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Research Article

Vehicular Bidirectional Internal Antenna with Asymmetric Gain Characteristics to Compensate for Backward Link Path Loss due to Interior Obstacles

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Wireless communication technologies are expected to become essential in future self-driving vehicles. This study presents an antenna for vehicle wireless communication with a bandwidth of 75 MHz at a Wireless Access in Vehicular Environment frequency of 5.885 GHz. To compensate for the backward link path loss from the vehicle interior and passengers, the antenna is designed to have asymmetric gains of 0 and 6 dBi at 0° and 180°, respectively. The antenna is validated through an outdoor road test. We measured the received continuous-wave (CW) power, received signal strength indicator, and packet-delivered ratio (PDR) of the digital signal under vehicle-to-vehicle communication mode. Similar power is received in both the backward and forward scenarios. The forward and backward PDR are also similar.

1. Introduction

With the rapid development of communication technologies, a wide range of innovative services are now available to consumers. Development in the vehicle communication system has led to new method of data transmission that complements existing services [1]. One promising technology is Wireless Access in Vehicular Environment (WAVE) communication, which has been developed on IEEE 802.11p [2]. WAVE communication is classified into the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). If a driver wishes to mount a V2V antenna on the roof after buying a vehicle, several thru-holes must be drilled. In contrast, the installation of internal antennas does not decrease vehicle durability and reduces the overall cost, as shorter radio frequency (RF) cables are required. This could facilitate the commercialization of the WAVE communication service. On the other hand, most V2V communication systems use an omnidirectional antenna installed on the rooftop [3–5].

We previously reported a compact internal vehicular antenna that transmitted and received signals inside a vehicle [6]. The performance of the interior antenna was validated under V2V scenarios in the 5.85–5.925 GHz frequency band (within the WAVE band). However, the signal reception for the rear direction was lower than that for the front direction by about 10 dB. The reason was that the utilized dipole antenna had the symmetric pattern with the identical gain in the front and rear direction, but the interior furniture in the rear seat increased propagation loss in the reverse direction. This could cause frequent failures in backward link communication. As described in [6], one should note that the power transmitted to the front side was higher than the required level. Therefore, if the excess power of the front side is transferred to the rear side, the forward and backward links can be balanced; this is the main objective of this study.

Another advantage of the antenna with asymmetric gain is the possibility of changing the position of the antenna inside the vehicle. The antenna designer can choose the appropriate position depending on the interior structure of the vehicle and then adjust the power ratio between the front and rear sides.

One might think that the simple aperture antenna could be applied for asymmetric gain. However, it is difficult to adjust the power ratio, so it cannot be applied for different kinds of vehicles, which have the different ratio of power loss in the front and rear side. For example, one vehicle has the difference of 5 dB between the front and rear direction, meanwhile another vehicle could have the 10 dB. So, the structure adjusting the power ratio proposed in this study is most optimistic for the many kinds and installation positions of the vehicle.

On the other hand, WAVE communication could occur toward the side direction. Therefore, an antenna with a moderate gain of about 5 dBi will be more efficient than an omnidirectional antenna. This low-directional antenna can focus its beam toward the front and rear, and the nonzero radiation toward the side of the vehicle is acceptable.

The success of communication between vehicles and infrastructure can be improved by preventing fading effects through the application of a diversity technique. In [7], the use of diversity to improve WAVE communication was verified. Therefore, in this study, the diversity technique was adopted by introducing another antenna set composed of patches.

In this study, we propose an antenna that compensates for backward link power losses (Section 2), thereby improving V2V communication. The interior antenna designed in this study improves upon our previous work in the following ways:

(i) Patch antennas are integrated to support V2V communications

(ii) An antenna supporting the diversity technique is designed for interior installation

(iii) The radiation pattern shows an asymmetric gain, so the gain achieved by antenna placement inside the vehicle is the same in the forward and backward directions

The simulated and actual indoor performance of the antenna is presented in Section 3, and the outdoor test is discussed in Section 4, followed by concluding remarks in Section 5.

2. Design of the Proposed Internal Antenna

The proposed internal antenna, with an asymmetric bidirectional radiation pattern in the WAVE band, is shown in Figure 1. Here, the WAVE band is in the range 5.85–5.925 GHz according to the IEEE Standard [2] for vehicle and infrastructure (V2X) communication. The designed antenna comprises two substrates constructed from a 0.51 mm thick dielectric material with a permittivity of 2.2 and a loss tangent of 0.009. The ground layer is situated between the two substrates. The radiating elements are positioned on the top and bottom layers, as shown in Figures 1(a) and 1(b), respectively. A microstrip network connects the top and bottom layers by a thru-hole (Figure 1(c)), which contains a copper wire, creates an impedance of 50 Ω, calculated from the inner radius V_a and outer radius V_b. The optimized parameters are listed in Table 1.

As discussed, the proposed antenna radiation pattern should be asymmetric. Backward link losses due to the passenger and vehicle interior are estimated to be approximately 6 dB [6]. Therefore, more power should be delivered to the patch elements radiating toward to the backside of the vehicle. Asymmetric radiation patterns can be produced using different microstrip widths, W_2 and W_3, as shown in Figure 1(e), such that their impedance, and therefore, the amount of power transferred differs. The optimized width of the lines is $W_2 = 0.74$ mm (78 Ω) and $W_3 = 1.03$ mm (65 Ω). The bottom layer receives more power than the top layer, leading to the 6 dB gain difference.

As shown in Figures 1(a) and 1(b), two WAVE band patch pairs are used to support the diversity technology (WAVE 1 and WAVE 2).

3. Simulated and Measured Characteristics of the Proposed Internal Antenna

The proposed internal antenna was simulated using ANSYS HFSS software. One port is fed by the wave and the other port was terminated. Figures 2(a) and 2(b) show the simulated current distribution of a V2V antenna at 5.885 GHz. It can be inferred from the difference in impedance ratio at the feed-port junction that more current flows to the bottom layer. However, as shown in Figure 2(b), this current was divided by the nonsymmetric power combiner. As a result, the current density in the top layer was stronger than that in the bottom layer. We can also find the leak current on the adjacent patch antenna as shown in Figure 2(b)

We used a photoetching technique to fabricate the patch antennas, as shown in Figure 3. The ground plane was located beneath the top layer, and the patch antennas were linked by two holes with copper-plated interiors and filled with through holes with a diameter of 0.8 mm. Then, 50 Ω coaxial connectors were soldered to the feed port.

Figure 4 shows the reflection coefficients (S_{11}) for the WAVE band. The simulated and measured reflection coefficients agreed very well with each other. A network analyser was used to measure the reflection coefficient at 21.1 dB at the centre frequency, with a −10 dB bandwidth of 90 MHz. This result satisfies the requirements for V2V communications.

Figures 5(a) and 5(b) show the radiation pattern in the x-z plane (H-plane) and y-z plane (E-plane), respectively, at 5.885 GHz. The simulated and measured gains differed by about 6.2 dB between $\theta = 0^\circ$ (front side) and 180° (rear side) because of the power difference between the top and bottom radiating elements. The gains are given in Table 2.

The 3 dB half-power beamwidths (BWs) are shown in Figures 5(a) and 5(b) and are summarized in Table 2. The interesting point is that the 3 dB BW for the front side is narrower than that for the rear side, but the gain is smaller. This proves that the proposed design scheme shown in Figure 1 works well.

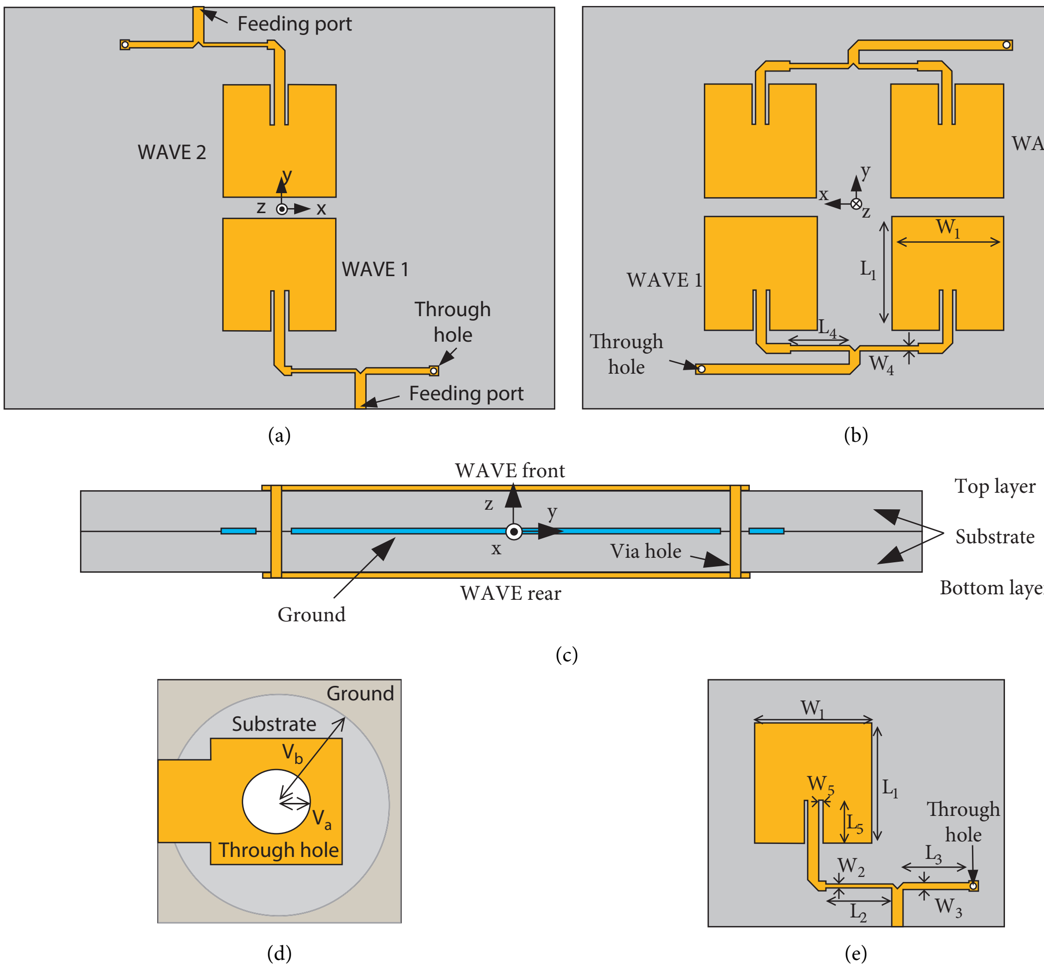


Figure 1: Proposed internal antenna design: (a) top view; (b) bottom view; (c) side view; (d) magnification of the hole; (e) magnification of the top-layer patch.

Table 1: Optimized parameters of the proposed internal antenna.

Parameter	Value (mm)	Parameter	Value (mm)
W_1	16.85	L_2	9.49
W_2	0.74	L_3	9.40
W_3	1.03	L_4	8.85
W_4	0.89	L_5	5.90
W_5	0.50	V_a	0.40
L_1	16.9	V_b	1.38

The proposed internal antenna has been compared with the previously reported 5.9 GHz vehicle antennas as given in Table 3. The reference antennas [8–10] are designed to be mounted externally. The proposed antenna has a greater gain than the other antennas, but with a whole volume and gain similar to exterior antennas.

The radiation pattern as shown in Figure 6 was measured, while the antenna was mounted inside a compact vehicle. This pattern corresponds to the *x*-*z* plane shown in Figure 5(a). The length and height of the vehicle were 3.6 and 1.7 m, respectively. Figure 6(a) shows a schematic of the whole experimental setup, with the proposed antenna mounted inside the vehicle and a probing omnidirectional antenna positioned outside the vehicle. The distance between the interior and exterior antennas was 3 m, and the angular step was 30°. The other instruments are placed in the vehicle. Each port of the network analyser is connected to the interior and exterior antennas via a low-noise amplifier. The experiment was conducted in a flat, open, outdoor area.

Figure 7 shows a graph of the measured transmission (S_{21}) response, where 0° and 180° represent the front and rear ends of the vehicle, respectively. As the proposed antenna radiates bidirectionally, the radiation gain at the rear is compensated. Thus, the responses at the front and rear of the vehicle are similar, but there is a difference of 2 dB that may arise from measurement errors (e.g., misalignment).

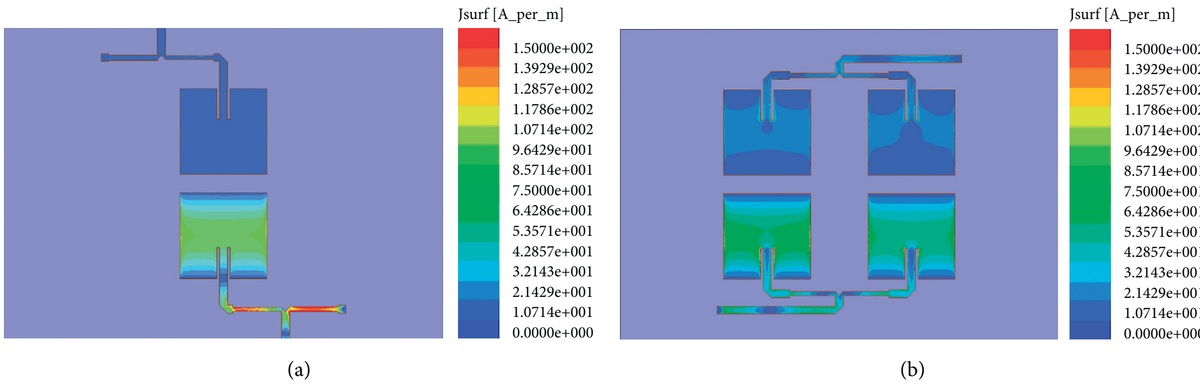


FIGURE 2: Current distribution of antenna: (a) top layer at 5.885 GHz; (b) bottom layer at 5.885 GHz.

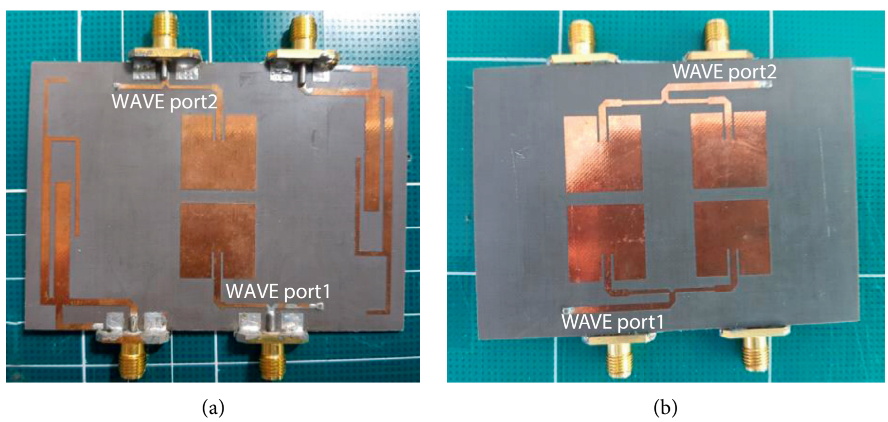


FIGURE 3: Fabricated internal antenna: (a) top view; (b) bottom view.

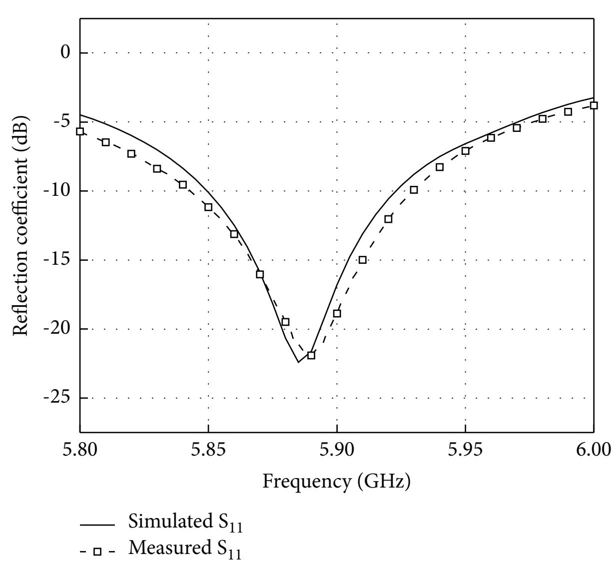
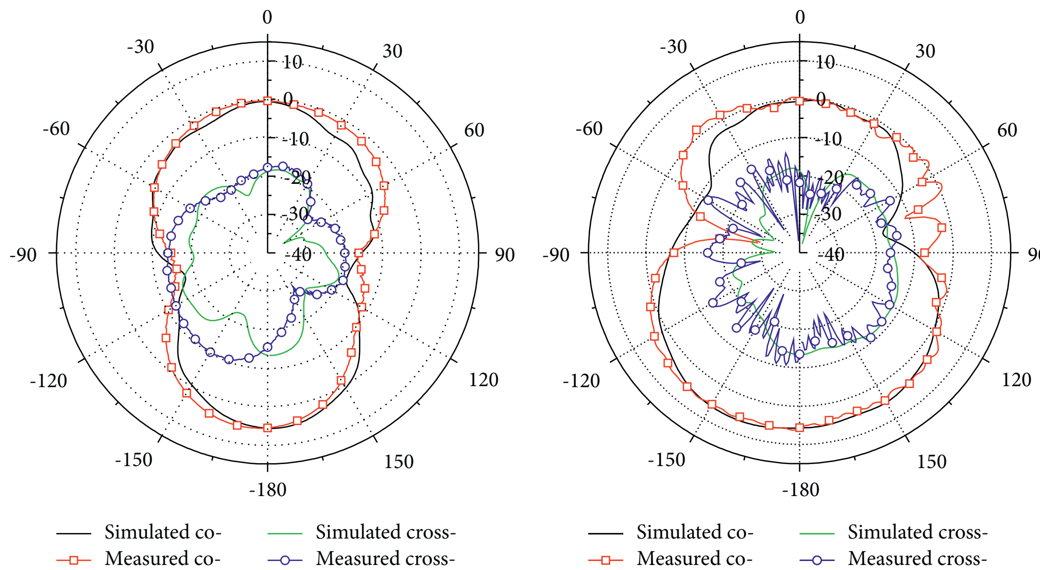


FIGURE 4: Reflection coefficients for the three measured bands.



(a) (b)

Figure 5: Simulated and measured radiation patterns: (a) *x*-*z* plane (*H*-plane) at 5.885 GHz; (b) *y*-*z* plane (*E*-plane) at 5.885 GHz.

Table 2: Summary of simulated and measured 3 dB beamwidth (BW) and gain for the proposed internal antenna.

Parameter	Simulation		Measurement	
	Front $\theta = 0^\circ$	Rear $\theta = 180^\circ$	Front $\theta = 0^\circ$	Rear $\theta = 180^\circ$
3 dB BW in *x*-*z* plane (H-plane) (°)	80	102	90	117
3 dB BW in *y*-*z* plane (E-plane) (°)	63	42	100	45
Gain (dBi)	−0.57	5.67	−0.52	5.77

Table 3: Comparison of antennas for vehicles operating at around 5.885 GHz.

Ref.	Topology	Dimensions (mm)	Volume (mm^3)	Gain (dBi)	Mounted location
[8]	Slot	22.6 × 22.6 × 6.9	3,524	4.9	Exterior
[9]	Patch	55.0 × 55.0 × 3.0	9,075	6.1	Exterior
[10]	Patch	80.0 × 80.0 × 5.1	32,640	4.7	Exterior
This study	Patch	82.0 × 60.0 × 1.0	4,920	5.7	Interior

4. On-Road Experiment on V2V Communication

A V2V communication experiment, as shown in Figure 8(a), was performed on a 1 km long, two-lane highway dedicated to line-of-sight experiments. This road is used to conduct experiments on vehicle technology development. The total length of the road is greater than 1.0 km; the left-hand side of the test road is an expressway, while the right-hand side is an open area with trees.

As shown in Figure 8(b), a monopole antenna connected to the transmitter (Tx) was installed at the centre of the vehicle's roof. The receiver (Rx) was installed inside the windshield, as shown in Figure 8(c). The position of the receiving antenna was carefully determined based on the maximum backward radiation.

Experimental scenarios in which the signal was received through the windshield and rear window were explored, as shown in Figures 9(a) and 9(b), referred to as the forward and backward links, respectively. The exterior and proposed interior antennas emulate the Tx and Rx, respectively. Therefore, the vehicle with the transmitting antenna mounted on the loop shown in Figure 8(b) was stationary, and the receiving vehicle moved around it within a 500 m radius, similar to a service user (Figure 9).

A continuous-wave (CW) signal was transmitted using an Agilent E827 C signal generator, and the received power was measured using an Agilent E4407 B spectrum analyser at a centre frequency of 5.885 GHz. The transmitted power was 20 dBm, and the measurement points were spaced at 50 m intervals. The receiving vehicle stopped at each measurement point, and the received power was recorded; the vehicle covered a total distance of 500 m.

Figure 10 shows the received power measured at 50 m intervals over a distance of 500 m. The received power of the forward and backward links was similar at all points. At a

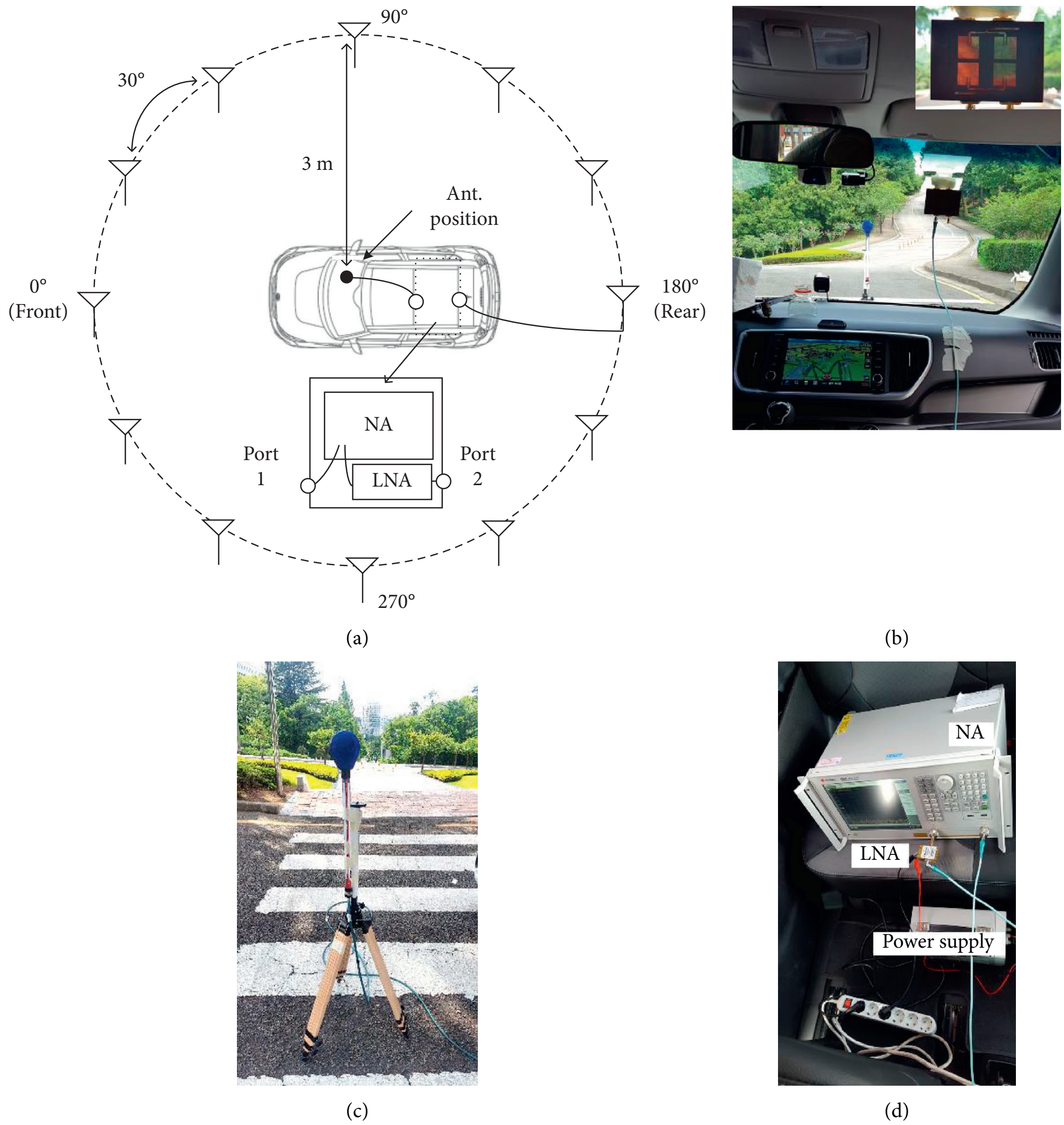


Figure 6: Experimental setup for antenna radiation pattern measurements: (a) schematic of the experiment; (b) internally mounted proposed antenna; (c) exterior probing antenna; (d) instrument (network analyser) used to record the data.

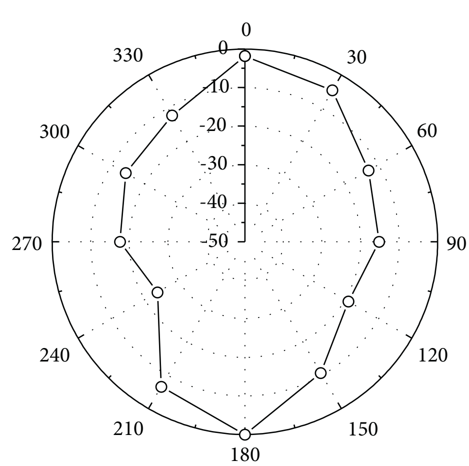
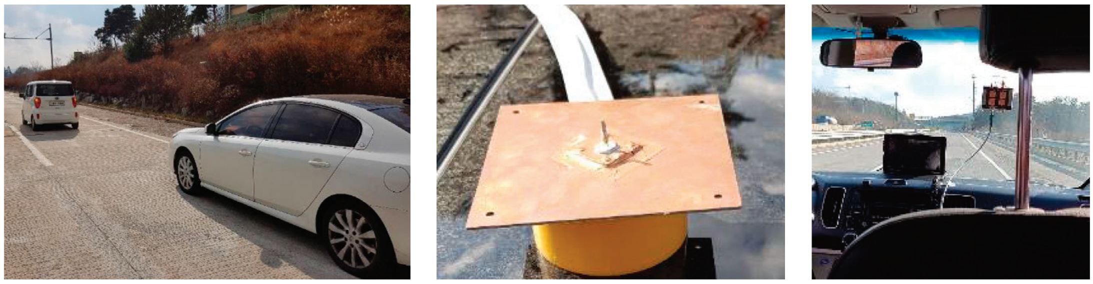


Figure 7: Measured transmission coefficient (S21) response in the x-z plane.



(a) (b) (c)

Figure 8: On-road experimental setup for vehicle-to-vehicle (V2V) communication: (a) transmitting (right) and receiving (left) vehicles; (b) transmitting monopole antenna; (c) receiving antenna installed inside the vehicle.

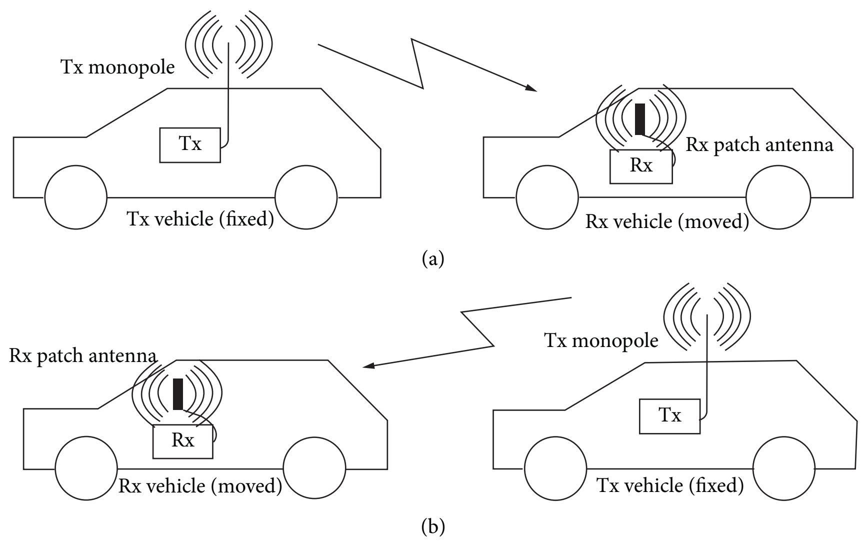


Figure 9: Definition of configurations in V2V communication: (a) forward link; (b) backward link.

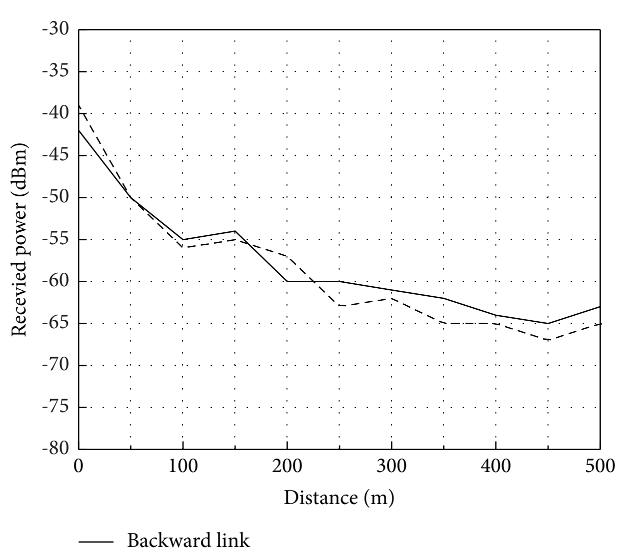


Figure 10: Received power for V2V continuous-wave communication.

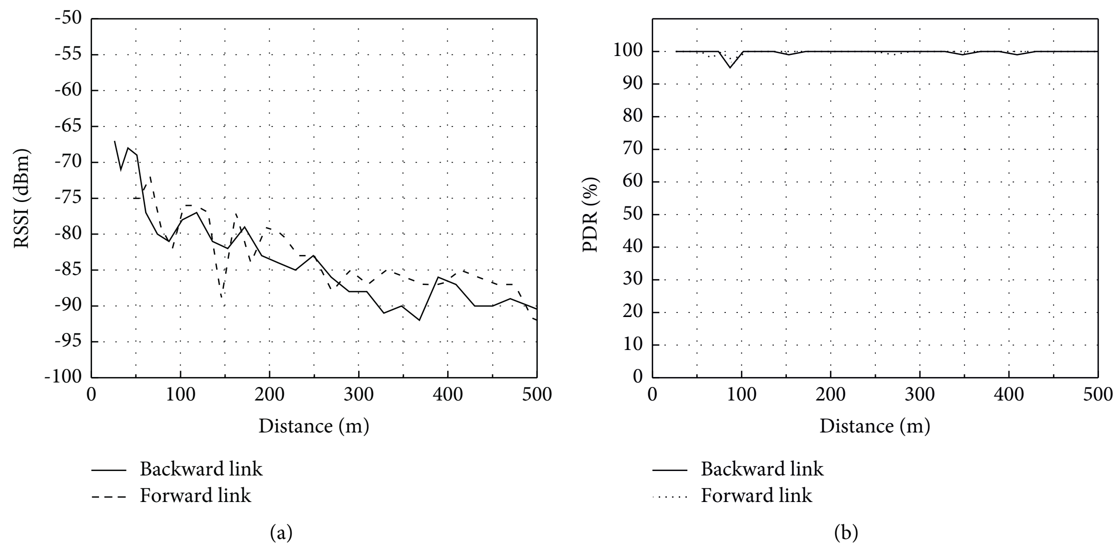


Figure 11: Results of V2V digital communication test: (a) received signal strength indicator (RSSI); (b) packet-delivered ratio (PDR).

separation of 500 m, the received power was −65 and −63 dBm for the forward and backward links, respectively.

In the previous work reported in [6], the received power differed between the forward and backward links. However, in this case, the power received from both directions was similar; this can be explained as follows. The forward link was attenuated only by the windscreen, whereas the backward link was obscured by the car interior, passengers, and rear window. However, the antenna was designed to radiate more power to the backward link.

Next, a digital V2V communication experiment was conducted using an orthogonal frequency division multiplex (OFDM) modem. The average output power of the modem was 20 dBm in the range 5.85–5.93 GHz. The received signal strength indicator (RSSI) and packet-delivered ratio (PDR) were measured by the distance between Tx and Rx. When the PDR was <95% or the RSSI was < −95 dBm, the communication was considered severed. This experiment was conducted by driving the receiving vehicle at a constant low speed over a distance of 500 m without stopping.

Figure 11 shows the measured PDRs and RSSIs. The forward and backward link PDRs and RSSIs show similar values, as already shown in Figure 10. Therefore, the proposed antenna has potential for use in V2V communication. However, as shown in Figure 11, a drop at around 80 m may occur due to the metallic structure over the load. This could overcome through diversity technology, as demonstrated by Choi et al. [7].

This may give rise to concerns over the usefulness of the proposed antenna over an intersection in an urban street. Assuming communication with a vehicle 50 m away from the right lane of an intersection, the received power of OFDM modem at 50 m is expected to be approximately −60 dBm. However, the gain at 90° is about −10 dBi instead of 0 dBi, as shown in Figure 5. Therefore, the RSSI might be −85 dBm, which is greater than the required standard of −95 dBm (Figure 11), and therefore, V2V communication should be possible at an intersection using a low direction antenna.

5. Conclusion

We developed an interior antenna for V2V communication. Based on diversity technology, the antenna is composed of two pairs of patch antennas. The patch antennas were resonant at 5.885 GHz and exhibited a bidirectional pattern with asymmetric gain that allowed efficient V2V communication. For the implementation of asymmetric gain, a microstrip connected both layers of the patch antenna via a thru-hole and radiated more power to the rear end of the vehicle. The measured gain was −0.52 and 5.77 dBi at 0° and 180°, respectively. The received CW power in a road test (separation of 500 m) was −65 and −63 dBm for the forward and backward links, respectively, indicating that the proposed antenna compensated sufficiently for the loss of the backward link. The digital OFDM-based communication channel achieved 100% forward link PDRs over 500 m. At the intersection, the RSSI was estimated at −85 dBm, which is greater than the required standard of −95 dBm. Therefore, the proposed low-directional antenna could be utilized for V2V communication along a straight road, as well as over an intersection. As there is no necessity for a thru-hole on the metallic loop of the vehicle, the proposed internal antenna could also facilitate the commercialization of the WAVE communication service.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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