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Research Article

A Miniaturized Planar Monopole Antenna Based on a Coupling Structure for Compact Mobile Internet of Things (IoT) and Electric Vehicles (EVs) Device Applications in 5G, LTE, WLAN, WiMAX, Sirius/XM Radio, V2X, and DSRC Wireless Systems

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A miniaturized internal antenna with monopole structure is constituted, including three radiating strips of a compact prototype and a back-coupling pad to improve the impedance matching, which achieves a wide bandwidth of 2.972 GHz between the operating frequencies of 2315–5285 MHz, and is introduced and researched. There is an urgent need for a complete frequency-continuous and large bandwidth design in the current wireless communication design to achieve a multimode, multifrequency, physical phenomenon design with large bandwidth and continuous operating frequency. The recommended antenna provides a broadband operation in an electric vehicles (EVs) and Internet of Things (IoT) devices application embedded in the wireless communication standard for 5G, LTE, V2X, WLAN, WiMAX, Sirius/XM Radio, V2X, and DSRC to support the multiband application. This design is embedded side edge of overall placement in the device and is integrated applicable to the trend of heterogeneous wireless multiple access networks in electric vehicle and Internet of Things system devices, which covered the 5G with supporting the band of n7/n38/n40/n53/n77/n78/n79/n90, the 4G with supporting the band of 7/38/40/41/42/43/48/67, the V2X and DSRC for the operating frequencies between 2500 and 5000 MHz, the Sirius/XM Radio for the operating frequencies of 2320–2345 MHz, the ISM band of WiFi and BT covering the band of 2450–2483.5 and 5150–5350 MHz, and the WiMAX also supporting the band of 2300–2690 and 3400–3690 MHz. Moreover, the compact antenna manufactured an FR4 material with the antenna area of $5 \times 10 \times 0.8\ mm^3$ and the ground area of $33.5 \times 10 \times 0.8\ mm^3$. The proposed design better benefits a narrow space on the PCB with a low profile and is easy to make with a circuit board design.

1. Introduction

To welcome the 5th generation mobile network communication era's arrival, all industries are facing innovation and upgrading and undoubtedly need to use 5G technology to promote industrial development [1]. Imaginative life scenarios include the vigorous development of emerging technologies such as AI, autonomous driving, and various significant data operations. Therefore, electronic devices are made rich and diverse and full frequency band coverage [2–12]. There are four main characteristics of high mobility, high throughput, high connection density, and low latency to establish the fifth-generation mobile communication system [3]. Although the emerging 5G wireless communication is on the rise, the 5G mobile communication system still needs to work together and peacefully with other wireless communication systems (LTE, WiFi, WiMax, and 3G/2G).

Mobile operators also need access to a spectrum between 1 GHz and 6 GHz, critical to 5G terrestrial mobile service [13–17]. This spectrum range deployment's physical characteristics, including structure penetration, range, and propagation around obstructions, are more suitable for applications. 5G wireless communication will establish a wide-ranging range of applications, which are usually classified into Ultrareliable and Low Latency Communications (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine Type Communications (mMTC) [18–25]. The spectrum range of 3.4–3.6 GHz has been distributed to worldwide consumers and acknowledged for International Mobile Telecommunications (IMT) organization. Already 50 countries/regions have begun to adopt the spectrum between 3.3 and 3.4 GHz defined by IMT. Europe also announced the opening of the 5G spectrum of 3.4–3.8 GHz. Moreover, the United States Federal Communications Commission (FCC) also recommended the issuance of 5G in the frequency band between 3.7 GHz and 4.2 GHz in May 2018, which can be used in commercial activities. These countries make full use of the 500 MHz spectrum and seek commercial help and other investments.

Mobile communication and cooperation's rapid development is to achieve outstanding achievements in the application of Internet of Things (IoT) commercial applications. The IoT is made up of physical phenomena, buildings, vehicles, and integration of other components and connected to the networks, software, electronic equipment, and sensors so that these objects can gather and enjoy together data networks. Using the 5th wireless mobile system and the currently existing cloud communications can become better precise and efficient [26–28]. As IoT products have stricter requirements for wireless communication specifications, the space requirements for system circuit design tend to shrink. Therefore, the space design of multiband and broadband antennas is also facing significant challenges. In the limited design space, making multiband and broadband antennas with functional performance has become a significant issue and has attracted great attention.

The communication system network connects and catches hold of specific physical parameters, such as moisture, overwhelming force, or temperature. Converting these meaningful events into meaningful information is the event defined by the IoT scenario [26, 29–32]. IoT devices are small, compact, and easy to install in the environment the user wants. An antenna is designed to meet the miniaturization requirements without affecting its antenna performance. Therefore, antenna design should be regarded as one of the primary themes regardless of any wireless communication product. Look for any possible design practices. Thus, antenna engineers are more challenging when making design decisions including the manufacturing cost, size, reproducibility, and mass production that should be paid attention to when designing. Commonly used antenna types for IoT in products include printed circuit board and chip antenna design. [33–35].

Enough bandwidth and multiple frequency bands, simple and easy to replicate the design, and miniaturization are the design goals that must be considered for the antenna design of IoT devices. The monopole antenna with multiband operation technology has so far been an attractive and promising solution [36–52].

In references [36, 38, 53], the authors use a modified monopole or inverted-F antenna structure with a plurality of branches to create multiband operation and following WLAN applications in the wireless communication device. Some documents have proposed the planar monopole antenna with inverted-F type and wideband design, as shown in documents [39, 40]. Even though these designs have excellent coverage frequency band features, the antenna area is comparatively large. Documents [41, 43, 54] point out that these designs have slot elements on the ground area application of multiband frequency operation and are used for WLAN and LTE applications. Furthermore, several antenna designs utilize coplanar waveguide feed structures and radiating rectangular patches, such as in literatures [42–52]. According to the research and investigation of the literature, as mentioned earlier, compact antenna design recommendations and multiband operations are a significant trend and research direction in IoT devices and portable electronic devices.

In our research, a miniaturized planar monopole antenna with a coupling structure design is proposed. The proposed antenna showed the advantage of low-cost and low-profile features and is suitable for embedded compact mobile Internet of Things (IoT) and electric vehicles (EVs) device applications. The wireless device specification is defined to design in the frequency band with 2315–5285 MHz, and the bandwidths are 2972 MHz when the condition is $|S11| \leqq -6$ dB. Therefore, the supported wireless mobile system includes the application of the fifth-generation (5G), Long-Term Evolution (LTE), Wireless LAN (WLAN), Worldwide Interoperability for Microwave Access (WiMAX), dedicated short-range communication (DSRC), Sirius/XM Radio, and vehicle-to-everything (V2X) wireless communication standards. The proposed study of the planar monopole antenna with stabilizing radiation patterns is apposite for mobile and fixed IoT devices that integrate multiple heterogeneous access networks, for example, electric vehicle applications for 5G, LTE, WLAN, WiMAX, Sirius/XM Radio, V2X, and DSRC communication systems. The high-frequency finite element simulator analyzed the performance of the proposed antenna and verified the measurement results in the anechoic chamber. The detailed working mechanism of the planar monopole antenna is studied and discussed in the following sections.

2. Proposed Planar Antenna Design Configuration

The proposed planar monopole antenna design with coverage in the frequency ranges of 2315–5285 MHz is suitable for mobile wireless communication IoT and EV electric equipment, demonstrating the construction of an embedded planar antenna as Figure 1. Six wireless communication systems can be supported and applied including the 5th wireless standard covering the operating frequency between 2500 and 5000 MHz with the new radio band application including n7, n38, n40, n53, n77, n78, n79, and n90. The second supported wireless system is the DSRC, and V2X bands in 2500–5000 MHz belong to the based wireless technology of IEEE 802.11p. The third wireless system supported has operated frequencies between 2320 and 2345 MHz for Sirius/XM Radio. The fourth supported

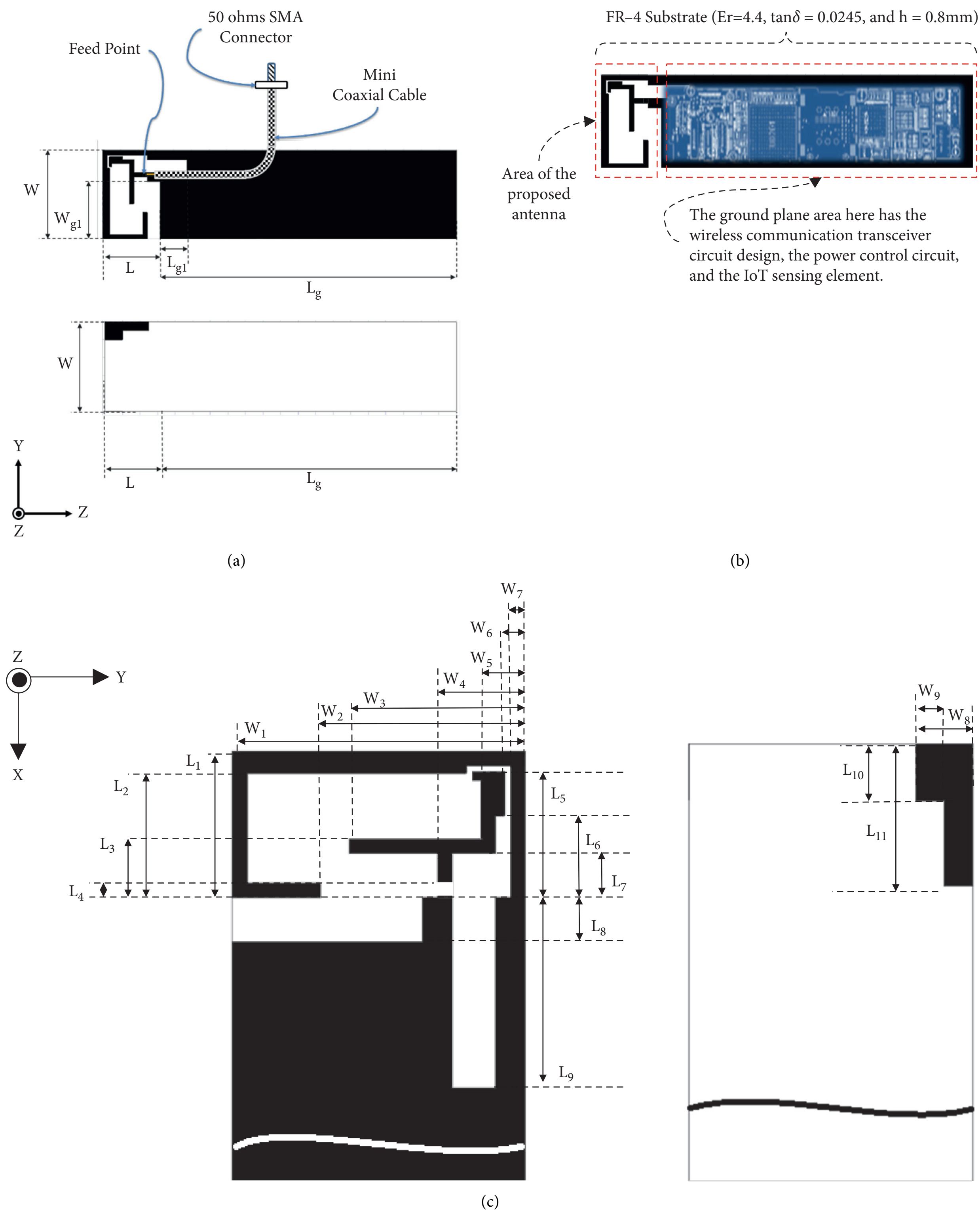
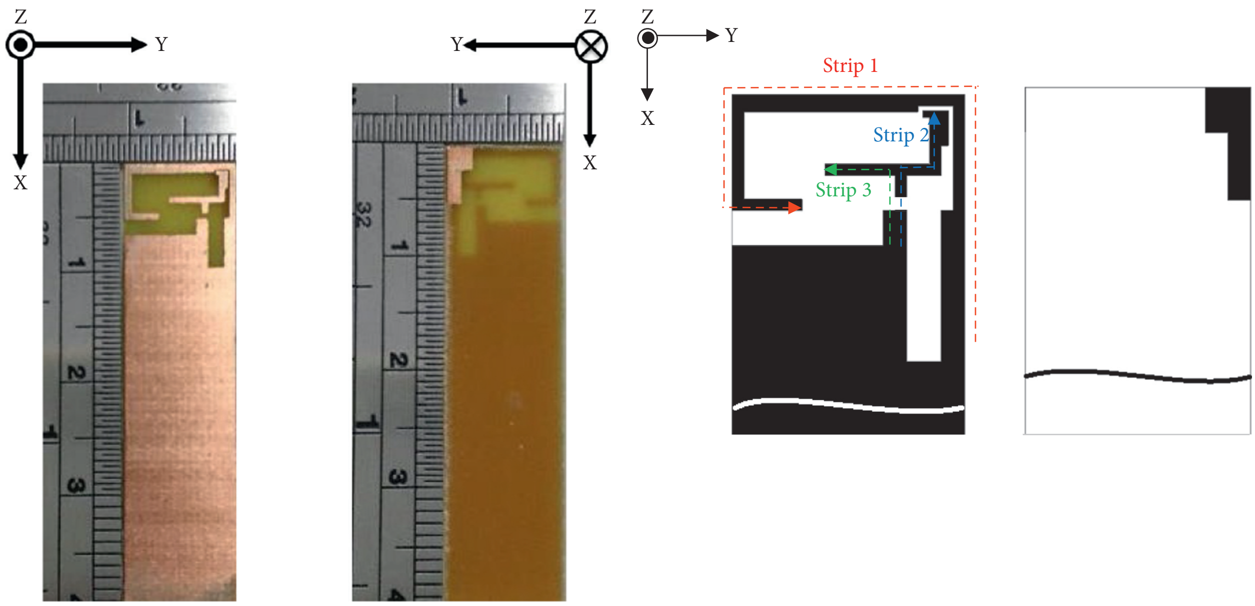


Figure 1: Continued.



(d) (e)

Figure 1: Construction of the suggested planar antenna design: (a) full view of the planar antenna geometry; (b) planar antenna design architecture with equipment layout; (c) specific dimensions on the top and bottom layers; (d) multiband antenna manufactured by shooting with both sides view; (e) the planar antenna includes three strips and one pad on both layers.

wireless system has worked the frequencies in 2300–2690 and 3400–3690 MHz for the standard of the WiMAX system. The fifth supported wireless system has used the frequencies in 2450–2483.5 and 5150–5350 MHz for the WLAN wireless communication. At last, the sixth supported wireless system is the LTE wireless application, which covered the frequencies in 2300–5250 MHz, supporting the bands of 7, 38, 40, 41, 42, 43, 48, and 67.

This antenna design has selected FR4 substrate material to make the antenna. The relevant design parameters of the substrate such as relative permittivity of 4.4, loss tangent of 0.024, and thickness of 0.8 mm are presented in Figure 1(b). The integrated circuit chip components, including microcontroller unit, central processing unit, sensor elements, radio frequency unit, baseband system unit, and power management IC, are embedded in the system ground area for our proposed planar antenna for vehicle or IoT infrastructure applications. Figure 1(a) shows that the total size of the entire system circuit is 40 mm × 10 mm, the antenna part is 5 mm × 10 mm, and the ground plane is 33.5 mm × 10 mm. Figure 1(c) also demonstrates the detailed dimension of the planar antenna layout. Figure 1(d) shows that the proposed embedded multiband monopole antenna prototype with low cost and low profile is fabricated, verified, and displayed in the top and bottom layers. The proposed antenna architecture is assembled with four elements: three branches in the front and a back-coupled small piece. The path of strip 1 is connected with the ground plane, and the strip 2 and 3 are with the same node to be linked to the main feed point on the top layer; besides, the back-coupled small piece is over cover with the top view of partial areas of the branch lines with the strip 1 and 2. The overall dimensions are shown in Table 1, and the measurement method is designed with a 50-ohm coaxial cable connected to the feed point between the system ground plane and the branch line of the strip 2 and 3, and the structure can that let the proposed monopole antenna be excited and exhibit the antenna performance to arrive the multiband frequency supported. Hence, the operating frequency bandwidth is generated in the frequency range of 2500–5000 MHz when the impedance matching is better and suitable with the proposed antenna and coaxial cable's feeding point.

The proposed antenna design is obtained from the ground plane with a width of 10 mm and a length of 33.5 mm for design reference to simulate the device application on wireless communication with real IoT devices and electric vehicles. Furthermore, the system ground with a rectangular slot can contribute to the resonance frequency during 2350 MHz and 2450 MHz. Therefore, the proposed antenna layout position of the edge side is suitable for the wireless communication technology standard with the fourth-generation (5G), Long-Term Evolution (LTE), Wireless LAN (WLAN), Worldwide Interoperability for Microwave Access (WiMAX), Sirius/XM Radio, dedicated short-range communication (DSRC), and the vehicle-to-everything (V2X) communication systems. The miniaturized planar monopole antenna is studied by an electromagnetic simulator and analyzed the antenna related performance of electrical and radiative properties.

There are six conditions for the current distribution of the operating frequency with 2350 MHz, 2450 MHz, 2600 MHz, 3050 MHz, 3500 MHz, and 3750 MHz shown in Figure 2. The simulated surface current distribution at 2350 MHz, 2450 MHz, and 2600 MHz can be observed to show a firm surface current effect around the main path of strip 1 with a back-coupled small piece with a rectangular

Table 1: Detail dimensions of the planar proposed antenna (unit: mm).

L_1	L_2	L_3	L_4	L_5
5	4.25	2	0.5	4.3
L_6	L_7	L_8	L_9	L_{10}
2.8	1.5	1.5	4.5	2
L_{11}	W_1	W_2	W_3	W_4
5	10	7	6	3
W_5	W_6	W_7	W_8	W_9
1.5	0.7	0.5	2	1
L_g	L_{g1}	L	W_{g1}	W
33.5	3	6.5	6.5	10

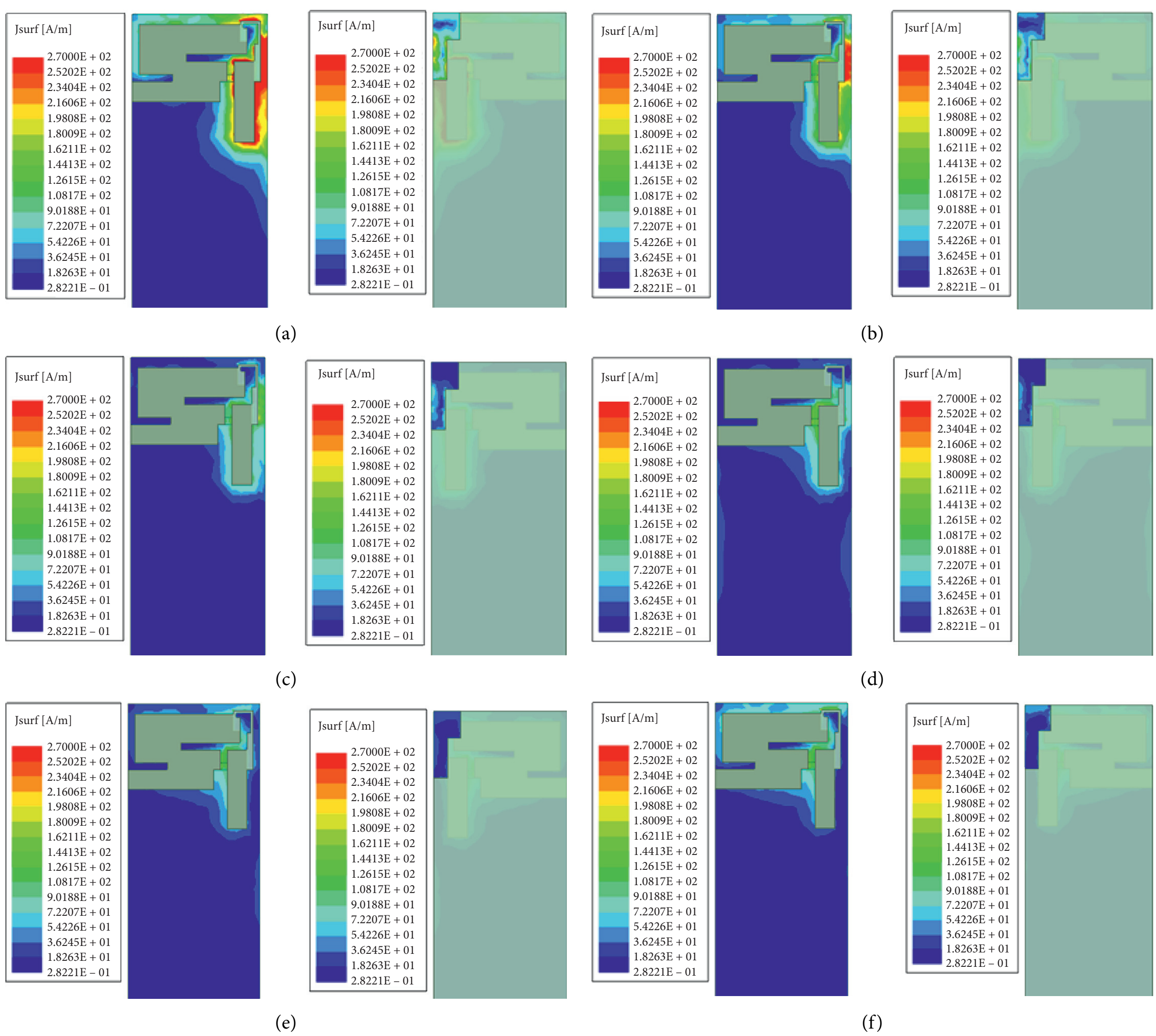


Figure 2: The surface current distributions at different operating frequencies: (a) 2350 MHz; (b) 2450 MHz; (c) 2600 MHz; (d) 3050 MHz; (e) 3500 MHz; (f) 3750 MHz.

slot, which is a combined result, as shown in Figures 2(a)–2(c). Furthermore, the simulated surface current distribution at the operating frequencies with 3050 MHz, 3500 MHz, and 3750 MHz is analyzed to show that the strip 2 contributes a current solid effect accompanied by a small current of strip 3 composed of surface current distributions shown in Figures 2(d)–2(f), respectively. Furthermore, it is worth mentioning that the coupling patch on the back can produce broadband benefits. From the current distribution diagram, it can be seen that the coupling patch on the back produces a current effect at each frequency to adjust the broadband effect of the antenna.

The proposed antenna design with suitable structure design with miniaturized layout and product okay performance covers the bandwidth approximately 2972 MHz. Therefore, the antenna can handle suitable wide applications for multimode wireless communication for users. Next, corresponding parameters analysis and evaluation of the reflection coefficient will be discussed in Section 3.

3. Results and Discussion

Including monopole antenna capability and related parameter analysis, simulation and measurement results are carried out in this result and discussion section. There are three paths with meander-shaped type distributed on the top side; in addition, it also has a coupled-pad in the back layer to enhance the bandwidth of operating frequencies. The proposed planar antenna has been manufactured and acquired on FR4 substrate, as shown in Figure 1(d). Also, the overall analysis is obtained by a full-wave electromagnetic simulator. The return loss performance of this prototype was evaluated and verified by Agilent E5071C using a vector network analyzer. The impedance bandwidths of simulated and measured are defined by 3 : 1 VSWR, which is extensively adopted for the specification of embedded WWAN antenna design and meets the 3GPP wireless system requirement composed of RF active circuits. Thus, the operating band's result with 6 dB return loss has been achieved 2315–5285 MHz, corresponding to 78.21% bandwidth. The bandwidth is designed between the operating frequencies of 2315–5285 MHz, as shown in Figure 3; the bandwidth can support cooperation with different multiband wireless communication systems and be adopted in a heterogeneous system together at the same time. The heterogeneous wireless system can be recommended and suggested to design in the mobile wireless communication IoT and EVs device to support IEEE 802.11p of the DSRC and V2X bands, the Sirius/XM Radio, the WiMAX, the WLAN, the LTE, and the 5G FR1 band. As shown in Figure 4, the proposed antenna's parametric studies are offered, discussed, and performed using an EM simulator. The parameter analysis scheme of the planar antenna proposed by us is composed of six parameter analysis antenna performances. The proposed prototype achieves the proposed multiband and miniaturized design. Figure 4(a) demonstrates various parameters with the lengths of W_9 in the strip 3 which are simulated and calculated; and these return loss responses are compared. The result shows that the matching impedance can be controlled by the length of W_9. Therefore, it is recommended to set the length of W_9 to 3 mm. The lengths W_{10} belong to strip 1, which is observed as the performance variation with different strip 1 lengths between 1.5 to 3.5 mm. The length of W_{10} is recommended to use 2.5 mm to meet the proposed planar antenna design requirement, as demonstrated in Figure 4(b). The parameter of ground slot design is discussed that the slot length of L_9 modified the three parameters of 1, 3, and 5 mm; thus, the length is at 1 mm that

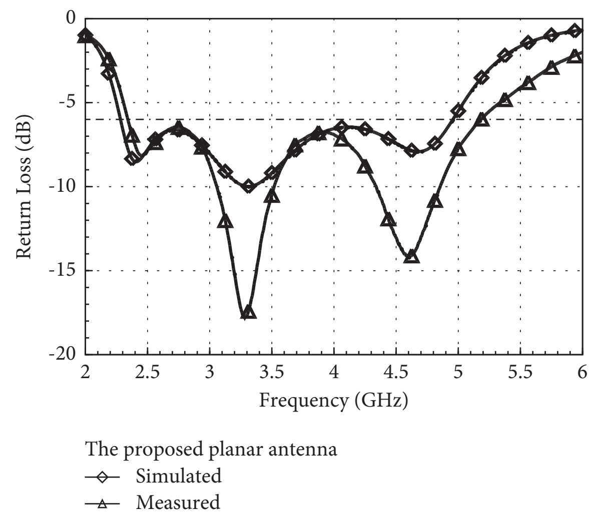


Figure 3: Simulation and measurement reflection coefficients for the suggested planar antenna.

the resonant frequency is shifted to low frequency and obtained the smaller bandwidth. When the length is 5 mm, the resonant frequency generated narrow bandwidth and shifted to higher frequency band operation, as shown in Figure 4(c). From the parameters of the L_9 study, the length of the ground slot design is suggested with 3 mm for design.

On further research on strips 2 and 3, their prominent contribution lies in the fact that the bandwidth is stabilized and the matching effect is achieved. This analysis method uses progressive parameters to analyze the design changes in strips 2 and 3 with types 1 to 4, as shown in Figure 4(d). Thereupon, the bandwidth is formed and covered correctly from type 1 to 2 conditions. The type 3 condition then generated a better matching effect than the type 2 condition at the same operation bandwidth. The bandwidth design achieved the return loss under 6 dB requirement for the proposed antenna design when the back-coupled small piece is adopted from the condition of type 4. Finally, Figures 4(e) and 4(f) show that coupled effects can help the proposed antenna obtain a better matching in the required frequency band. Therefore, W_8 and L_{11} are recommended to use 2 mm and 5 mm, respectively; that is the best solution. As the above analysis, the proposed antenna structure can quickly control the operation frequency band and avoid manufacturing tolerance, making it easy to make. Furthermore, the proposed system can also achieve suitable impedance matching in the operation band that we want, and this proposed planar antenna can be employed and designed in the related electric vehicle devices and IoT devices with a wide bandwidth to be adopted.

Further, the performance of antenna gain and radiation efficiency is discussed. The measurement is adopted a far-field anechoic chamber, whose product name is the ETS-Lindgren measurement system for validation infrastructure detailed in website (http://www.ets-lindgren.com) for reference. The radiation pattern with simulated and measured results is obtained and compared with the form of *xy*, *yz*, and *zx* planes in Figure 5. The radiation

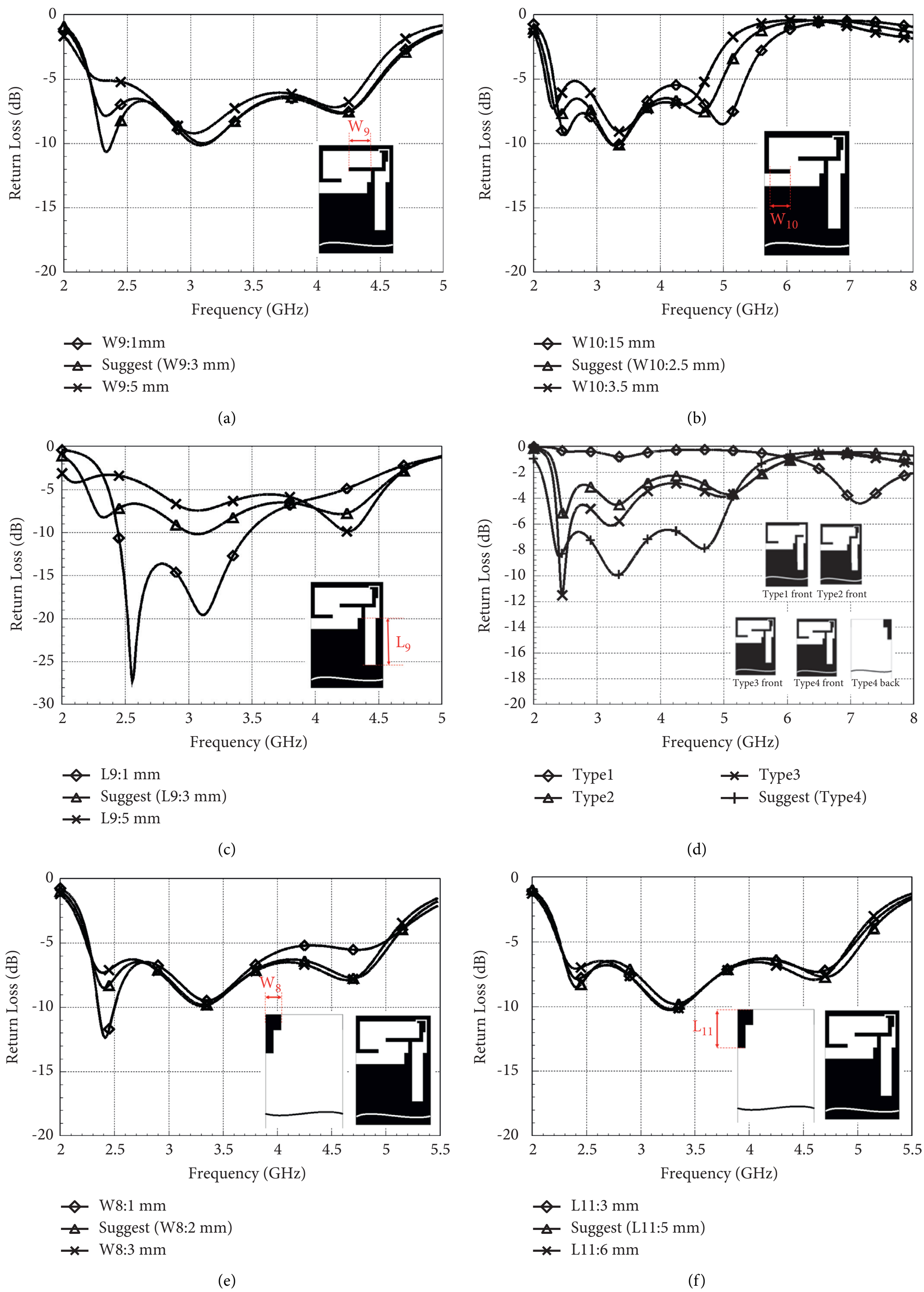


Figure 4: Study on the parameters of the reflection coefficients of the various lengths of the proposed antennas: (a) adjust parameters for W_1 strip length; (b) adjust parameters for W_6 strip length; (c) adjust parameters for L_a strip length; (d) various types with strip 2 and 3 and with/without the back-coupled patch; (e) adjust parameters for W_8 strip width; (f) adjust parameters for L_{11} strip length.

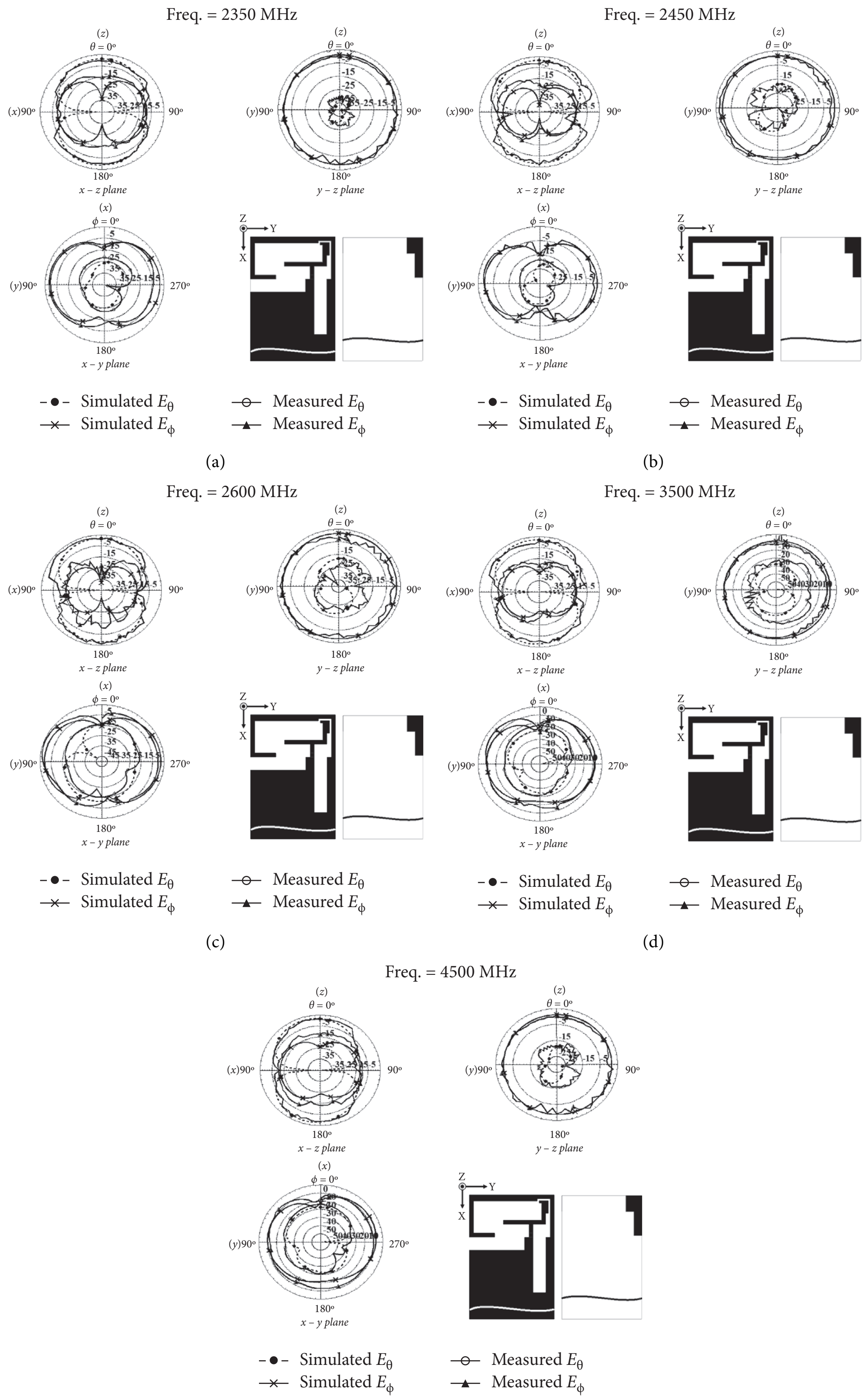


Figure 5: The simulation and measurement antenna radiation patterns under different operating frequency conditions: (a) 2350 MHz; (b) 2450 MHz; (c) 2600 MHz; (d) 3500 MHz; (e) 4500 MHz.

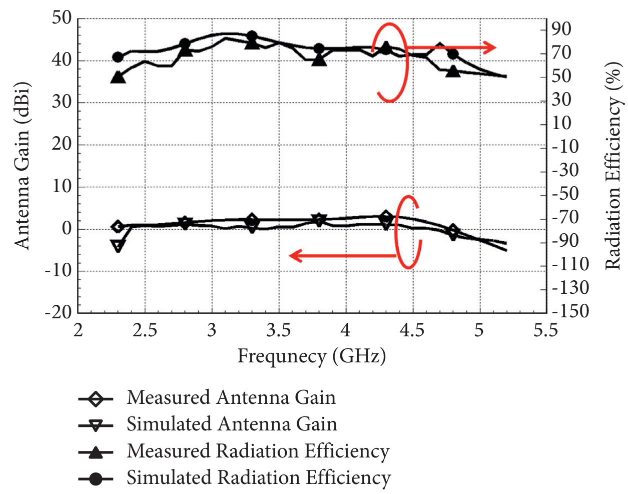


Figure 6: The simulation and measurement of antenna radiation efficiency and peak gain.

Table 2: Antenna size comparison with other literature studies.

References	Publication year	Overall sizes (mm^2)	System ground size comparison (L mm × W mm)	Antenna size comparison (L mm × W mm)	Operation frequency range (GHz)	Bandwidth (%)	Applications
[55]	2020	118 × 42	100 × 42	39 × 17	0.85–1.1 1.75–2 2.19–2.75	25.6% (250 MHz) 13.3% (250 MHz) 22.6% (560 MHz)	GSM900/Wi-Fi2400/RFID2450/LTE
[56]	2020	54 × 37	5 × 54	54 × 32	1.6–2.2	31.5% (600 MHz)	A novel printed monopole antenna
[57]	2019	27 × 12	6 × 4.4	2.28 × 27	2.38–2.48	4.1% (100 MHz)	SFCW radar-based
[58]	2019	12.6 × 7.5	8.6 × 7.5	75 × 4	2.4–2.5	4% (100 MHz)	Bluetooth system
[59]	2021	21 × 8	160 × 200	21 × 8	2.25–2.64 3.25–3.63 5–6.41	5.8% (390 MHz) 13.3% (380 MHz) 6.6% (1410 MHz)	LTE/WIFI/sub-6 GHz/5G bands
Proposed	—	40 × 10	33.5 × 10	10 × 9.5	2.15–5.28	84.2% (3130 MHz)	Bluetooth (2.4 GHz)/5G NR/WiMax (2.5/3.5 GHz)/4G LTE

performance is analyzed by the operation frequencies with 2350 MHz, 2450 MHz, 2600 MHz, 3500 MHz, and 4500 MHz, respectively. Good agreement can be observed between the simulated and measured radiation patterns. Stable radiation patterns are also achieved within the impedance bandwidth. The discrepancies in the simulated and measured results are attributed to measurement errors, including the cables and measurement setup. Good coverage and quality of communication in the mobile wireless IoT and EVs device support multiband multiwireless systems. Moreover, the radiation efficiencies and peak gains also are simulated and measured in Figure 6. The antenna gain obtained the best of 3 dBi, and the antenna efficiency obtained the best at 87% for the suggested antenna design. Good agreement can be observed between the simulated and measured antenna gain and efficiency. Therefore, the proposed multiband antenna design with steady antenna gain and radiation efficiency is suitable for IoT and vehicle device applications.

The proposed antenna is also compared with other literatures [55–59] for the last three years and is reported in Table 2, which is compared with the parameters of antenna size, operation frequency range, bandwidth, and application. Compared with the overall antenna size, the overall antenna size we designed is smaller than [55, 56]. However, if we use system ground size to compare, its system ground size is smaller than [55, 59], and this antenna size is smaller than [55–59]. Comparing the operating frequency and bandwidth, this design is the most continuous and extremely wideband design. After comparing with other antenna research literatures, the proposed antenna provides ultra-wideband operation characteristics with complete frequency continuity, and it also has a smaller antenna area and system ground area in the Internet of Things (IoT) and electric vehicle (EV) device applications embedded in the wireless communication standard for 5G, LTE, V2X, WLAN, WiMAX, Sirius/XM Radio, V2X, and DSRC to support the multiband application.

4. Conclusion

In addition to the essential Internet of Things, wireless communication is becoming increasingly important in electric vehicles or portable Internet of Things devices. Therefore, we need a hardware specification that has an ultralarge bandwidth and a continuous operating frequency. The proposed antenna is with three strips and one back-coupled small piece design. It is mainly because the small back-coupled piece is covered with the top view of partial areas of the branch lines with strips 1 and 2. Let the coupling patch on the back produce a current effect at each frequency to adjust the broadband effect of the antenna. This design uses simple geometric figures to build a wideband antenna and is used in many wireless communication systems. It is a beautiful design and easy to make. It is also a very standardized design process and a structure that can be copied anywhere.

Furthermore, a smaller system area can be used to design a compact antenna. This work reports a successfully built, highly compact multiband monopole antenna. This design is embedded side edge of overall placement in the device and is integrated appropriately for the trend application of heterogeneous wireless network in electric vehicle and Internet of Things system devices, which covered the 5G with supporting the band of n7/n38/n40/n53/n77/n78/n79/n90, the 4G with supporting the band of 7/38/40/41/42/43/48/67, the V2X and DSRC for the operating frequencies between 2500 and 5000 MHz, the Sirius/XM Radio for the operating frequencies of 2320–2345 MHz, the ISM band of WiFi and BT covering the band of 2450–2483.5 and 5150–5350 MHz, and the WiMAX also supporting the band of 2300–2690 and 3400–3690 MHz. The embedded antenna is adapted to wireless communication device IoT. Simulated and measured results meet the IoT system requirements. The proposed planar antenna is attractive to be used in emerging wireless communication devices.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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