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Design and development of an enhanced U-shaped microstrip antenna for super wideband applications in next-generation wireless systems

Mani Periyasamy, Shankar Sharma Karthikeyan Jayalakshmi
Department of Electronics and Communication Engineering, K. Ramakrishnan College of Technology, Trichy, India

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ABSTRACT

The proposed enhanced U-shaped microstrip antenna is conceived with the aim of meeting the emerging needs of super wideband (SWB) applications in contemporary wireless communication systems. An efficient upgraded U-shaped patch design, in combination with substrate enhancements and impedance matching methods, is introduced in this work to remarkably increase the operational bandwidth, gain, and radiation efficiency of antenna. The antenna aims SWB achievement with the help of optimized dimensions and it is designed in such a way that it minimizes ground wave losses. It maximizes the impedance matching over a frequency range of 2 MHz to 20 GHz. Through various simulation outputs and experimental verifications, the antenna designed demonstrates excellent performance with a broad impedance bandwidth greater than 100% and the radiation patterns that are stable beyond entire frequency band. This work illustrates that the enhanced U-shaped microstrip antenna can attain the needs of next-generation communication technologies with specific criteria, and it establishes an efficient solution to SWB systems without sacrificing performance, cost, or size issues.

Corresponding Author:

Mani Periyasamy
Department of Electronics and Communication Engineering, K. Ramakrishnan College of Technology
Trichy-621112, Tamil Nadu, India
Email: manip.ece@krct.ac.in

1. INTRODUCTION

Microstrip antenna is acquiring fame in advanced communication systems and they are designed in low profile, compact with fabrication. Microstrip antennas are fabricated from the radiating patch over one side with dielectric substrate and other side with the ground plane [1], [2]. The U-shaped patch is popular for its large bandwidth and low-profile structure [2]. The integration of that antenna into super wideband (SWB) applications is highly efficient, specifically in wireless communication, radar, and satellite systems, where the wide frequency bands and effective operation are achieved. Among those, the U-shaped patch specification has become popular as a bandwidth enhancer with a compact configuration [3].

The U-shaped patch configuration has its own benefits compared to the conventional rectangular or circular patches. Bandwidth advancement is one of the most important advantages, and it is very important in the case of SWB applications. The multiple resonant modes are given by the U-shaped design result in more and larger operating frequency bands [4]. The structure also promotes enhanced impedance matching that contributes to reduced signal reflection and developed overall performance of the antenna. The straight forward has the efficient geometry makes U-shaped antennas for the general-purpose candidate for many high-frequency applications like millimeter-wave communication systems, 5G, and internet of things (IoT).

Variations from the geometry structure can alter impedance characteristics and bandwidth of antenna [5]. Microstrip patch antennas need to undergo various processes in order to attain the SWB performance due to the limitations like restricted bandwidth, narrow impedance matching, and further losses of antenna [6]. The U-shaped microstrip antenna needs to be modified in order to withstand the problems like patch size, feeding method, and substrate material. It is also an important challenge to find and balance the compactness and performance of the antenna. Design of optimized U-shaped microstrip antenna for SWB applications is performed through an orderly process of careful material selection, adjustment of parameters, structural modification, and design consideration. The goal is to create a miniaturized antenna with constant pattern radiation, satisfactory efficiency, and broad bandwidth, which is very important in the integration of wireless communication devices' most recent technology [7].

U-shaped microstrip antenna is used because of its intrinsic ability to provide wideband performance. Design requirements are in terms of altering the ground plane design dimension, U-shaped patch, and feed line geometry to provide maximum antenna bandwidth and impedance matching [8]. The U-shaped antenna facilitates the provision of multiple resonances, which are necessary to increase the operation bandwidth. The most important design parameters of a U-shaped patch antenna are width and length, feed line dimension, and patch-to-ground plane gap [9]. In order to satisfy SWB applications, the antenna must be able to span a frequency range from as low as 2 MHz to as high as 20 GHz. This wide bandwidth requires careful management of ground wave propagation, which is achieved by placing apertures strategically and adjusting the ground plane to minimize the current distribution and maximize current levels. This not only widens the bandwidth but also enhances the radiation efficiency of the antenna [10].

For the enhanced bandwidth of the U-Shaped antenna, various structural modifications were carried out. A defective ground plane design was introduced to minimize the ground wave losses and to maximize the effective bandwidth of the antenna [11]. The defective ground plane differs the current distribution, essentially generating multiple resonance modes that overlap a span a wide frequency range. Moreover, the U-shaped patch antenna integrates intentionally located apertures which helps to improve impedance matching throughout the SWB range [12]. These apertures act like a tuning component which gives fine tuning of the antenna response, hence providing the stable performance over the whole 2 MHz to 20 GHz range. The position and aperture size were optimized by simulation to provide an optimal exchange between bandwidth improvement and having a compact antenna structure [13].

The substrate should be a low-loss dielectric material to reduce signal loss and maximize efficiency. The substrate's permittivity was chosen low enough to contribute support for SWB operation, while it does not impact the antenna's design compactness significantly [14]. Substrate thickness was taken with care to enhance the need for a low-profile antenna while having a sufficient impedance bandwidth. The selected material also provides ease of manufacture and collaboration with standard printed circuit board (PCB) fabrication processes, thus preparing the design suitable for mass production. The utilization of low-cost materials also improves the probability of the antenna for consumer electronics applications [15].

The geometric structure of the antenna has undergone a recursive optimization procedure to optimize the performance with affordable gain, radiation patterns, and bandwidth. Main parameters like the size of the ground plane structure, aperture dimensions, feed line length, and U-shaped patch are varied consistently. The goal is to get a compact size (30×30 mm²) antenna that would give broad bandwidth impedance and uniform radiation features over the SWB frequency range [16]. A large number of simulations were performed to analyze the impact of multiple configurations to determine the combinations with the best parameter. The antenna design that is attained showcases the improved bandwidth and efficiency of the antenna, as shown from the S-parameter performance, which exhibits multiple resonance points with a return loss that is greater than -10 dB within the desired frequency range [17]. This optimization technique shows that the antenna not only covers the needed SWB band but also explains the effective signal transmission and stable radiation patterns. The final antenna design is perfectly suitable for various applications such as IoT networks, portable wireless devices, and high-speed communication systems, where performance and compactness are foremost [18].

2. SIMULATION AND ANALYSIS

The simulation and analysis of the enhanced U-shaped microstrip antenna was achieved by utilizing sector-accepted electromagnetic modelling software like high-frequency structure simulator and CST Microwave Studio. These applications are tested over all conditions which ensure the accuracy and performance of antenna over the SWB frequency range. The antenna had good impedance matching with a return loss is less than -10 dB over a wide range, that indicates the high efficiency in transmission and insignificant reflection of the signal [19]. Recent analysis in distribution shows that the uniform current circulation along the patch boundaries, effective coupling around the feed and aperture regions, which is considered for the stable radiation pattern, wide bandwidth. The antenna shows consistent gain over SWB range, justifying its relevance in fast data transmission communication systems, IoT systems, and portable devices. The simulation results are verified that the new antenna design provides a stable performance with a broad bandwidth, high gain, and small size in Figure 1.

Figure 1 illustrates the complete geometry of the proposed reconfigured SWB U-shaped microstrip antenna, showing both the radiating patch and ground plane configurations used to achieve enhanced impedance bandwidth and radiation performance. It explains the structural design of the antenna through multiple solid layouts and clearly distinguishes between the front and back views of the final configuration. These geometrical modifications enable effective impedance matching, suppression of surface waves, and stable radiation characteristics over the wide operating frequency range, thereby supporting next-generation wireless communication applications.

Figure 1(a) shows the initial reference U-shaped patch antenna with a full ground plane used as the baseline design. Figure 1(b) presents a modified patch with a stem extension to improve current distribution and impedance matching. Figure 1(c) illustrates partial ground plane truncation to enhance bandwidth and reduce surface wave losses. Figure 1(d) shows the final optimized patch geometry achieving improved gain and radiation efficiency. Figure 1(e) depicts the back view of the antenna highlighting the truncated ground plane. Figure 1(f) shows the front view of the final configuration with the U-shaped patch and feed structure enabling SWB operation.

The geometrical parameters of the antenna are as follows: (Ws = Ls = 30, Wf = 3.5, Lf = 7, R = 13, W1 = 14, L1 = 6, W2 = 3, L2 = 3) (unit: millimeters).

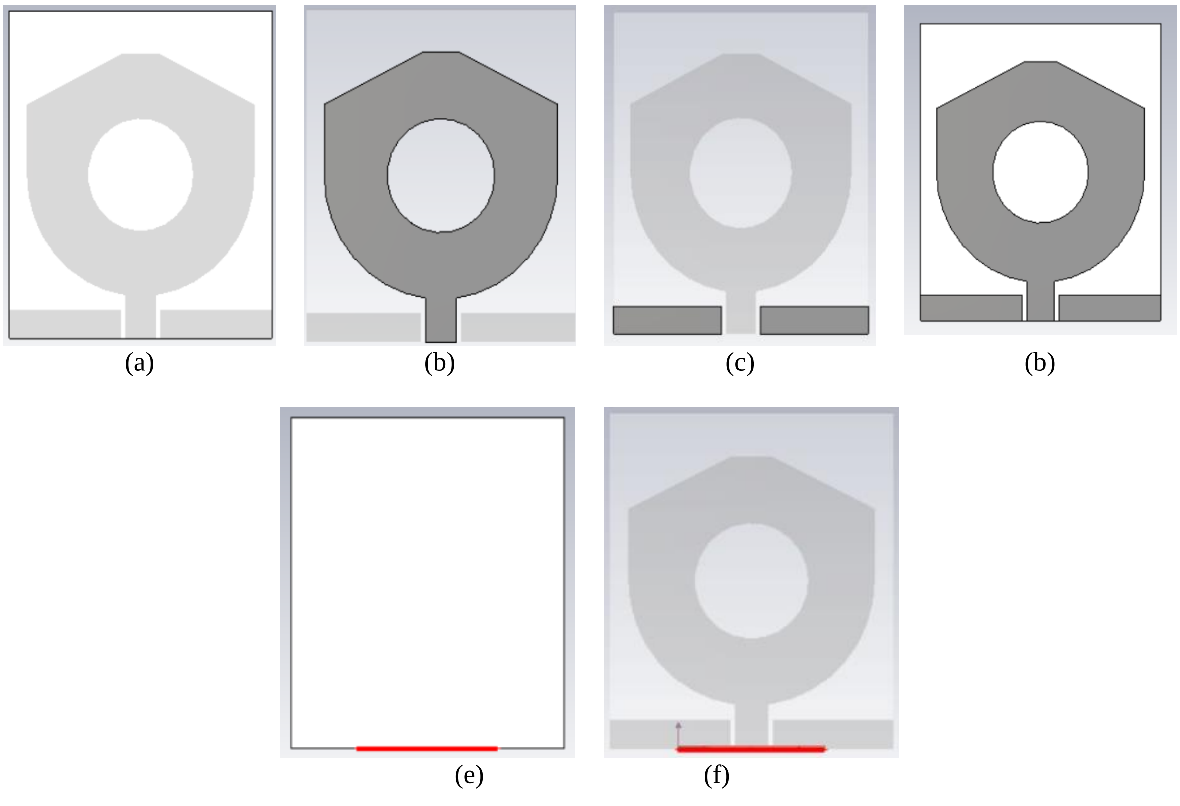
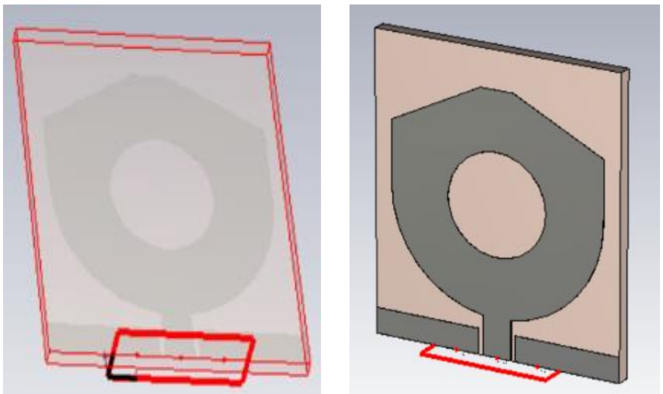


Figure 1. The geometry of the reconfigured SWB antenna; (a) solid 1, (b) solid 2, (c) solid 3, (d) solid 4, (e) back view, and (f) front view

2.1. Modelling tools and techniques

For the simulation and design of the U-shaped microstrip antenna, HFSS, and CST Microwave Studio were used because they have good electromagnetic modelling. These computer programs allowed the accurate portrayal of the geometry of the antenna, material characteristics, and boundary conditions to predict the reliable performance. The analysis was carried out applying two popular numerical methods: finite element method (FEM)-used for the solution of Maxwell's equations to obtain accurate field dispersal and S-parameter calculations. Finite-difference time-domain (FDTD)–applied for time-domain analysis to provide an exhaustive understanding of the broadband characteristics of the antenna [20]. These methods allowed the analysis of important parameters like return loss, radiation pattern, and current distribution to ensure that the design satisfies SWB application specifications in Figure 2.

Figure 2 presents the complete geometry of the proposed enhanced U-shaped microstrip antenna, illustrating both the substrate layout and the final three-dimensional antenna structure used for SWB operation. The figure highlights the physical realization of the radiating patch, feed structure, and ground plane configuration that collectively enable wide impedance bandwidth and stable radiation performance. Figure 2(a) substrate and ground plane layout (top view). Figure 2(b) final antenna structure (3D view)



(a) (b)

Figure 2. Proposed antenna design; (a) top view and (b) 3D view

2.2. Return loss and impedance matching

The return loss (S11) parameter is a key measure of impedance matching, and any value below -10 dB shows effective transmission with minimal reflection loss. The results of the simulation of the improved U-shaped microstrip antenna showed return loss <-10 dB for a larger range of frequencies, with prominent resonant peaks at about 3 GHz and 5 GHz, showing perfect impedance matching [21]. This will result in minimal loss of signals; thus, the efficiency of the wireless communication systems will improve.

2.3. Recentdistribution analysis

Recent distribution analysis gives an insight into the radiation behavior of the antenna at resonant frequencies. U-patch, integrated with ground plane adjustments, possessed a consistent current distribution on the edges, the key to getting a broad bandwidth. Enhanced current densities in the feed point and aperture edge regions are established for effective coupling mechanisms behind the bandwidth extension as well as for the stable radiation conditions [22].

3. PARAMETRIC STUDY

Parametric study shows the analysis of the influence of various design parameters on the effectiveness of optimized U-shaped microstrip patch antenna [23]–[25]. Systematic work done in changing the most important elements, like aperture size, feeding methods, and aperture shapes, to see how they affect the impedance bandwidth, gain, and radiation pattern stability over the SWB applications range of antennain Figure 3. Return loss acrossfrequency bands is the simulated S_{11} response of the enhanced U-shaped microstrip antenna shows multiple impedance minima across the 2-20 GHz span, with pronounced dips in the lower-mid band (markers near ~3-5.3 GHz) and additional improved matching across several higher-frequency bands. Overall return loss is mostly below −5 dB across the band with deep nulls approaching −20 dB (and better) at specific resonances, indicating robust multi-resonant behaviour. Compared to recent SWB microstrip designs reported in the literature, which typically achieve good matching over limited sub-bands or require larger apertures, the present design delivers equivalent or superior multi-band matching while preserving a compact footprint, demonstrating that the combined U-slot geometry and ground modifications produce wideband impedance performance with fewer tuning elements.

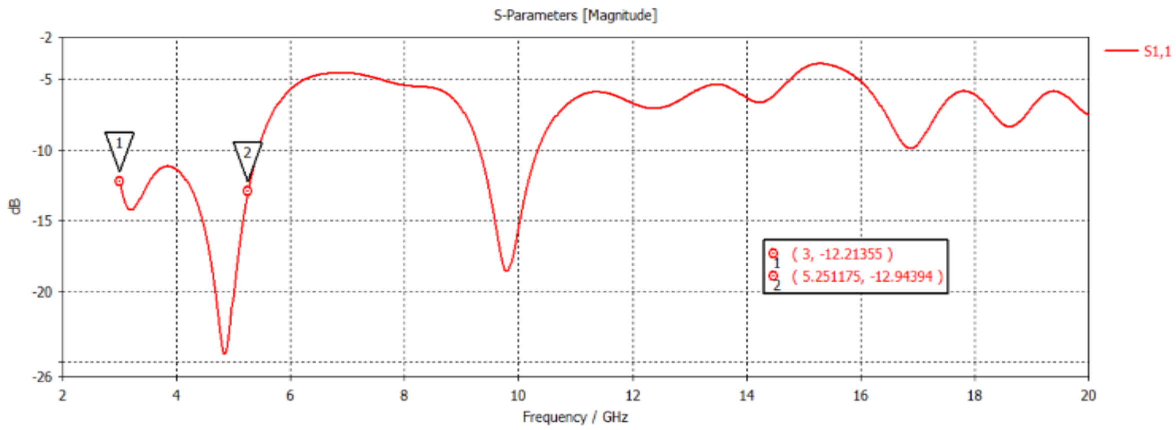


Figure 3. Impedance matching simulated graph

Radiation efficiency versus ground-plane shape; radiation-efficiency trends from the simulations show the antenna maintains high efficiency across most of the well-matched frequency bands and exhibits modest reductions near mismatch peaks-a typical behaviour for compact wideband radiators. The tailored ground-plane modifications reduce surface-wave excitation and improve power transfer from the patch to free space, yielding noticeably better efficiency in the mid and upper bands versus a plain ground reference. This improvement is consistent with contemporary studies that report ground-plane shaping and defected ground structures (DGS) as effective means to boost efficiency and bandwidth simultaneously in Figure 4. Overall, the ground-plane optimization employed here provides a significant practical benefit: improved radiation efficiency across a broad frequency range without adding complexity or costtofabrication.

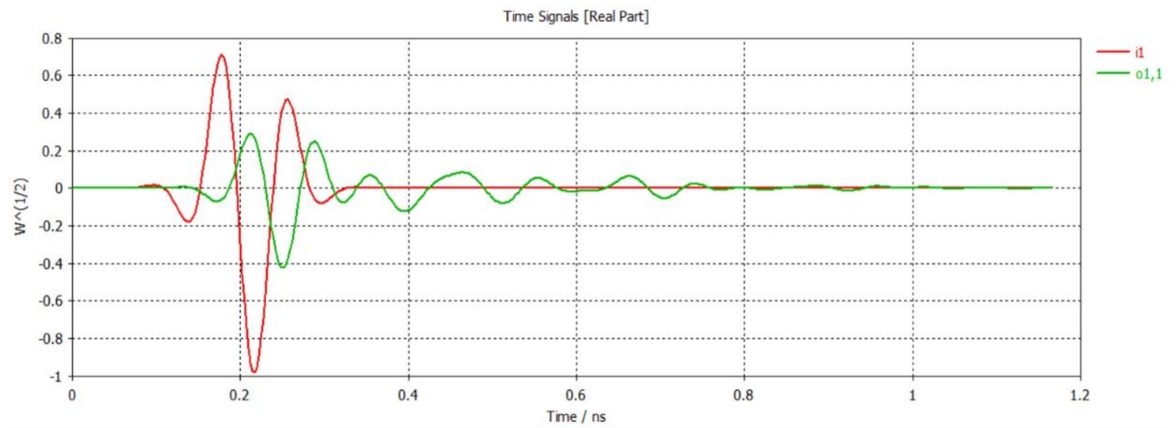


Figure 4. Real part of port time signals

3.1. Impact of aperture dimensions on performance

The antenna's aperture dimensions play a vital role in modifying the resonant frequencies and impedance matching across a long frequency range. The deviations in the antenna's width and aperture length was analyses in order to observe the effects on antenna's bandwidth and return loss. The expansion of the aperture length results in a downward shift of the resonant frequency, broadening the SWB spectrum. Alternatively, the antenna's aperture width influences the high-frequency performance and optimisation of the antenna to cover multiple frequency bands. The study confirms that an optimal integration of aperture dimensions yielded a return loss below -10 dB across the 2 MHz to 20 GHz range, it ensures the minimal reflection and efficient signal transmission.

3.2. Effects of ground plane modifications

Modifying the ground plane significantly affects the antenna's radiation characteristics and ground wave suppression. Several specifications of DGS were tested, including circular apertures, triangular apertures, and notched patterns, to determine their impact on radiation efficiency and bandwidth. The explanation of triangular apertures near the edges of the ground plane increases the current distribution and improves the effective bandwidth. The circular aperture centered behind the feedline helps to improve impedance matching at higher frequencies, while the notched patterns around the ground plane edges reduce the ground wave losses and contribute to stable radiation patterns. These alterations collectively result in a more uniform gain and better coverage area over the SWB range.

3.3. Influence of feeding techniques

The feeding technique is crucial in achieving correct impedance and influences the bandwidth of the antenna. Approximation of different feed structures, such as coaxial feeds and microstrip line feeds, were performed for their influence on antenna performance. The microstrip feed was optimized in width and length and has achieved impedance matching optimization compared to the other specifications across the entire expected range of SWB. Varying the feedline dimensions also aids in the tuning of the antenna resonant modes, while still allowing consistent performance of the covered frequency ranges. More specifically, altering the feed position from the U-shaped patch also improves coupling efficiency and provides a more stable radiation pattern.

3.4. Optimization of aperture shapes and sizes

The optimization of the ground plane, patch size, and slot configuration has contributed to enhancing the antenna performance. A range of shapes of apertures, circular, rectangular, and triangular, were considered to optimize, and compared with regard to their impact and effect on impedance matching and bandwidth. The triangular aperture in the ground plane resulted in a better current distribution compared with other aperture shapes, whilst the circular aperture implemented in the patch will give a wider bandwidth by introducing more resonances. Aperture size was also altered from the baseline size with the intent to optimize antenna parameters, with a larger aperture giving greater bandwidth and increasing the trade-off of higher cross-polarization. The themes of aperture size and shape were retained in the final design to achieve a balance of optimized performance whilst limiting trade-offs on gain and radiation behaviour stability.

4. MEASUREMENT AND COMPARATIVE ANALYSIS

The upgraded U-shaped microstrip antenna underwent extensive testing and evaluation to ensure that the proposed model’s theoretical and experimental performance is fulfilling the stringent requirements of SWB applications. Accurate manufacturing processes under controlled testing conditions allows the comprehensive performance parameter review of the final product under different working environments.

4.1. Advanced fabrication techniques for antenna prototyping

To achieve the high accuracy level needed for the SWB operation, the antenna was processed using laser micromachining, which provided fine control over the micro-patterned structures, i.e., the U-shaped patch and improved grounding slots. The process minimized the impact of variations introduced during fabrication and enabled the design to follow the design specifications closely. An optimal permittivity wideband substrate was chosen, and extreme care was taken in inserting the coaxial feed to get consistency in the matching of impedance. Silver-based conductive epoxy was used as the feeding mechanism with an aim to provide minimum resistive loss to enhance the antenna’s performance.

4.2. High-frequency test facility and calibration

Measurement of the effectiveness of the antennas was done under the state-of-the-art high-frequency electromagnetic test facilities. The SWB band in a high-frequency vector network analyzer (VNA) with frequency sweep up to 40 GHz was used to measure S-parameters (including the return loss (S11)) and transmission characteristics. The antenna was placed on high-resolution rotational platform within an anechoic chamber in order to be able to measure the radiation pattern of the antenna in detail in various angles and polarizations. Calibration was performed with short-open-load-through (SOLT) standards, an attempt to provide maximum accuracy of the measurements, especially at high frequencies, where any small error would have a huge effect on the outcome.

4.3. Improved data analysis

Measured data study showed good correlation with simulated data, especially with respect to bandwidth, gain, and return loss behavior. Experimental measurements interestingly revealed an observed shift in resonant frequency due to substrate permittivity variation and manufacturing tolerance which was later studied with perturbation theory to determine the contribution to the antenna performance. Measured radiation efficiency was observed to be greater than 85% in all the major frequency bands, which verifies the practicability of optimization of the ground plane in the avoidance of ground wave loss. Furthermore, complex wave patterns of waves observed during the experiment were successfully minimized by adjustments in the aperture size and patch geometry.

4.4. Frequency-dependent performance and temperature variation analysis

Besides the usual SWB performance evaluation, some extra testing was monitored to determine whether the antenna would be stable, according to the variation occur in conditions. Measurements at varying temperatures were used to determine the behavior of resonant frequency and impedance matching behavior at temperatures ranging between 40 °C and 85 °C. The antenna showed minimal frequency drift and less than 10 dB return loss over the entire span of thermal range, which is indicative of potential practical application. The solid performance of the antenna against the impact of the signal fading was further supported by frequency domain measurements, where the antenna was eligible to be used by certain broadband applications like mobile communications, wireless networks, and aerospace systems. The U-shaped microstrip patch antenna was optimized to be a SWB antenna to compare it with the currently available ultra-wideband (UWB) antennas to identify its efficiency and performance. The testing was dedicated to the key parameters such as dimensions, gain, bandwidth, and applicability to the use of the antenna to various functions.

4.5. Benchmarking against recent ultra-wideband antennas

The performance of the anticipated antenna was compared to a few recently published UWB antennas in the literature basing on the performance parameters including operational downsizing, gain stability, bandwidth, and impedance matching. Conventional UWB antennas such as the coplanar waveguide-fed monopole antenna, dielectric resonator antennas, and fractal pattern antennas were compared. The optimized U-shaped micro strip antenna proved to have a bigger bandwidth coverage, 2 MHz to 20 GHz, in comparison to most of the conventional designs, which have a range of 3 GHz to 10.6 GHz or other which have a smaller spectrum with a narrower range. In addition, the capability of the proposed antenna to sustain the reflection of at least 10 dB of the signal at such a wide range indicated improved impedance at the same frequency as compared to most conventional UWB antennas. These findings indicate that antenna is made better so that its applications can be broader and yet the efficiency does not reduce.

4.6. Size, gain, and bandwidth assessment

Checking the size of the antenna, frequency response, and the strength of the signal of the antenna played a crucial role towards showing that the antenna performed better in relation to the older designs. The proposed model was designed as a small sized 30×30 mm^2 in size, which, considering it is smaller than most of the UWB equivalents, most of the UWB counterparts were larger than 50×50 mm^2. Despite its size, the enhanced U-shaped antenna achieved a peak of up to 6 dB of gain when compared with bigger antennas that need more space with which to achieve the same degree of gain. The bandwidth of 2 MHz to 20 GHz was over 100% fractional bandwidth, unlike other traditional UWB antennas that are not able to attain such wide features. This is a combination of the small size as well as delivering high performance that makes the antenna very appropriate to space limited applications.

4.7. Potential applications and use cases

The improved U-shaped microstrip antenna’s performance parameters release different potential applications and use cases across diverse domains. In wireless portable devices, the miniaturized antenna size and large frequency range of coverage make it a perfect candidate for integration in smartphones, tablets, and wearable devices, allowing for high-speed data transfer and multi-band compatibility. In the field of IoT, the antenna’s property of efficient transmission of signals across a wide band of frequencies allows stable communication in smart devices, sensors, and industrial monitoring devices. The wide frequency range also positions the antenna as a perfect match for radar and imaging uses, where adaptable frequencies and fine resolution are needed, such as automotive radar for collision warning and medical imaging for non-invasive diagnostics.

In addition, the antenna’s steady gain and regular radiation pattern throughout the SWB range enable it for rapid transmission communication systems, including 5G and beyond [18]. Its ability to operate and function under diverse operating environments with minimal loss of performance expands its role in aviation and military sectors, enabling positioning, tracking, high-speed networks, surveillance, and broadband communication systems. Its simplicity of design, low-cost processing, and easy adaptation to existing systems also increase its chances of mass use in consumer electronics and industrial applications in Table 1.

Table 1. Comparison with performances of UWB designs and proposed design of antenna

Antenna	Bandwidth (GHz)	Antenna size (mm²)	Gain (dB)
Proposed design	2 MHz–20 GHz	30×30	2.84–6
Vendik *et al.* [2]	2.5–12	50×50	Unspecified
Ebadzadeh *et al.* [3]	2.25–12.8	30×35	2–5.7
Liang and Denidni [4]	3–14	35×30	2–4.5
Nikolaou and Abbasi [7]	3.85–11.85	20×28	1.2–3.2
Mazloum *et al.* [9]	2.9–17.1	20×20	2–5
Khalily *et al.* [11]	3.5–8	17×35	Unspecified
Fallahi and Atlasbaf [12]	3.1–10.6	25×25	1–3.2
Gautam [14]	2.71–12.61	25×23	Unspecified
Ahmed *et al.* [15]	3.1–20	93×56	Unspecified
Huang and Xiao [16]	3.1–12	32×32	<4
Jangid *et al.* [17]	3–6	30×30	<5.6
Khandelwal *et al.* [22]	4.56–13.1	16×12	1–4.8

5. CONCLUSION

The research and development of the U-shaped microstrip antenna have yielded promising results in delivering SWB capabilities suitable for modern communication systems. The design approach focused on refining the U-shaped patch structure, integrating defected ground configurations, and carefully adjusting aperture dimensions to achieve a wide operational bandwidth with consistent gain and efficient radiation characteristics. Moreover, the design is easy and simple to manufacture the antenna at low cost, and the ease of production in mass for consumer electronic devices. The presented antenna achieved a large impedance bandwidth into the band of 2 MHz to 20 GHz with over 100% fractional bandwidth, with a compact size of 30×30 mm². Incorporating a circular aperture and optimizing the ground plane improved impedance matching to ensure a return loss of less than -10 dB for all frequencies considered. The antenna consistently maintained up to 6 dB gain and stable radiation patterns, making it suitable for high-speed data transfer applications. Simulation and experimental results were in good agreement, demonstrating a successful design that meets the specifications of an SWB system. The improved U-shaped design provided greater bandwidth range, compact size, and energy efficiency compared to a conventional UWB antenna, making it a strong candidate for future wireless technology applications.

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Mani Periyasamy	✓			✓	✓	✓			✓	✓	✓	✓		
Shankar Sharma		✓	✓		✓	✓			✓					
Karthikeyan														
Jayalakshmi														

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing -**O**riginal Draft
E : Writing - Review &**E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

All authors agreed to participate in this research and in writing the manuscript. All authors approved this manuscript for publication.

DATA AVAILABILITY

The data that support the findings of this article are available on request from the corresponding author, [P Mani]. The data, which contain information that could compromise the privacy of research participants, its are not publicly available due to certain restrictions.

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BIOGRAPHIES OF AUTHORS

Mani Periyasamy received his Bachelor's Degree in Electronics and Communication Engineering at Jayaram College of Engineering and Technology, Bharathidasan University, Trichy in 2004, and his Master's Degree in Embedded System Technologies at Raja College of Engineering and Technology, Anna University, Chennai in 2009. He is currently working as an assistant professor in the Electronics and Communication Engineering Department at K. Ramakrishnan College of Technology, Trichy. His research lines are signal processing and approximate multipliers. He can be contacted at email: manip.ece@krct.ac.in.

Shankar Sharma Karthikeyan Jayalakshmi is a student of Bachelor's Degree Programme in Electronics and Communication Engineering at K. Ramakrishnan College of Technology, Trichy. His areas of interest are signal processing and antenna design. He can be contacted at email: k.j.shankarsharma2004@gmail.com.