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REVIEW ARTICLE - ENGINEERING (MISCELLANEOUS)

A Systematic Review of Designs, Techniques, and Applications for Ultra-Wideband Vehicle Antennas

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Abstract

Ultra-wideband (UWB) is a wireless communication technology with a wide frequency band that transmits and receives signals. This technique has gained significant attention in recent years due to its capacity for supporting high data rates high precision ranging and positioning, and reliable communications in different vehicular environments. This systematic review highlights the UWB antennas' design techniques and applications for vehicle communication. This review aims to explain different antenna designs, improve techniques, and various applications of vehicles using UWB antennas. The results of this systematic review led to the understanding of UWB antenna development and its power to support vehicular communications. This review focuses on the innovations of UWB antenna designs for vehicular communication. It focuses on studies conducted between 2022 and 2024, exploring various design techniques and applications. It looks at different design techniques and applications, emphasizing the advancements that allow for high data rates, precise positioning, and reliable communication in various vehicular environments. The review identifies key innovations in UWB antenna technology that improve MIMO designs, addressing the needs of modern communication systems and the upcoming 5G technology. By binding existing research and identifying areas for further exploration, this review provides valuable insights that can guide future developments in UWB antennas, ultimately leading to improved performance and efficiency in vehicular communication systems. Therefore, this review article aims to enhance MIMO antenna designs, essential for high data transmission rates in current communication systems and the upcoming 5G technology.

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Keywords: Vehicle Antennas; UWB Antennas; Vehicular Communication; MIMO Antenna Design; V2X Technology; V2V Communications; 5G Technology.

1. Introduction

Recently Broadband technology has reached the apex in the world of communications, attracting great attention due to its ability to communicate easily with more accurately and its adaptability, especially for modern applications. Regardless of the various applications of WIMAX, WIFI, and many wireless communications applications, one of these applications that use ultra-wideband is vehicular applications that achieve great benefits for navigation and sensing purposes thanks to ultra-wideband characteristics [1]. The aspect related to road safety has also gained greater importance to avoid accidents and to provide appropriate communication to save precious lives. Intelligent and advanced transportation systems Traffic management systems use highly efficient simulation tools to analyze different scenarios and predict different possible solutions for collision avoidance. Effects of buildings, and trees. The propagation of electromagnetic waves, and the performance of associated infrastructure can be analyzed using high-performance computing for EM (electromagnetic) simulation. Fig. 1 illustrates various vehicular communication scenarios and the potential signal interference from different surrounding objects [2]. So, Vehicle-to-Everything (V2X) Engineering is greatly increasing attention in modern automotive engineering. The Vehicle roof-mounted antennas are Utilized for a Broad Range of Platforms such as (V2V) vehicle-to-vehicle, (V2I) Vehicle-to-Infrastructure, Vehicle-to-Network (V2N), (V2P) Vehicle-to-Pedestrian, and Keyless Entry [1] So the V2X technology has mainly two types. The first is DSRC (Dedicated Short-Range Communication) specified in IEEE 802.11c and the second is C-V2X (Cellular-V2X) defined in 3GPP (3rd Generation Partnership Project). The two technologies operate in the 5.9 GHz band. However, A contemporary vehicle's wireless communications system must accommodate a variety of roadside assistance features, such as emergency cellular connectivity, Bluetooth pairing, Wi-Fi hotspot functionality, and Navigation systems [3]. The main developments in these types of vehicle applications are communication units such as antennas and sensors. As careful design of antennas

Nomenclature & Symbols			
UWB	Ultra-wideband	V2I	Vehicle-to-Infrastructure
MIMO	Multiple-Input Multiple-Output	V2N	Vehicle-to-Network
V2X	Vehicle-to-Everything	V2P	Vehicle-to-Pedestrian
V2V	vehicle-to-vehicle	DSRC	Dedicated Short-Range Communication
EM	Electromagnetic	C-V2X	Cellular-V2X
3GPP	3rd Generation Partnership Project	WiMAX	Worldwide Interoperability for Microwave Access
WiFi	Wireless Fidelity	IEEE	The Institute of Electrical and Electronics Engineers
HIS	High Impedance Surface Structure	WLAN	A Wireless Local-Area Network
C2C	Car-to-Car	LLM	L-Sleeve L-Monopole

is highly required for the successful establishment of vehicular communications, they must have a good impedance bandwidth and good radiation performance to provide services for ultra-wideband applications. Many antenna models have been designed by researchers for vehicular communications applications. A vehicle antenna printed on a glass window was designed, and the model was verified at 100 MHz. These glass windows affect the impedance matching, causing signal dispersion [2], Madhav et al. [4]. Proposed a low-cost, conformal wheel-shaped antenna by applying the fractal concept to work in the vehicular communications band. A gain rate of 5.9 dBi obtained confirmed that the proposed antenna had adequate integration for vehicles at the top or side locations. He et al. [5] designed a directivity-enhancing antenna that has been used in vehicular wireless local area networks (WLAN) IEEE 802.11a (4900 ~ 5935 MHz) and it also applied in.

In addition, various vehicle communications systems can resist polarization distortion occurring from the top of the vehicle. Ref. [6] studied a microstrip antenna using FERN fractal shape and aperture coupled feed for blind spot detection in smart vehicles. The bandwidth was approximately 410 MHz tuned from 3.49 GHz to 3.9 GHz, and the axial ratio was found below the 3D range was obtained from 3.62 GHz to 3.71 GHz. Artnert et al. [7] proposed a hidden antenna cavity for integration into the vehicle body. The feasibility of future composites with CFRP structure was demonstrated by building a prototype. Kim et al. [8] designed a conformal resonator composite antenna with a high-impedance surface structure (HIS) in the ground plane. Khan et al. [9] designed an antenna with a maximum gain of 11.84 dBi and bandwidth of 17.6 which can be used in various broadband and multimedia applications. Lopez et al. [10] studied an inverted tri-band antenna for vehicle-based applications. The first band of the designed antenna was above 1% and the second band was near 0.4%, and the proposed antenna is suitable for various communication purposes of flying vehicles, toys, etc. Nguyen Trong et al. [11] The compact dimension wideband studied a monopole design that was integrated into the helmet. Initially, four symmetrical tapered slots were added to reduce the antenna size for vehicle mounting applications. Later, Hill helmet material was included in the design to complement the helmet's limited curved ground plane. Abbas et al. [12] studied the effect of complementary antenna with its placement on vehicles and the effect of diversity in vehicle-to-vehicle communications based on measurement analysis. Navarro-Mendez et al [13] design a 3D antenna for vehicular applications.

It is a shark fin antenna located inside the plastic cover. They are covered by two monopoles, i.e. a short dual monopoly covering the LTE 700, GSM 850, and GSM 900 bands and a drop-shaped monopole operating at 1.7-2.7 GHz covering DCS 1800, PCS 1900, WCDMA 2100, WLAN 2400, LTE2600, WiMAX2350, and 5. 1 to 6 GHz which covers the Wi-Fi and Car-to-Car (C2C) bands. Tseng [14] designed an LTE system to support V2X service and Prose service for direct exchange of information between two entities with/without E-UTRAN support. Alsath et al. [15] studied the utilization of the folded microstrip line concept to obtain a compact quad-band antenna. The designed asymmetric planar strip line antenna covers some IEEE standards, DCS 1800, Wi-Max, and V2X communications. Dzagbleti et al. [16] proposed a dual C-V2X Vivaldi antenna to improve low-frequency input impedance matching with a dual-stage balun in the test antenna. The proposed antenna provides 560 MHz to 7.7 GHz, i.e. 173% of the partial bandwidth, which covers current V2X communication frequencies. It also provides better cross-polarization isolation of −28dB and 17.2dB and up to 9.2dBdB gain. Sakthi Abirami et al. [17] designed and developed a (1.575 GHz) L1 armband self-balancing conformal antenna for automotive applications. The optimized antenna was fabricated on a windshield substrate, and the arms were asymmetrically shortened to achieve circular polarization. Wong et al. [18] presented a monopole patch antenna with V-shaped slots for vehicle-to-vehicle (V2V) and WLAN communications. Shortening pins and V-shaped slots were applied to the equilaterals.

Triangle-shaped patch to expand the impedance bandwidth. Wu et al. [19] presented a shark fin-equipped L-sleeve L-monopole (LLM) antenna for vehicular applications. To fix different shark fin modules, the effect of the ground plane and its position is checked with the position and curvature of the LLM. The proposed antenna is prototyped on a printed circuit board (PCB) which covers the frequency range 5-6MHz. It can be placed on a shark fin module to provide services for WLAN and C2C communication. Bhaktavachalami and Rajakani [20] extensively studied the design, setup, and testing of a band slot antenna with its applications. Designed a multiple-input multiple-output (MIMO) antenna consisting of a slot-structured antenna fed by a modified line-fed microchip, connected to a suitable impedance former and in combination with a patch Square. Designed for communications applications, the slot cover of the antenna has a frequency range of 3 to 6.75 GHz centered around 4.8 GHz with a gain of a boost of 2.45 dBi at 5 GHz. A monopoly antenna with dual loops and dual operating bands was proposed by the authors in [21]. A monopole antenna with PLA circular slots operating for ultra-wideband has been proposed by the authors in [22]. It achieved a gain of 4.2 dB, and the maximum radiation efficiency was 97%.

The flexible nature of the antenna in practical scenarios has proven to play a vital role in operating efficiently in various applications. There are types of ultra-wideband antennas for vehicular applications. Models include shark fins [23-25]. Transparent rooftop modules, conformal integrated side mirror modules, transparent antennas, and certain cavity-based antennas may be an integral part of the antenna. Most compatible antennas operate on single/dual band applications to work in new services [26-28]. Since the research on flexible antennas is limited and can be studied for compatibility with different paths, it chose to design and analyze the antenna compatible with broadband applications and analyze it for vehicular applications, as shown in Fig. 1.

This systematic review provides a comprehensive overview of UWB antenna designs, technologies, and applications used in vehicular communication. Comparison tables have been made between the antennas used, including the types of UWB antennas in size, frequencies used, gain, and efficiency. The MIMO antenna technique used for vehicular communication was also highlighted, and the difference between them in terms of gain, efficiency, interference reduction, and isolation between the antenna layers and the frequencies used and reviewed the development of advanced UWB antenna designs and its optimization techniques for vehicular communication.

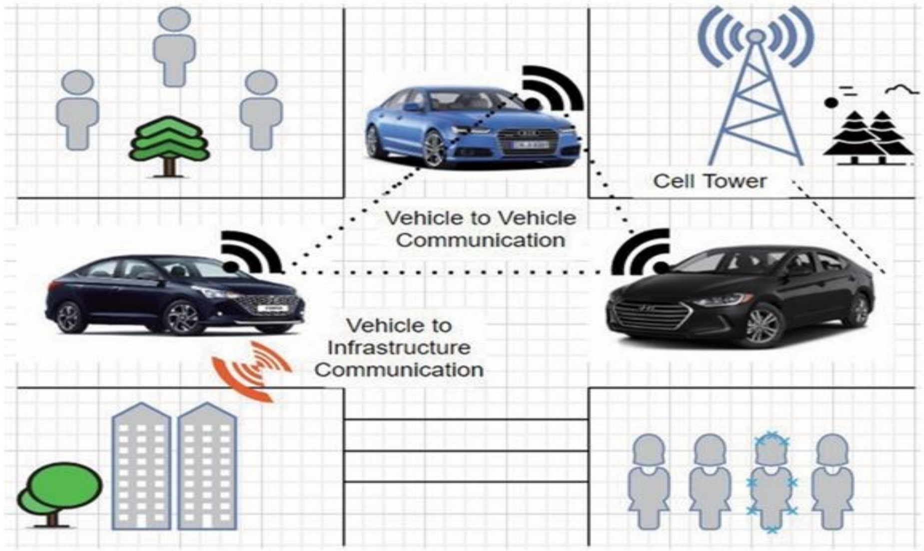


Fig. 1. Inter and intra-vehicular communication scenarios [29]

In this article, it focused on three contributions:

- Comprehensive Overview: Delivers an in-depth analysis of UWB antenna designs and their applications in vehicular communication.
- Comparison Tables, Presents comparison tables for various antenna models, detailing specifications such as size, frequency, gain, and efficiency.
- MIMO Technique Emphasis: Highlights the significance of MIMO antenna techniques in enhancing the performance of vehicular communication systems.

The rest of the sections are organized as follows: Section 2 introduces antenna parameter parameters to determine the working efficiency of ideal antennas. Section 3 provides a comprehensive and analytical comparison of the latest work presented by a team of researchers for the most important techniques they have achieved in antenna manufacturing. Section 4 provides a brief discussion of this analytical methodological review and presents the most important solutions and obstacles facing antenna designers. Section 5 provides conclusions and suggested future work.

2. Antenna Metrics Parameters

Recently, in wireless communications systems MIMO antennas have garnered significant attention due to their ability to use numerous transmission routes to transmit or reception data, leading to enhanced scope and improved and good performance for the output [30]. It is crucial to note that good and great isolation between the elements within an individual MIMO system is necessary to ensure MIMO antenna components able to operate autonomously and simultaneously to transmit or receive signals Devoid of compromising the efficiency of the antenna factors. To ascertain the efficiency, value, S-parameters, and radiation characteristics of the MIMO antenna, specific diversity factors are employed. For practical applications, MIMO antennas meet the Predetermined values of these diversity elements. This section outlines some basic diversity factors that are important for MIMO antennas.

2.1. Envelope Correlation Coefficient (ECC)

It is the correlation between Single contiguous elements in the MIMO antenna. Calculates from S parameters or radiation patterns. Using the remote-field radiation scheme is preferable due to the value evaluated of the ECC, so using this pattern is very preferable. The ECC clears the extent of the independence (in MIMO systems) of the multiple radiating elements in their radiation scheme. Furthermore, it has been observed that most flat antennas struggle from a loss; thus, determining the ECC using the S-elements must avoided. The arithmetical expression for calculating the ECC using the radiation scheme data of the MIMO design is given by Eqs. (1), (2), and (3)[31].

$$\mathrm{ECCqp} = \frac{\left| \int_0^{2\pi} \int_0^{\pi} (E_{\theta P}^* E_{\theta q}\, \rho_\theta XPR + E_{QP}^* E_{Qq} P_Q) d\Omega \right|^2}{\alpha \times \beta} \quad (1)$$

$$\alpha = \int_0^{2\pi} \int_0^{\pi} (E_{\theta q}^*\, E_{\theta q}\, P_\theta XPR + E_{Qq}^* E_{Qq} P_Q) d\Omega \quad (2)$$

$$\beta = \int_0^{2\pi} \int_0^{\pi} (E_{\theta P}^*\, E_{\theta P}\, P_\theta XPR + E_{QP}^* E_{QP} P_Q) d\Omega \quad (3)$$

Where the definition of the cross-polarization ratio (XPR) is the proportion of the mean power along the phi (φ) and theta (θ) directions. In an actual environment, the favourable limit of cross-polarization discrimination (XPD) must be less than 0.5.

2.2. Diversity Gain (DG)

It refers to both the reliability and quality of the MIMO antenna. Hence, the DG of the MIMO antenna must be high (≈ 10) within the suitable frequency range. Can be calculated the DG value using the ECC value can be given by Eq. (4) [31, 32].

$$DG = 10 \times \sqrt{1 - |ECC_{qp}|^2} \quad (4)$$

2.3. Channel Capacity Loss (CCL)

It is defined as the supreme at which the configuration transport may be almost zero loss in the connection channel. The predetermined CCL worth for MIMO systems is <0.4-bit/s/Hz. The Phrasing of the CCL by using S-factors by Eq. (5) to (10) [33].

$$CCL = -log_2 \det(\vartheta^{\mu}) \quad (5)$$

Where

$$\vartheta^{\mu} = \begin{bmatrix} \xi_{11} & \xi_{12} \\ \xi_{21} & \xi_{22} \end{bmatrix} \quad (6)$$

And

$$\xi_{11} = \left(1 - \left[|S_{11}|^2 + |S_{12}|^2 \right]\right) \quad (7)$$

$$\xi_{12} = (- [S_{11}^* S_{12} + S_{21}^* S_{12}]) \quad (8)$$

$$\xi_{21} = (- [S_{22}^* S_{21} + S_{12}^* S_{21}]) \quad (9)$$

$$\xi_{22} = \left(1 - \left[|S_{22}|^2 + |S_{21}|^2 \right]\right) \quad (10)$$

2.4. Mean Effective Gain (MEG)

It is defined as the proportion of the energy received by a MIMO antenna to the energy received by the isotropic antenna with equal characteristics. For optimal rendering of a MIMO antenna at an equal energy level, the MEGj/MEGi proportion should be < 3 dB. Evaluate the MEG using Eq. (11) and (12) [33].

$$MEGi = \left(0.5 \left[|1 - s_{ii}|^2 - |s_{ij}|^2 \right]\right) \quad (11)$$

$$MEGj = \left(0.5 \left[1 - s_{ij}|^2 - |s_{jj}|^2 \right]\right) \quad (12)$$

2.5. Total Active Reflection Coefficient (TARC)

It is defined as the proportion of the total energy the radiating elements reflect the total power incident on the patch. The expression for the generalized whole active reflection factor, Eq. (14) can give TARC and the N-port MIMO antenna could be by Eq. (13) [34]. Also, for a 2-port MIMO antenna, TARC is possible given by Eq. (14) [34].

$$TARC = \left(\frac{\sqrt{\sum_{i=1}^{N} |b_i|^2}}{\sqrt{\sum_{i=1}^{N} |a_i|^2}} \right) \quad (13)$$

$$TARC = \left(\frac{\sqrt{\left(|S_{11} + S_{12^{ej\theta}}|^2 + |S_{21} + S_{22^{ej\theta}}|^2 \right)}}{\sqrt{2}} \right) \quad (14)$$

Where bi = (s), (b), and (a) represent the scattering array, the scattering vector, and the excitement vector, respectively. TARC is the proportion of the reflected power to the incident power, and the ideal Multiple-Input Multiple-Output antenna is expected to accept all the incident power. Therefore, the TARC merit for the MIMO antenna should be typically zero. When designing a Multiple-Input Multiple-Output antenna, one must optimize the values of all antenna diversity factors within the predetermined limits.

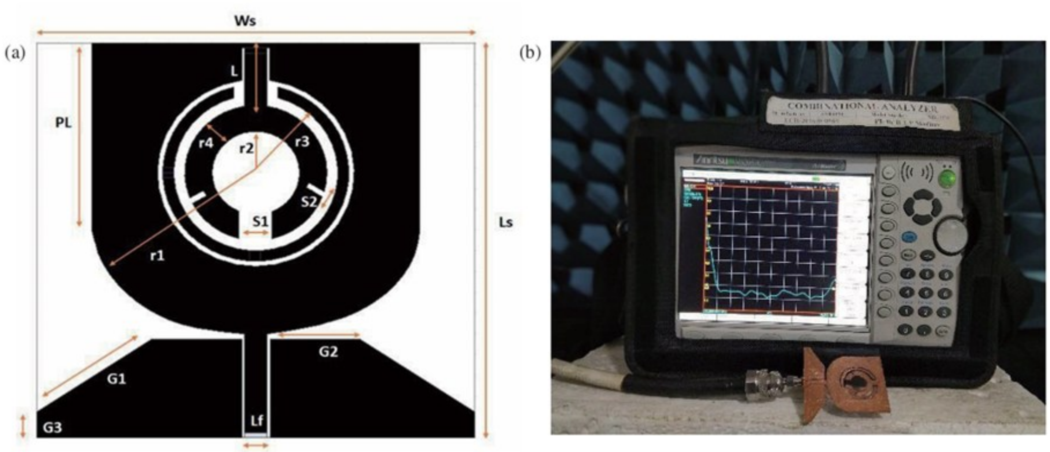
3. Modern Works on Single and Multi-Ports Antennas

UWB is one of the newest wireless telecommunication technologies that has ability the to transmit large amounts of digital data over a wide range of frequency bands by using very low power levels over short distances. In this section, various UWB single and MIMO antenna designs are mentioned. UWB technology operates within a frequency band of 3.1 to 10.6 GHz, with channel widths exceeding 500 MHz [35].

Therefore, first, the numbered research paper [29] focuses on the single antenna, Fig. 2(a) illustrates a single antenna structure, with dimensions of 40 × 38.5 × 0.2 mm^3, fabricated on a flexible photo paper substrate as mentioned. The antenna is constructed on a polyethylene terephthalate (PET) substrate. The fabricated antenna structure and its real-time measurement results are shown in Fig. 2(b). The step-by-step design iteration process is illustrated in Fig. 3.

In addition, Fig. 4 presents the designed antenna model's reflection coefficient (S11) parameters. The voltage standing wave ratio (VSWR) of the recommended antenna is depicted in Fig. 5. The simulated results have been precisely verified through measurement data. The antenna exhibits triple-band operation, with the S11 parameter being less than or equal to ≤-10 dB, and the VSWR being less than or equal to ≤ 2. The reflection coefficient (S11) plot demonstrates the triple-band characteristics, with resonant frequencies at 3 GHz, 5.8 GHz, and 8 GHz, respectively. The designed antenna resonates at three frequency bands based on the measurement results. The 10 dB impedance bandwidth extends from 2.40 GHz to 3.85 GHz for the first band, 5 GHz to 6.15 GHz for the second band, and 7.15 GHz to 9.02 GHz for the third band.

The designed antenna covers the frequency bands used by various commercial communication technologies, including Bluetooth, LTE, Wi-Fi, WLAN, and satellite communications.



(a) (b)

Fig. 2. Antenna design with a measure of the performance of this antenna [29]

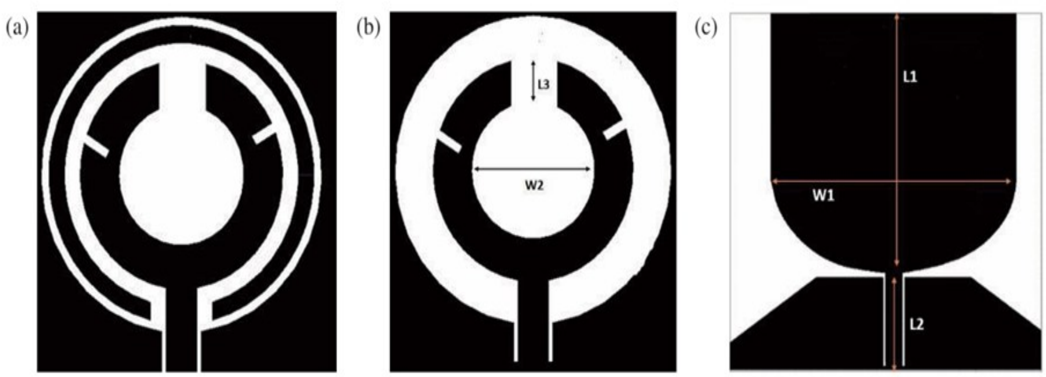


Fig. 3. Antenna design steps until the ideal design is obtained [29]

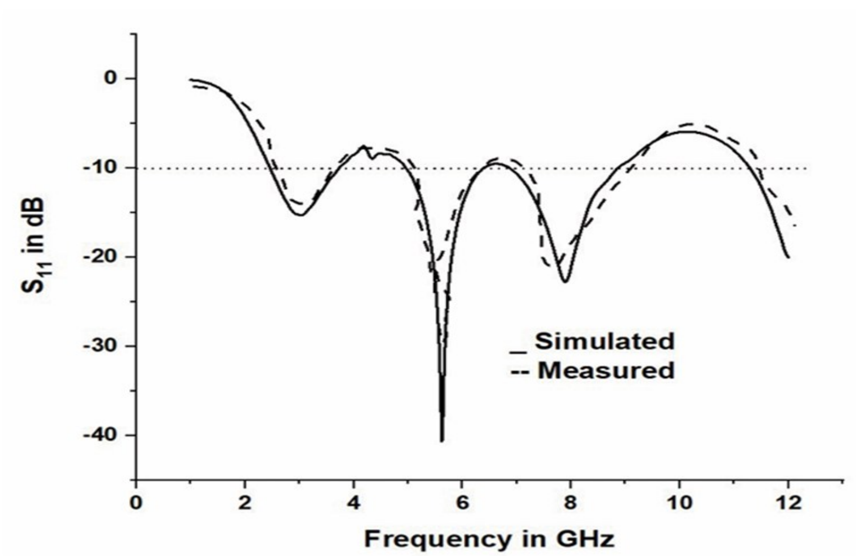


Fig. 4. S-Parameter curves versus different frequencies [29]

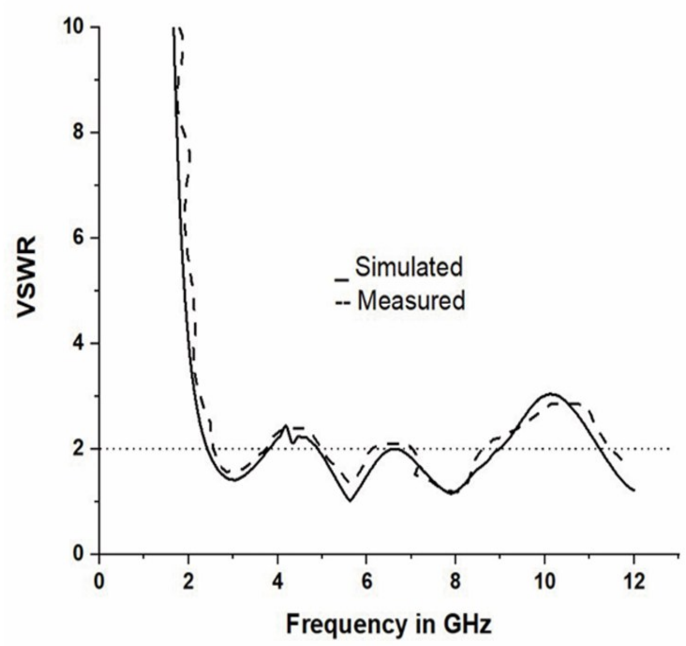
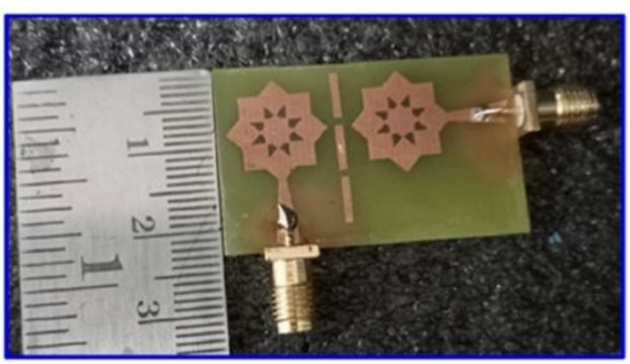


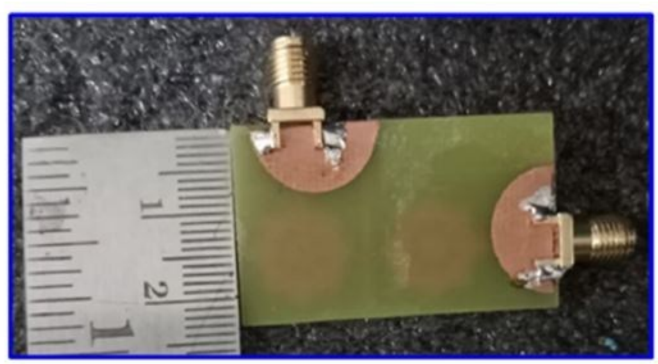
Fig. 5. VSWR parameter versus various frequencies [29]

On the other hand, For the MIMO antenna to decouple a compact UWB MIMO antenna, a Wideband-neutralized line is utilized [36]. This UWB MIMO antenna exhibits a mutual coupling of less than -22 dB, covering the lower UWB Bandwidth of 3.1-5 GHz. MIMO designs should display broadband characteristics to address the demands for increased spectral efficiency while keeping minimal reciprocal coupling between the radiating elements [36-38]. A decoupling network using two inverters and two connected split-ring resonators (SRRs), as presented in [39], provides excellent isolation between the ports.

In addition, the second, numbered research paper [40] focuses on the MIMO antenna, Fig. 6 shows the structure of the 2×2 UWB MIMO antenna mentioned in the reference. The dimensions of the reported antenna are 40 × 23× 1.6 mm^3, The radiator is etched on a FR4 substrate. The radiator is etched on a FR4 substrate withε_r of 4.40 a thickness of 1.6 mm, and δ of 0.02. A triangular tapered feed line is used for feeding the exponentially tapered feed region and patch of the proposed antenna. Tapered structures are employed so that the input signal to the antenna can radiate freely without any disturbance from the antenna. It has been observed experimentally that the antenna is well-matched for a very broad frequency range [36, 37]. As shown in Fig. 7(a), the two-port MIMO antenna system demonstrates an applied wide frequency range, extending from 3.28 GHz to 17.8 GHz. As depicted in Fig. 7(b), the mutual coupling between the antenna elements is impressively below -20 dB, indicating a significant reduction in the undesired electromagnetic coupling when the antenna elements are separated by a distance of 3.38 mm. Furthermore, as shown in Fig. 7(c), the gain of the MIMO antenna system is reported to be greater than 2 dBi across the specified frequency range. As shown in Fig. 7(d), the radiation efficiency of the antenna system exceeds 90%, which indicates that the antenna system minimizes losses and maximizes the conversion of electrical power into useful radiated signals.



(a)



(b)

Fig. 6. Proposed dual-port manufacturing antenna, (a) front view, and (b) back view [40]

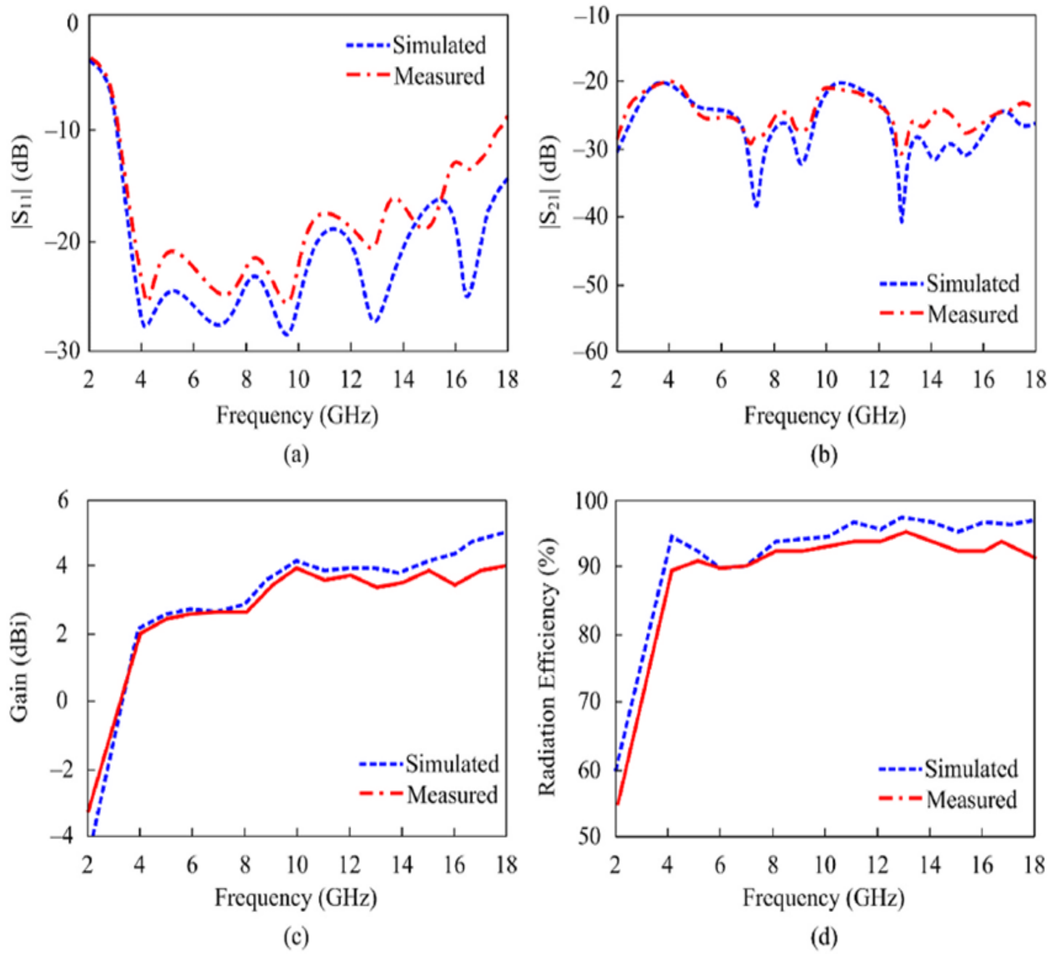


Fig. 7. Antenna performance metrics parameters, (a) S-Parameter curves, (b) mutual coupling curves, (c) gain curves, and (d) Radiation Efficiency curves [29]

The rest of the comparisons of recent work presented by a group of researchers for single-port antennas are listed in Table 1 and for multi-port antennas in Table 2.

Table 1. Comparison of recent works on single-port antenna design

References	Years of Publication	No. of Ports	Antenna Size (W × L × h) mm^3	Operating Frequency (GHz)	Gain (dB)	Efficiency (%)
[41]	2017	1	24 × 24 × 1.6	2.9-13.9	5.1	65 to 90
[42]	2022	1	17 × 23 × 1.524	2.8–10.6	4.9	80 to 90
[43]	2022	1	35 × 25 × 0.254	2.12–8.91	5.8	80
[44]	2022	1	65 × 27 × 0857	28 & 38 & 60	15 & 12 & 11	86 & 87 & 78
[45]	2022	1	50 × 50 × 1.6	3.6 & 5.3	2.78 & 5.32	88.5 & 84.6
[46]	2022	1	40 × 40 × 1.6	2.10–2.70 4.82–6.10 12.73–18	2.35 4.41 4.71	NA
[47]	2023	1	24 × 30 × 1.6	2.19–4.43 4.8–7.76 8.04–11.32	1.074 4.19 4.01	68.35 64.15 62.7
[48]	2023	1	45 × 55 × 1.6	2.4–18.4	4.5	92
[49]	2023	1	15 × 15 × 5	7.6	5.5	92
[50]	2023	1	55 × 34 × 1	2.4	6.48	NA
[51]	2023	1	36 × 36 × 1.6	3.45–3.85 4.65–5.4	5.64 4	89 73
[52]	2023	1	40 × 45 × 1.6	2.20–2.63 2.73–3.80 5.13–6.30	0.9–2.0 2.0–3.8 4.8–5.7	80 85 90
[53]	2023	1	30 × 26.6 × 0.1	3.5 5.9	4.8	90
[54]	2023	1	28 × 21 × 1.6	2.4	2.09	98

Continue Table 1. Comparison of recent works on single-port antenna design

[55]	2023	1	27 × 25 × 1.5	3.581 – 14	4.7	82
[56]	2023	1	40 × 38 × 1.6	2.45 6 14	6	87
[57]	2023	1	36 × 36 × 1.6	3.45 -3.85 4.65 - 5.4	5.64 4	89 73
[58]	2023	1	24 × 25 × 1	5.8	4.68	NA
[59]	2023	1	10 × 15 × 0.254	3–14.55	4.93	NA
[60]	2023	1	25 × 27 × 0.13	4.9–19	5.37	98
[61]	2023	1	40 × 40 × 1.6	3.36 –4.48 4.45–7.27 8.58–9.79	12	95.2
[62]	2023	1	56.0 × 21.2 × 2.6	2.3- 23	5	96 to 98
[63]	2023	1	40 × 34 × 1.6	2.30 - 4.10 6.10 - 10.0	9	92
[64]	2024	1	35 × 50 × 1.6	5.8	3.93	76.5
[65]	2024	1	17.75 × 20 ×1.6	3.01 - 12.41	6.3	98.3
[66]	2024	1	60 × 60 × 2	8.75–11	7.7	NA
[67]	2024	1	16 × 22 ×1.6	3.78–109.86	3.22 to 7.23	93.3
[68]	2024	1	5.1 × 4.7 × 0.8	24.03 - 30.27	1.5-5.5	70 to 100
[69]	2024	1	195 × 195 × 1.524	5.8	8.29	95
[70]	2024	1	34 × 30 × 1.6	3.2–7.5	6.8	91 to 94
[29]	2024	1	40 × 38.5 × 0.2	2.40–3.85 5–6.15 7.15–9.02	5.8	82
[71]	2024	1	1.5 × 1 × 0.15	123 180.4	4.12 5.05	81.6 89.3
[72]	2024	1	40 × 43 × 1.6	2.30–2.50 3.65–9.77	3.62	NA
[73]	2024	1	39 × 10 × 0.254	40 - 70	14.97	NA
[74]	2024	1	45 × 24.5 × 1.6	3.1-10.6	6.62	NA
[75]	2024	1	47 × 35 × 1.6	2.38–22.5	6.5	88 to 92
[76]	2024	1	19.7 × 23 × 0.508	7-10	6.8	98
[77]	2024	1	27 × 28 × 0.7	3.01–15.98	5.81	90.11
[78]	2024	1	17 × 45 × 1.2	2–6	4.98	NA
[79]	2024	1	32 × 32 ×0.8	3.15 - 4.3	3.3	94
[80]	2024	1	12 × 14 × 1.6	16.2 - 34	3.85	82.9
[81]	2024	1	26.33 × 19.39 × 1.60	3.780 - 10.460	4.8	NA
[82]	2024	1	33 × 22 × 1.6	3.19–3.96 4.65–5.33 6.78–7.54 10.03–14.29 15.74–19.98	2.51 1.52 2.48 3.58 3.62	81.28 79.98 82.34 76.84 86.52

Table 2. Comparison of recent works on multiport antenna design

Ref.	Years of Publication	No. of Ports	Antenna Size (W × L × h) mm^3	Operating Frequency (GH)	Isolation Performance (dB)	Diversity Gain (dB)	ECC	Gain (dB)	Efficiency (%)
[83]	2022	2	40 × 70 × 1.6	4.89 - 6.85	≤- 60	10	<0.002	6.45	84
[84]	2022	4	51 × 51 × 1.5	3.1–12	<-17	9.99 to 10	< 0.04	4.62	92
[85]	2022	4	28 × 28 × 1.6	3.1–10.6	<-20	9.90 to 10	< 0.001	3	65
[86]	2022	4	65 × 65 ×0.1	2.9–10.86	< -22	9.999	< 0.01	4	85 to 97
[87]	2022	4	45 × 45 × 1.6	3.1 – 13.1	<-17	9.9985 to 10	< 0.02	4	73 to 98
[88]	2023	4	30 × 30 ×1.6	3.1–12	< -17	9.9 to 10	<0.001	6.2	87
[89]	2023	4	40 × 40 × 1.6	3.2–12.44	< -26	10	< 0.0016	4.9	89
[90]	2023	4	78 × 78 × 1.5	2.33–16	< -20	9.98 to 10	<0.05	5.1	90
[91]	2023	4	40 × 40 × 0.8	3.1–10.6	< -20	9.99 to 10	< 0.1	4.6	85
[92]	2023	4	20 × 20 × 0.254	25–38	<-18	9.95 to 10	<0.012	3.5	88 to 95
[93]	2023	2	20 × 29 × 1.6	5–13.5	<- 21	10	< 0.002	5.5	NA
[94]	2023	2	27 × 22 × 0.8	3.07 – 11.1	<-20	9.986 to 10 9.993 to 10	< 0.05	1.1 to 3.7	75 to 83
[95]	2023	2	30 × 20 × 1.6	3.01–12.34	<-22	10	<0.5	1 to 6	77.3 to 95.3
[96]	2023	4	80 × 80 × 1.6	1.5 -5.5	< -15	9.6	<0.016	3	84
[97]	2023	4	30 × 30 ×1.6	5.8–11	< -20	9.97 to 10	<0.004	4	80 to 95
[98]	2023	2	35 × 35 × 1.6	24–40	< - 28.7	9.992 to 10	0.0016	4.6	95

Continue Table 2. Comparison of recent works on multiport antenna design

[99]	2023	4	62.5 × 60.5 × 1.6	3.5–11	< -20	9.95	<0.01	4	70 to 90
[100]	2023	4	33 × 33 × 0.233	25 - 50	<-10	9.999	< 0.005	NA	NA
[101]	2023	4	58 × 58 × 0.787	4.4–14.4	<-22	10	<0.01	5.3	NA
[102]	2023	4	24 × 24 × 0.787	23.5-29	< -33	9.99	<0.005	11.4	84
[103]	2023	4	40 × 40 × 1.6	5.68–8.01	< -20	10	<0.001	2.5 to 6.5	79 to 93
[104]	2024	2	18 × 9.2 × 0.787	28 & 38	< -30 & <- 38	9.99 to 10	<0.0001	7.8 & 6	NA
[105]	2024	2	47.7 × 38 × 1.6	2.83–7.21	< -22	9.8 to 10	< 0.003	4.8	92
[106]	2024	2	40 × 45 × 1.6	1.29–15.09	<-32	10	< 0.04	3.26	83.11
[107]	2024	2	20 × 31.5 × 1.6	3.25–3.85	< -19	9.85 to 9.99	< 0.011	3.259	92
[108]	2024	2	30 × 17 × 1.6	5.45 - 91.25	<-31.5	10	<0.011	8.9	NA
[109]	2024	2	20 × 32 × 1.62	15.94 -17.97	< −15	9.89 to 10	< 0.025	6.25	NA
[110]	2024	4	48 × 48 × 1.6	4- 20	< -20	10	< 0.1	6.6	90 to 98
[111]	2024	2	20 × 32 × 1.62	15.94 - 17.97	< −15	9.89 to 10	<0.025	6.25	NA
[112]	2024	2	29 × 29 × 0.8	3-50	<-20	9.99	<0.002	8	80 to 95
[113]	2024	4	41 × 41 × 1.6	1.9–20	<-25.5	9.98	<0.002	8	89
[114]	2024	4	50 × 50 ×1.6	2.62 - 20	< -15	10	< 0.023	6.53	NA
[115]	2024	2	52.8 × 29 × 1.6	3.3 - 13.5	<-22	9.96 to 10	≤ 0.02	4.9	95
[116]	2024	2	52 × 30 × 0.79	2.8–15	<-20	9.90 to 10	< 0.01	7.92	99.2
[40]	2024	2	40 × 23 × NA	3.28–17.8	<-20	9.997	<0.03	4.93	95.34
[117]	2024	4	23 × 18 × 0.254	26-40	<-18	9.95 to 10	0.001	6.6	90 to 97
[118]	2024	4	65 × 56 × 0.25	3.55–5.3	<–24	9.99	<0.001	4.9	NA
[119]	2024	4	20 × 30 × 1.6	3.1–12	<-25	9.9 to 10	<0.25	8	NA
[120]	2024	4	30 × 30 × 0.254	5.2–5.7 11.8–17.3 23.4–37.3	<-20	9.9 to 10 9.9 to 10 9.9 to 10	<0.004 <0.002 <0.002	3.05 5.27 6.67	93 to 98
[121]	2024	4	66 × 66 × 0.13	3–4.12	<-20	9.95 to 10	<0.005	4	84 to 96
[122]	2024	8	150 × 80 × 0.8	3.4–3.6 4.6-4.8	<-17	10	<0.05	2.4 3.8	64 71

By adhering to these recommendations, researchers can significantly advance UWB antenna technology and its role in enhancing vehicular communication systems, ultimately promoting safer and more efficient modern transportation. Based on the review, here are the recommendations for future UWB antenna research:

- Explore Different Designs: Study a wider range of UWB antenna designs to fit different vehicular environments.
- Improve MIMO Techniques: Enhance MIMO techniques for UWB antennas in complex vehicular settings.
- Do real-world testing: Test UWB antennas in diverse conditions and against interference from buildings.
- Set Standard Measures: Create standard testing methods and performance measures for UWB antennas.
- Combine with New Technologies: Explore how UWB antennas can work with new technologies like 5G and IoT.
- Focus on Safety Uses: Develop UWB antennas that support vehicular safety features.
- Use Eco-Friendly Materials: Consider using environmentally friendly materials and practices in UWB antenna development.

4. Discussion

A significant number of pertinent research publications have been discussed in this review article about antenna research aimed at super-wide bandwidth. In Table 1, a comparison of the latest works on designing single-port UWB antennas specialized in vehicular communications was presented. The comparison focused on the dimensions of the antenna, the frequency at which the antenna operates, and the highest gain and efficiency reached by the antenna. In addition to the design methodology, the main focus is on the design and structural image.

In Table 2, a comparison was presented of the latest studies on the design of multi-port UWB antennas specialized in vehicular communications. The comparison focused on the antenna dimensions, the number of ports, the mutual coupling, the frequency at which the antenna operates, the highest directional gain, the efficiency reached by the antenna, and the ECC metric parameters. Establishing the review to provide a comprehensive and insightful analysis that contributes to the understanding and advancement of UWB antennas in vehicular applications. Furthermore, when reviewing the existing literature on UWB antennas for vehicular communications, several key weaknesses were identified that prompted us to conduct this study. These weaknesses are:

- Limited Design Variety: Many previous studies focused on a narrow range of antenna designs, lacking diversity in configurations that could cater to various vehicular applications and environments.
- Inadequate Performance Metrics: Several works did not comprehensively evaluate critical performance metrics such as gain, efficiency, and bandwidth, essential for effective vehicular communication.
- Neglect of Real-World Conditions: Previous research often overlooked the impact of real-world conditions, such as signal interference from surrounding objects and environmental factors, which can significantly affect antenna performance.
- Insufficient MIMO Implementation: While MIMO techniques are crucial for enhancing communication performance, many studies failed to adequately explore or optimize these techniques within the context of UWB antennas for vehicles.
- Lack of Standardization: A notable absence of standardized testing methods and parameters across different studies makes it challenging to compare results and gauge advancements in the field.

- Future Research Gaps: Many existing studies did not adequately address future research directions or the evolving needs of vehicular communication systems, particularly emerging technologies like 5G.

Therefore, it concluded from these works mentioned in Tables 1 and 2 that the ideal UWB antenna design for vehicular communication is in three stages, and these stages are summarized in the flowchart as shown in Fig. 8(a, b, and c). The flowchart illustrates the process of designing and optimizing a MIMO antenna for vehicular communications applications. The explanation of these steps is:

Stage 1:

- The process begins with "Initializing Appropriate Design Shape Parameters," where the initial antenna design parameters are set up. This is followed by "Antenna Design Simulation by Numerical Analysis of Computer Systems Technology (CST) Studio Suite," where the antenna design is simulated and analyzed using computational electromagnetic software, as shown in Fig. 8(a).
- The next step is "Changing Antenna Dimension Values & Updating Parameters Manually," where the antenna dimensions and parameters are manually adjusted based on the simulation results, as shown in Fig. 8(a).
- If the simulation results are satisfactory (Sij < -10 and Pij < 0.05), the process moves to the next stage; otherwise, the parameters are further updated, as shown in Fig. 8(a).

Stage 2:

- This stage is focused on "Introducing Superstrate & Different Dielectric Parameters," where new materials or dielectric layers are introduced to the antenna design, as shown in Fig. 8(b).
- The antenna parameters are then manually updated, and the simulation is checked again. If the new parameters do not meet the desired criteria (Sij < -25 and Pij < 0.05), the process goes back to the previous step; otherwise, it proceeds to the next stage, as shown in Fig. 8(b).

Stage 3:

- In this stage, the focus is on "Optimizing all Parameters of the Proposed MIMO Antenna," where the parameters of the MIMO antenna design are further optimized, as shown in Fig. 8(c).
- The antenna parameters are manually updated, and the simulation is checked again. If the new parameters do not meet the desired criteria (Sij < -25 and Pij < 0.05), the process goes back to the previous step; otherwise, the "Achieving the Ideal Design for the Proposed MIMO Antenna" is considered complete, and the process ends, as shown in Fig. 8(c).
- The flowchart demonstrates a systematic approach to designing and optimizing a MIMO antenna for vehicular communication applications, involving multiple stages of simulation, parameter adjustments, and performance evaluation to achieve the desired antenna characteristics, as shown in Fig. 8(c).

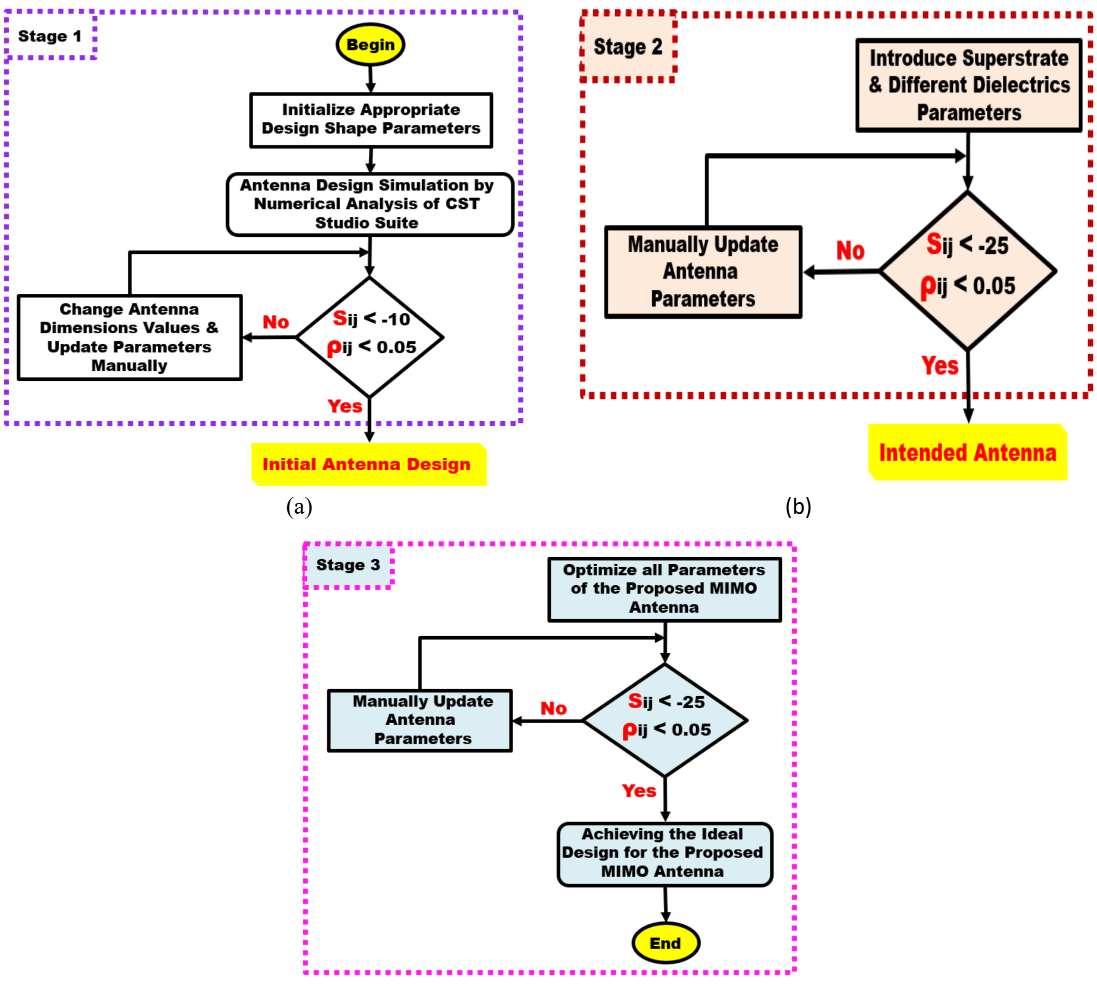


Fig. 8. Stages of designing an ideal antenna for various applications; (a) The first stage, (b) The second stage, and (c) The third stage

5. Conclusion

This systematic review provides a comprehensive overview of UWB antenna designs, technologies, and applications used in vehicular communication. Comparison tables have been made between the antennas used, including the types of UWB antennas in size, frequencies used, gain, and efficiency. The MIMO antenna technique used for vehicular communication was also highlighted, and the difference between them in terms of gain, efficiency, interference reduction, and isolation between the antenna layers and the frequencies used and reviewed the development of advanced UWB antenna designs and its optimization techniques for vehicular communication. A group of related works were analyzed that distinguish our work from those presented by researchers in previous recent research. The research on advanced UWB antenna designs shows optimization methods that improve isolation between antenna layers by 30%, which is crucial for reducing interference in multi-antenna systems. The review also sets this work apart by analyzing 83 recent research papers on similar topics, providing a clearer context for the progress discussed. In summary, this systematic review not only advances the understanding of UWB antennas in-vehicle environments but also emphasizes their potential to significantly improve communication and sensing functions. The results indicate that improved UWB antenna designs could lead to data transfer rates exceeding 1 Gbps, meeting the requirements of successive-generation vehicle communications systems. The quantitative measurements included specific data on frequency bands, gain, efficiency, and interference reduction, highlighting the implications for future vehicle communication systems. This systematic review contributes to the understanding of antennas in general and vehicular UWB antennas and their capabilities to enhance communication and sensing capabilities between different vehicular environments. In the future, research should focus on the following fields:

- Integration with 5G Technology: Investigating how UWB antennas can be seamlessly integrated into 5G networks to leverage higher data rates and lower latency.
- Adaptive Antenna Designs: Developing UWB antennas that can dynamically adjust their characteristics based on environmental conditions to optimize performance.
- Advanced Materials: Exploring the use of novel materials, such as metamaterials, to enhance antenna performance and miniaturization.
- Field Testing: Conducting extensive field tests in various vehicular environments to validate theoretical findings and ensure reliability in real-world applications.
- Interference Mitigation Strategies: Further research on advanced algorithms for interference mitigation in dense vehicular networks to enhance communication reliability.

Finally, by addressing these fields, future work can significantly advance the field of UWB antenna technology and its application in vehicular communication systems.

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