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Design of an Optimal Patch Antenna Operating in the 12 GHz, 15 GHz, and 16 GHz Bands for the 5G Vehicle-to-Vehicle Mobile Network Service

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Abstract

The arrival of fifth-generation mobile networks has given rise to several services such as vehicle-to-vehicle (V2V) communication, known as the Internet of Vehicles. This refers to all the technologies, protocols, and systems that enable the exchange of information between vehicles. This research work presents the design of a high-performance multiband antenna operating in the X and Ku bands (12 GHz, 15 GHz, and 16 GHz bands) and intended for in-vehicle Internet applications. The design of this antenna involves three steps. The optimal length and width (Ls × Ws) of the final step are 23.5 × 8.5 mm. The designed antenna achieves a maximum gain of 4.85 at a frequency of 15.8 GHz, a bandwidth of 1.1 GHz, and a radiation efficiency of 99%.

Keywords

Antenna, Internet of Things, Telecom Services, Internet of Vehicles, Efficiency, RF Energy Harvesting

1. Introduction

For several years now, there has been a growing demand for antennas for automotive communications systems with the rise of connected and autonomous vehicles. This growth has led to the establishment and development of a new subset of the Internet of Things (IoT): the Internet of Vehicles, which aims to make traffic smarter, safer, and more efficient. The Internet of Vehicles refers to all the technologies, protocols, and systems that enable vehicles to exchange data with each other (V2V: Vehicle-to-Vehicle), with road infrastructure (V2I: Vehicle-to-

Infrastructure), with pedestrians (V2P: Vehicle-to-Pedestrian), and even with the cloud (V2C: Vehicle-to-Cloud). The rise of these new technologies for vehicles brings great convenience to everyday life and promotes the safe mobility of people and goods.

One of the most important challenges in automotive communications is ensuring a stable and continuous connection, which is essential for the quality of service (QoS) expected for in-vehicle applications. To meet these challenges, antennas play a central role. Indeed, it is imperative that antennas installed in or on vehicles are highly efficient, particularly in terms of bandwidth. A wide bandwidth allows for high-speed signal transmission, which is essential for supporting modern standards such as 5G, Wi-Fi, and V2X (Vehicle-to-Everything) technologies, which include exchanges with other vehicles, infrastructure, pedestrians, and the cloud.

In addition to electrical performance, antennas must meet strict mechanical and aesthetic requirements dictated by vehicle design. This means designing antennas that are compact, discreet, and easy to integrate into the bodywork without compromising their performance. This requires miniaturization, robustness in the face of environmental conditions (rain, temperature, vibrations), and electromagnetic compatibility with other onboard electronic systems.

Furthermore, multiband or multi-standard integration in a single antenna has become a necessity. A single antenna must be able to handle multiple protocols simultaneously, which poses challenges in terms of co-design, interference reduction, and optimization of directivity and gain.

In the design of communication systems for smart vehicles, the choice of antenna is a critical step, both from the point of view of electromagnetic performance and mechanical integration. Scientific and technical literature abounds with antenna solutions that have been tested and proposed to meet the specific requirements of the automotive sector. Among these solutions, monopole antennas [1] [2] and patch antennas [3] [4] are the most commonly encountered. While monopole antennas are recognized for their simplicity and efficiency, patch antennas have attracted increasing interest in recent years, particularly due to their numerous advantages. Their compact size, low weight, low cost, and manufacturing process compatible with mass production technologies make them a particularly attractive option for manufacturers and integrators. Their planar structure, compatible with printed circuit boards (PCBs), facilitates their integration into embedded electronic modules, which is a major advantage in the context of a vehicle where space is often limited [5]. Faced with rapidly changing requirements in onboard communications, particularly in terms of throughput, latency, multi-standard compatibility (4G, 5G, Wi-Fi, V2X, etc.) and space reduction, patch antenna technology has made significant advances. Research has pushed the limits of miniaturization, maintaining acceptable performance despite a drastic reduction in size [6]. In addition, engineers have developed structures capable of significantly expanding the operational bandwidth or operating on multiple frequency bands, thus avoiding the need for a multitude of separate antennas for each protocol [7]. These innovations make the patch antenna a key element in the architecture of connected vehicles, capable of meeting connectivity needs for applications as diverse as vehicle-to-vehicle (V2V) communication, exchanges with road infrastructure (V2I), and interaction with pedestrians (V2P) and the cloud (V2C). Thanks to their versatility, reliability, and ease of integration, patch antennas appear to be a strategic solution for future generations of embedded systems [8].

In the context of the Internet of Vehicles, the choice of antenna frequency bands is a critical factor. While lower bands (sub-6 GHz) are already used for certain communications (Wi-Fi, LTE), millimeter bands such as the X band (8 - 12 GHz) and Ku band (12 - 18 GHz) offer significant advantages in meeting increasing connectivity needs. These bands offer greater available bandwidth and therefore much higher data transmission rates. In addition, they are commonly used in satellite communications, particularly for vehicle tracking. The use of X and Ku bands in the Internet of Vehicles thus enables advanced communication performance and meets the growing demands for connectivity, throughput, and reliability in autonomous and intelligent vehicles.

Several planar antennas operating in the X and Ku bands are described in the literature. In [9], a dual-band antenna measuring $30 \times 13 \times 0.254$ mm^3 operating in the 10.87 - 12.76 GHz (X band) and 15.19 - 16.02 GHz (Ku band) frequency bands exhibited a maximum gain of 6.08 dBi in the X band and 4.65 dBi in the Ku band with a maximum radiation efficiency of 80.8%.

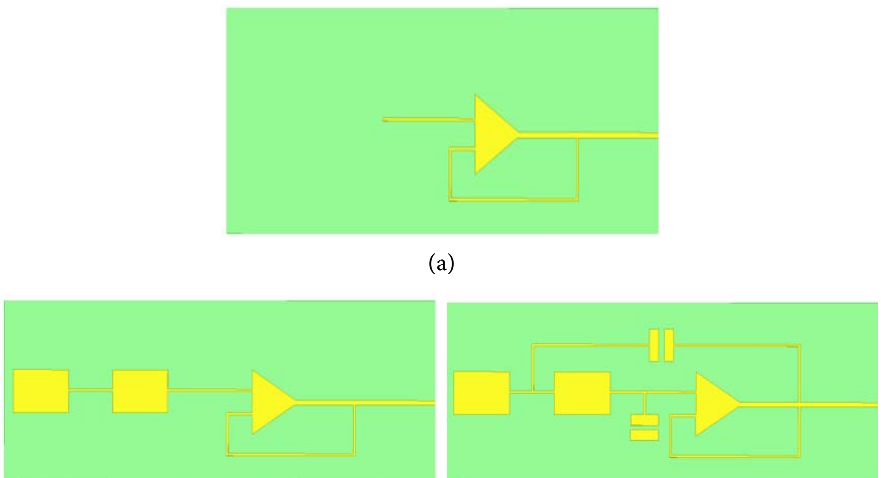
The objective of the study presented here is to design a high-performance multiband antenna operating in the X and Ku bands and intended for vehicle internet applications. More specifically, in addition to an antenna operating in these frequency bands, we are looking for a good compromise between performance, size and cost. Section 2 describes the antenna design methodology, with particular emphasis on the structure of the different parts of the antenna leading to its optimization. Section 3 focuses on the impact of the topology and the simulation results of the antenna. A comparative study of the antenna's performance with the literature is also presented. Section 4 concludes this study and offers some perspectives for the future.

2. Four-Band Antenna Design Methodology

The objective is to design a compact, low-cost four-band antenna that operates in both the X and Ku frequency bands. It should be noted that high-frequency simulation software (HFSS version 13.0) is used for the antenna design.

In order to obtain an antenna that is easy to manufacture and inexpensive, the antenna structure is chosen to be a rectangular patch antenna. The radiating element and the 50 Ω microstrip feed line are simply etched onto the substrate, as is the ground plane located on the opposite side. For this study, the substrate is a Rogers RT/duroid 5880 substrate with a thickness h of 0.508 mm, a relative permittivity εr of 2.2, and a loss tangent of 0.0009. The copper thickness is 35 µm.

The antenna's radiating element consists of several conductive segments arranged to optimize capacitive and inductive coupling. Its geometry, composed of interconnected triangular and rectangular portions, may visually resemble certain active filters in electronics, but this is only a graphic resemblance; the design is based on standard antenna principles. The ground plane contains two L-shaped slots of different sizes. Figure 1 illustrates the different stages of antenna design, from step 1 to step 3. It should be noted that each design step has a significant influence on the antenna parameters, particularly on impedance matching and radiation efficiency, as modifying the antenna results in a new distribution of surface current on the radiating element. Step 1 corresponds to the initial configuration with an off-center feed line. The microstrip feed line was used to excite the antenna. The radiating element at this stage consists of an equilateral triangle structure with sides measuring 3 mm, symbolizing the operational amplifier. A rectangular structure with a width of 0.1 mm, symbolizing the connection wire, connects the triangular structure to the feed line. In the second design step, two rectangular structures with a width of 2 mm are connected to the triangular structure by the connection wire. Finally, the last step consists of introducing two pairs of rectangular structures onto the patch, whose shapes symbolize two capacitors.

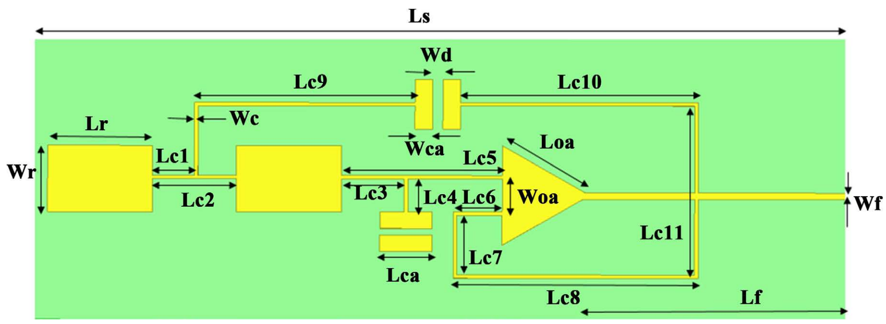


(a) (b) (c)

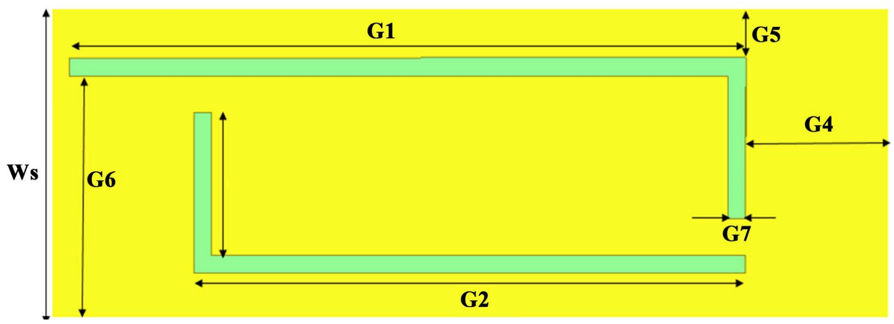
Figure 1. The design evolution of the proposed four-band antenna in three steps. (a) Step 1: initial with a triangular shape; (b) Step 2: configuration with rectangular structure insertion on the radiating element; (c) Step 3: structure with two pairs of rectangular structures on the radiating element.

The purpose of the extended shape of the radiating element is to promote current concentration points and the appearance of multiple frequency bands. Figure 2 shows the detailed structure of the patch antenna.

Table 1 presents the dimensions of each element of the antenna (slots, patch, feed line, substrate, and ground plane). The optimized dimensions of the antenna (Ls × Ws) are 23.5 × 8.5 mm.



(a)



(b)

Figure 2. Proposed four-band antenna optimized design: (a) top view and (b) bottom view of the patch antenna.

Table 1. Dimensions of antenna geometrical.

Antenna parameters	Values (mm)	Antenna parameters	Values (mm)	Antenna parameters	Values (mm)
Ls	23.5	Lc5	4.6	Lca	1.5
Ws	8.5	Lc6	1.4	Loa	3
Wf	0.2	Lc7	1.8	Woa	1.1
Lf	7.63	Lc8	7	G1	19
Wr	2	Lc9	6.3	G2	15.5
Lr	3	Lc10	6.8	G3	3.9
Lc1	1.2	Lc11	5.1	G4	4
Lc2	2.4	Wc	0.1	G5	1.34
Lc3	1.8	Wd	0.3	G6	6.65
Lc4	1	Wca	0.5	G7	0.5

3. Parameters Study and Simulation Results

The reflection coefficient of the designed patch antenna is shown in Figure 3. In step 1 of the design (Figure 1(a)), the antenna has a resonance frequency of 13.6 GHz and a reflection coefficient with a modulus greater than −10 dB. The antenna is therefore not suitable for this frequency. This unsuitability of the antenna is also observed in step 2. However, in step 3 (Figure 1(c)), the antenna has four frequency bands with reflection coefficients below −10 dB. More specifically, in the X bands, there are two resonance frequencies, 12.00 GHz and 12.70 GHz, with reflection coefficients of −25.59 dB and −40.37 dB, respectively. In the Ku bands, two resonance frequencies, 15.80 GHz and 16.30 GHz, with reflection coefficients of −20.79 dB and −10.23 dB, are observed. The patch antenna operates in four frequency bands and is suitable for both the X and Ku bands. In the X-band, it offers a wide impedance bandwidth of 1.1 GHz, corresponding to the frequency range where the reflection coefficient remains below −10 dB. The antenna exhibits two closely spaced resonant frequencies, at 12.00 GHz and 12.70 GHz, which together provide this effective X band bandwidth. In the Ku bands and at a frequency of 15.80 GHz, the bandwidth is 0.18 GHz. The improvement in the antenna's reflection parameters and bandwidth can be explained by the creation and positioning of the radiating surfaces on the patch. Indeed, the insertion of the structures in step 3 may have induced capacitive and inductive effects, which in turn would have led to an increase in the bandwidth.

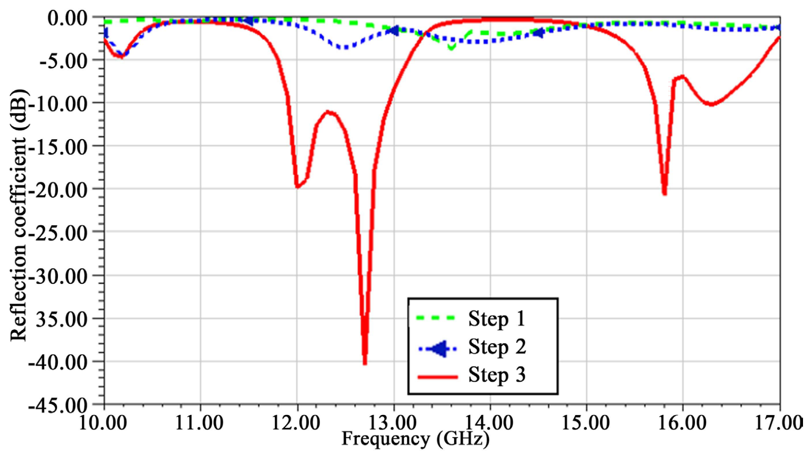


Figure 3. Simulated antenna reflection coefficient evaluation at three design steps.

Simulated 2D electrical radiation patterns (in dB) for the four frequency bands in the E-plane ($\varphi = 0^\circ$) and H-plane ($\varphi = 90^\circ$) are shown in **Figure 4**. In the X-band, the patch antenna exhibits a quasi-omnidirectional radiation pattern with a maximum electric field intensity of 22 dB. The radiation pattern at 15.80 GHz in the Ku-band is also quasi-omnidirectional. However, at 16.30 GHz, a directional electric field radiation is observed, with a maximum intensity of 13 dB.

Figure 5 shows the antenna gain at different frequency bands. In the X-band, the maximum antenna gain is 4.65 dB and 4.01 dB, respectively. In the Ku-band, the gain reaches 4.85 dB and 4.68 dB, respectively.

The curve in **Figure 6** shows the antenna radiation efficiency as a function of frequency. The radiation efficiency at 12.00 GHz is 90%, and 93% at 12.70. In the Ku-band, this efficiency is 75% and 99%, respectively. Despite its multi-frequency nature, the antenna exhibits good performance in terms of gain and radiation efficiency.

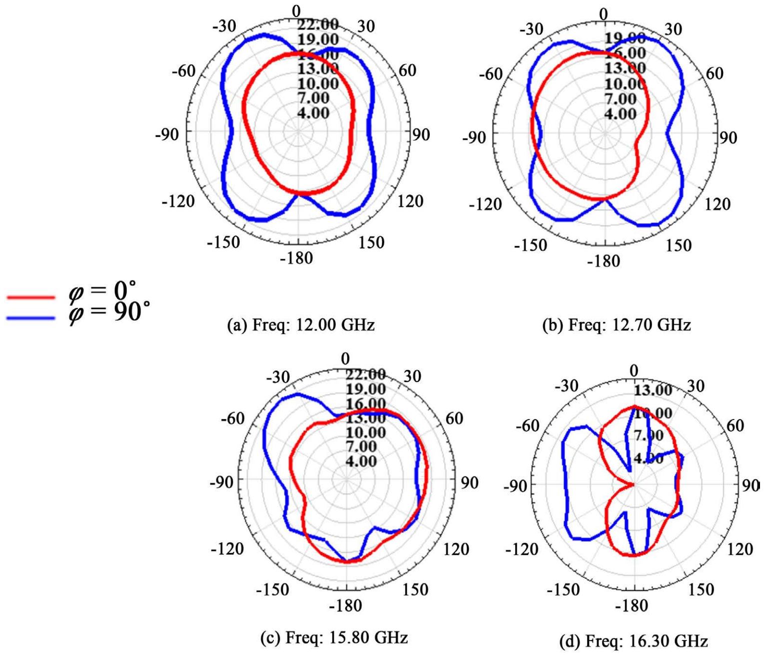


Figure 4. The 2D simulated electrical radiation patterns of the final antenna: at (a) 12.00 GHz, (b) 12.70 GHz, (c) 15.80 GHz and (d) 16.30 GHz.

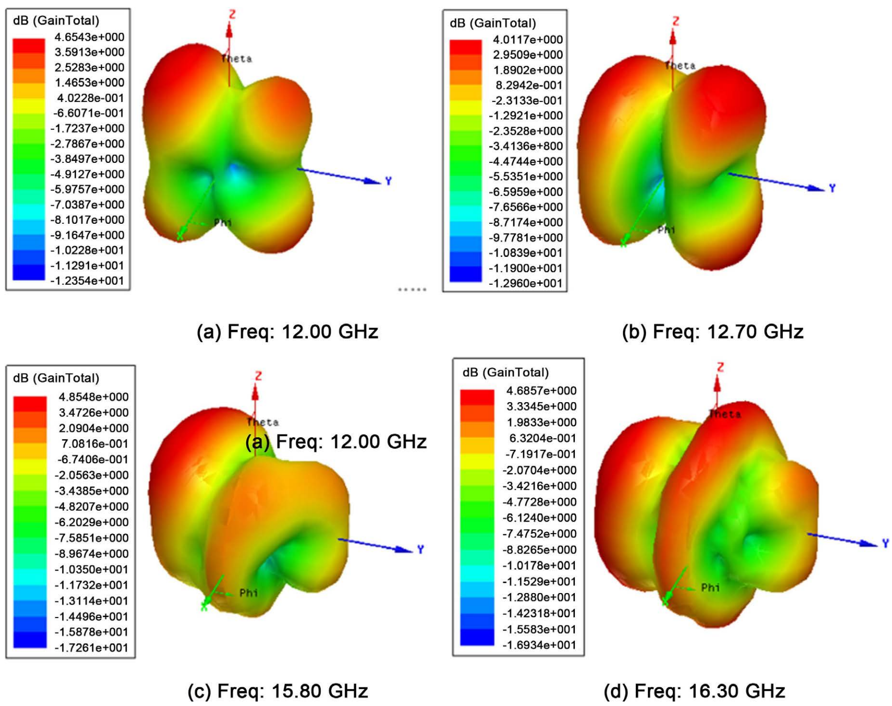


Figure 5. Antenna gain in the X- and Ku-bands.

Several antennas operating in X and Ku frequency bands have already been presented in the literature. Table 2 provides a comparative summary of the proposed antenna in terms of operating frequencies (Freq.), bandwidth, gain, radiation efficiency and dimensions. The symbol "-" indicates that the corresponding

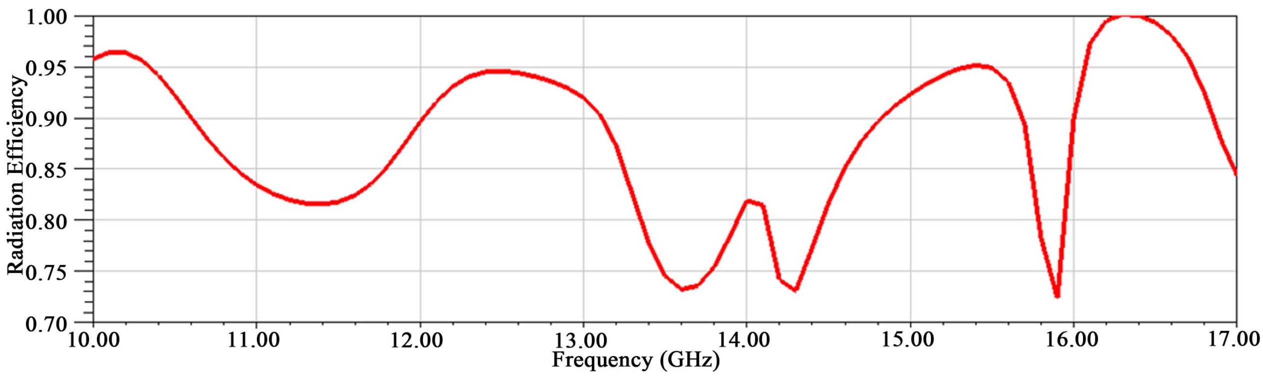


Figure 6. Simulated radiation efficiency.

value is not mentioned in the reference. According to **Table 2**, the proposed four-band antenna is very compact and performs well in terms of bandwidth, gain, and radiation efficiency. Consequently, the proposed antenna could be a very good candidate for embedded wireless systems, particularly the Internet of Vehicles.

Table 2. Comparative study of the antenna's performance with the literature.

Ref	Frequency (GHz)	Maximal Bandwidth (GHz)	Gain (dBi)	Maximal Efficiency (%)	Dimensions
9	11.79 15.65 15.77	1.31	3.18 3.21 3.10	80.8	30 × 13
10	12.24	0.51	7.4	-	22.46 × 21.95
Proposed	12.00 12.70 15.80 16.30	1.1	4.65 4.01 4.85 4.68	99	23.5 × 8.5

4. Conclusion

This article presents the design of a high-performance multiband antenna operating bands 12 GHz, 15 GHz, and 16 GHz bands (X and Ku bands) and intended for in-vehicle Internet applications. A detailed study of the design stages is carried out using simulation. Our study focused on antenna design and performance analysis. The performance achieved with the designed antennas was in line with the expectations defined in the specifications, demonstrating the effectiveness of our design approach. This performance of the proposed antennas is provided by ANSYS HFSS software. The radiation efficiency in the Ku-band is 75% and 99%, respectively. Despite its multi-frequency nature, the antenna exhibits good performance in terms of gain and radiation efficiency.

Conflicts of Interest

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

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