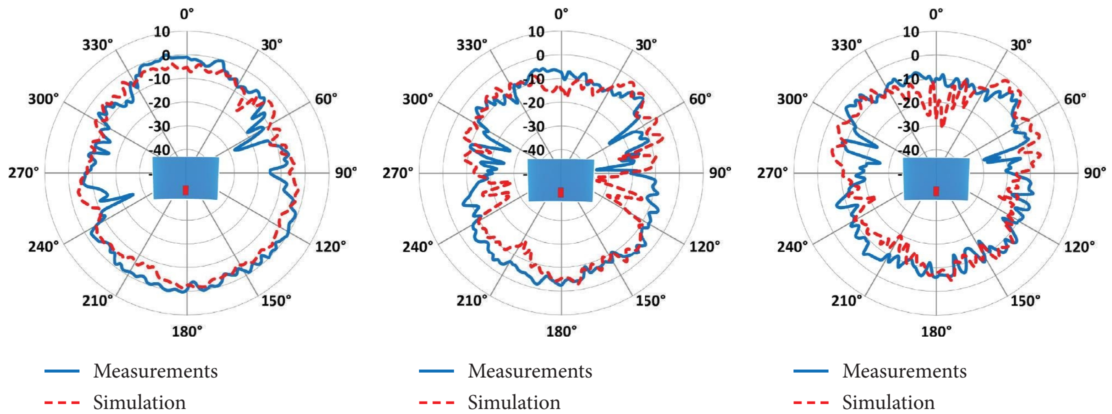


Figure 16: C-V2X monopole simulation on a full glass roof (a) simulation setup and (b) glass roof simulation stack up.

as expected due to more reflections as shown in the simulated radiation pattern.

From the simulation results, the main reason for the C-V2X antenna performance degradation on the glass roof sample is that the C-V2X electromagnetic wave propagates through different layers with different dielectric constants, which causes the wave to be reflected and scattered. The reflections that appeared in the measured radiation pattern can prove this analysis. To reduce the wave reflections, the low-E coating can be installed on the upper side of the glass



(a) (b) (c)

Figure 17: C-V2X monopole antenna measured and simulated radiation pattern on a full glass roof: (a) theta = 80°, (b) theta = 90°, and (c) theta = 96°.

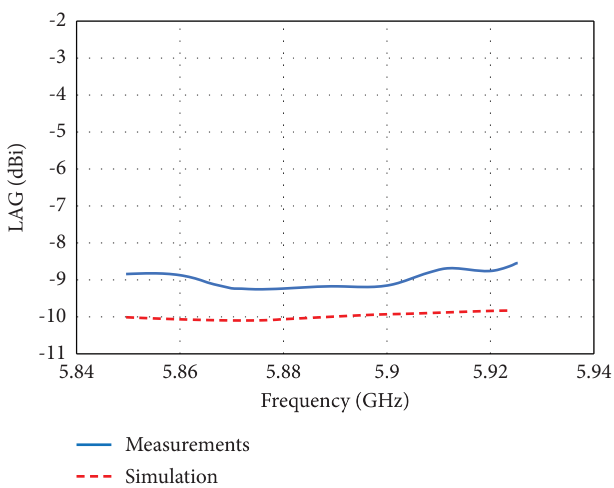


Figure 18: C-V2X monopole antenna measured and simulated LAG when mounted on a full glass roof.

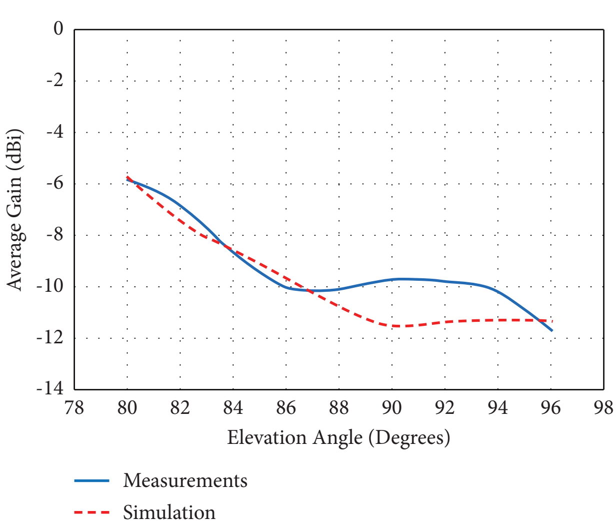


Figure 19: C-V2X monopole antenna mounted on a glass roof measured and simulated average gain vs. elevation angles.

to be between the antenna and the glass layer, as shown in Figure 20. An HFSS simulation is performed for the C-V2X antenna when mounted on a glass roof with the low-E coating on the upper side of the glass. Figure 21 shows the C-V2X monopole simulated radiation pattern with the low-E coating on the top side of the glass roof. The antenna had a good omnidirectionality in its radiation pattern at $\ominus = 80$, 90, and 96° without any nulls. Also, the LAG shown in Figure 22 was around −1.5 dBi, which is 8 dB better than when the low-E coating is on the bottom side. This finding shows that moving the low-E coating to the top layer of the glass is crucial for the C-V2X antenna performance improvement on a glass roof as the antenna performance when the low-E coating is placed on the top of the glass layer is comparable to when the antenna was mounted on a metallic roof.

6. SAR Study of the C-V2X Antenna on Glass Roof

With the presence of the vehicle's glass roof, the passengers inside the vehicle will be exposed to the radiation from the C-V2X antenna mounted on the glass roof. To check the C-V2X antenna's radiation effect on the vehicle's passengers, a specific absorption rate (SAR) analysis is conducted when the passengers are in the front and rear seats of the vehicle and the C-V2X monopole antenna is mounted on the top of the glass roof.

A simulation is conducted for the SAR using Ansys HFSS at the 5.9 GHz. The SAR simulation setup is shown in Figure 23 as the C-V2X monopole antenna is mounted on the glass roof with the low-E coating on the top of the glass, as shown in Figure 20. The front and rear passengers are included in the simulation. The C-V2X antenna signal power is set to 23 dBm (0.2W) which is the maximum power that can be fed to a C-V2X antenna according to the SAE J3161 standard [12]. The human body dielectric constant is 45.8 and conductivity is 0.77 S/m [13].

The HFSS SAR simulation shows that the maximum SAR value on the passengers is 0.007 W/kg which is negligible

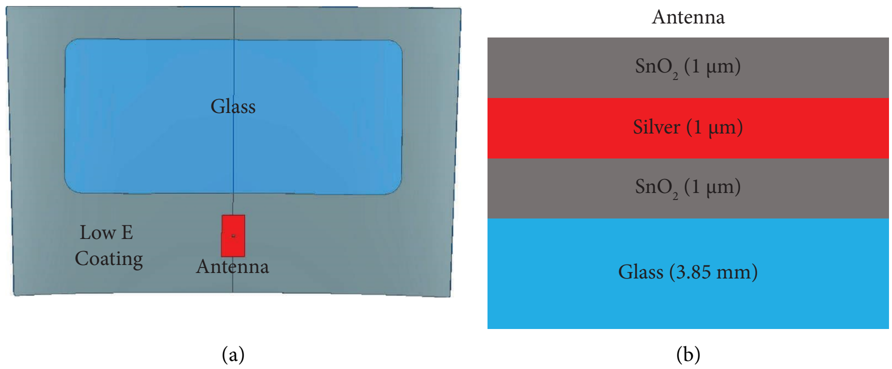


Figure 20: C-V2X monopole simulation on a glass roof with the low-E coating on the top (a) simulation setup and (b) glass roof simulation stack up.

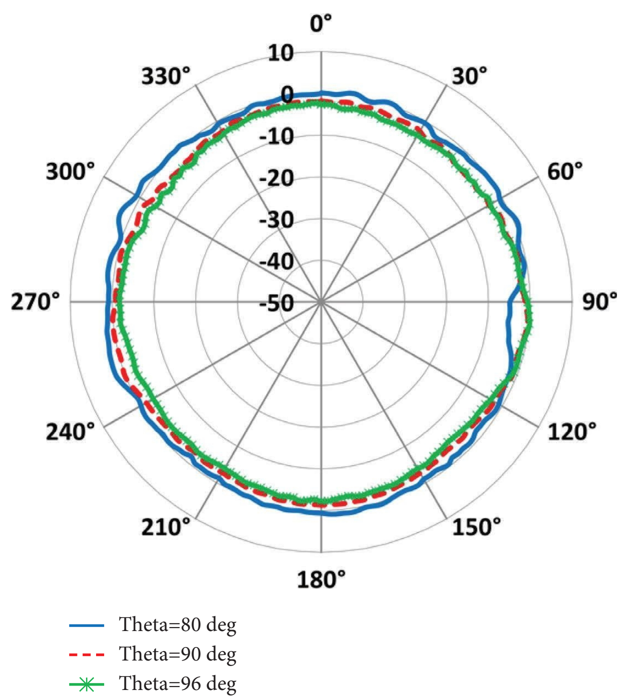


Figure 21: C-V2X monopole simulated radiation pattern when the low-E coating is on the top side of the glass roof for Θ = 80, 90, and 96° at 5.9 GHz.

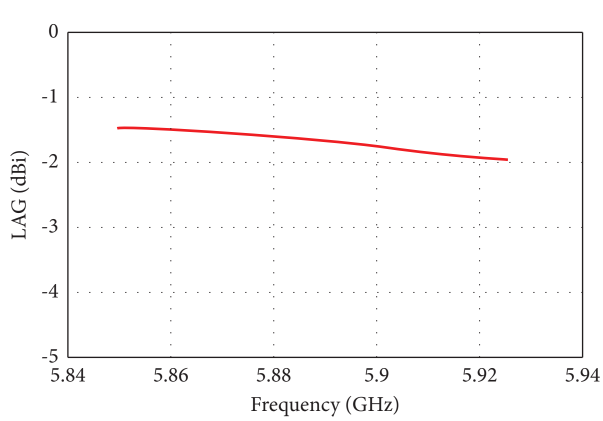


Figure 22: C-V2X monopole simulated LAG when the low-E coating is on the top side of the glass roof.

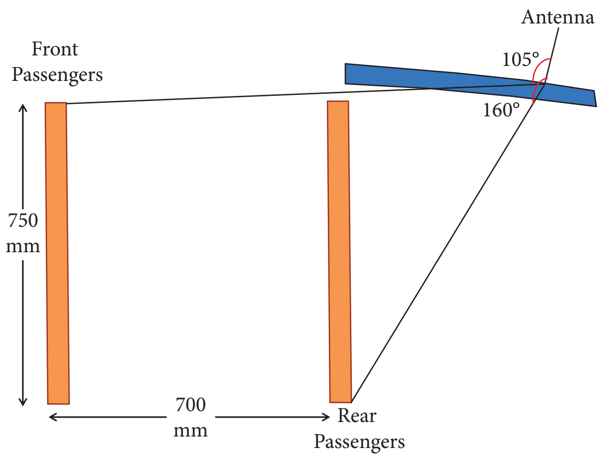


Figure 23: SAR simulation setup.

compared to the 1.6 W/kg which is the Federal Communication Commission (FCC)' specification in the United States. The SAR simulation shows that the passengers' radiation exposure from the C-V2X monopole antenna mounted on the glass roof is minimal, and this is expected as the C-V2X monopole antenna has a low LAG of less than −18 dBi in the elevation angles that affect the vehicle passengers ($\ominus = 105^{\circ}$ to 160°) as shown in Figure 23.

7. Conclusions

The performance degradation of the C-V2X monopole antenna when mounted on a vehicle's full glass roof section is analyzed through a series of measurements and simulations. Measurement of the C-V2X monopole antenna when mounted on vehicle's glass roof shows a performance degradation in the LAG of 8 dB compared to when the monopole antenna is mounted on 1-meter metallic ground plane. A half-wavelength C-V2X dipole antenna is then measured on the glass roof and on the 1-meter metallic ground plane. The dipole antenna measurements on the glass roof showed similar performance degradation as the C-V2X monopole antenna which indicates that the performance degradation is not related to the antenna type. The C-V2X monopole antenna is then measured on four different glass types in which the monopole antenna showed degraded performance when mounted on the wire-reinforced glass indicating the possibility of the existence of metallic coating or metallic particles inside the glass roof section structure. The simulation showed that the performance degradation is caused by the low-E coating layer underneath the glass in the opaque area at the edges of the glass roof, which caused reflections for the C-V2X electromagnetic waves. The simulation shows that if the low-E coating is moved from underneath the glass to the top, the antenna performance will improve significantly. A SAR study was conducted and showed that the passengers are exposed to negligible radiation from the C-V2X monopole antenna mounted on the glass roof.

Data Availability

The data used to support the findings of this study are made available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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