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Review on Bandwidth Enhancement Techniques in Ultra-Wideband (UWB) Planar Antennas

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ABSTRACT

Ultra-wideband (UWB) antennas have grown into fundamental constituents in advanced wireless applications owing to their ability to support significantly wide band frequencies demanded to achieve accelerated communication, radar, sensing, and imaging applications. However, achieving a broad and stable characteristic impedance bandwidth while keeping small-sized, tolerable gain, and stable radiation characteristics persists a considerable design challenge. To handle these challenges, the researcher has been centered on bandwidth enhancement techniques. This review paper presents an extensive survey of bandwidth improvement techniques utilized in UWB antenna designs published between 2018 and 2025. The reviewed techniques are methodically categorized into geometry-based techniques, ground-plane modification, optimized feeding methods, and the integration of electromagnetic configurations such as defected ground structures (DGS), frequency-selective surfaces (FSS), metamaterials, and fractal geometries. In addition, hybrid and optimization-assisted design techniques are explored due to their enhanced significance in achieving high-performance wideband. A comparative analysis of representative implementations is provided to demonstrate the performance, advantages, and trade-offs related to each technique. Finally, essential challenges and future research directions are determined to support the advancement of optimized UWB antennas for next-generation wireless applications.

Keywords: Ultra-wideband (UWB) antennas, Bandwidth enhancement, Impedance bandwidth, Defected ground structure (DGS), Hybrid antenna design.

1. INTRODUCTION

Ultra-wideband antennas play a key role in a wide range of advanced systems, such as radar, electronic warfare, medical imaging, and broadband wireless communication applications **(Schantz, 2005; FCC, 2002).** One of their primary benefits is the capability to operate with

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a comparatively simple RF front-end design, which minimizes system complexity and production cost. Wideband antenna structures systems are described by their wide range of operating frequencies. The precise bandwidth is generally defined by the specific system operational requirements and the designated center frequency **(Batra et al., 2004)**. Patch antennas have been extensively utilized in UWB configurations due to their low manufacturing cost and ease of implementation, making them particularly suitable for computational complexity and compact devices. The researchers have analyzed multiple patch configurations such as circular, triangular, and elliptical shapes to acquire a broader bandwidth frequency. Besides, geometrical adjustments to the ground layer, including shape-based taper and implemented etched slots, have been employed to increase impedance matching over abroad-band frequency spectrum **(Lee et al., 2005)**. While these performance improvements occur, growing necessity for wider bandwidths and antenna compactness remains to encourage research studies. In typical structures, the radiating patch is generally located on top of a rectangular ground plane that is implemented on the substrate where the ground or patch layer is etched with diverse shapes of slots to optimize bandwidth and antenna performance **(Jaglan et al., 2018)**. To overcome bandwidth restrictions, the literature presents various advancement techniques, for example etching slots on the radiating patch surface or the ground surface, employing defected ground structures (DGS), and incorporating multi-layer to introduce additional resonances and increase matching. However, for modern technologies, the researchers use to design meta surface and precisely designed resonant elements, in order to expose the frequency range as well as improving gain and polarization for 5G applications **(Lee et al., 2023; Singh et al., 2024; Singh et al., 2025)**. This work provides an overview of recent studies published between 2018 and 2025, where bandwidth enhancement methods are classified into geometry modification, ground plane improvement, and feeding techniques, in addition to electromagnetic configurations such as defected ground structures (DGS), frequency selective surfaces (FSS), metamaterials, and fractal geometries.

Wideband antennas have recently achieved significant interest due to their capability to provide high-data-rate communication and reliable localization. These characteristics make these systems suitable for next-generation wireless communication applications, including fifth generation (5G) networks, mobile communication devices, and Internet of Things (IoT) applications. In IoT systems, antennas enable reliable connectivity among a large number of interconnected devices used in smart homes, healthcare monitoring, and industrial automation **(Khan et al., 2024).** Furthermore, ultra-wideband (UWB) technology has been integrated with modern sensing platforms and 5G networks to enable advanced applications such as motion tracking and radar-based detection systems **(Martín-Sacristán et al., 2025).** In addition, flexible UWB antennas have been widely investigated for wearable systems and body- worn communications due to their compact size and stable radiation characteristics **(Jhunjhunwala et al., 2022)**. Recent studies show that improving UWB antenna bandwidth is based on geometrical modifications, optimized feeding techniques, and material choices to ensure stable operation. However, attaining broad bandwidth while preserving miniaturized, low distortion, and effective radiation remains a major challenge. These limitations motivate persistent research toward optimized antenna designs that balance performance, miniaturization, and practical implementation **(Rafique et al., 2022).** According to recent literature on UWB phased array antennas focus on enhancing wideband performance while minimizing mutual coupling, sidelobes, and gain fluctuation during beam steering. Several array types, including Vivaldi, coupled, metallic, helical, and meandered structures, have been analyzed, each providing different design compromises between bandwidth, gain, and polarization. High-gain characteristics are mainly based on coupled or metallic arrays, whereas helical and meandered antennas are selected for low-gain wideband operation due to their stable polarization characteristics **(Latha et al., 2021)**. Also the reviewed work surveys recent advances in wideband antenna models for current communication systems, it emphasizes essential challenges such as reaching wide impedance bandwidth, reducing radiation distortion, and keeping stable performance over a wideband frequency range, the study discusses several antenna design , including microstrip, slot, and notched designs, used to limit spurious frequency bands, design enhancements such as adapted patch geometries, optimized feeding methods, and ground-plane modifications are highlighted as effective approaches, the survey shows that meticulous structural optimization is key to achieve compact, efficient, and broadband antennas **(Kumar and Surekha, 2017)**. The paper reviews high-voltage antennas for IEMI applications and emphasizes essential challenges such as impulse distortion, dispersion, oversized antenna, and high-voltage breakdown, it describes that maintaining Pulse shape accuracy and handling very high voltages are the key design challenges to deal with these issues, researchers employ low-dispersion antenna shapes, enhanced impedance matching, dielectric insulation material, and reflector or array structures to increase gain, these solutions support enhance radiation efficiency and decrease distortion without increasing size **(Sanjay and Azeemuddin, 2021).** This review aims to present researchers and designers with a clear insight into recent trends in wideband MPA and to offer a significant contribution for the advancement of next-generation antenna **(Abd Hamid and Hock, 2025; Ahmed and Kabir, 2025).** The works considered in this review were recognized through a systematic search in major academic databases such as IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. The search emphasized publications associated with bandwidth enhancement in ultra-wideband (UWB) antennas using keywords such as microstrip wideband antennas, extended bandwidth, DGS, fractal antennas, metamaterials, and frequency-selective surfaces (FSS). In this review paper, the study was conducted on research published between 2018-2020, where all these studies dealt with the topic of improving bandwidth using certain techniques. These processes indicate that accomplishing effective bandwidth improvement is closely related to the ability of the antenna structure to support several resonant modes that overlap inside the desired frequency band for UWB antennas.

2. AN OVERVIEW ON UWB ANTENNA

Ultra-wideband (UWB) technology has evolved as a key contributor for a wide spectrum of modern wireless applications, containing large-bandwidth data transmission, radar systems, ground-penetrating radar (GPR), healthcare imaging, and short-range sensing. One of the most important elements in UWB technology is the antenna, which must provide a wide impedance bandwidth while preserving stable radiation properties, compact size, and suitable gain. According to statutory definitions, wideband systems typically operate over a bandwidth exceeding 500 MHz or a fractional bandwidth greater than 20%, which introduces stringent limitations on antenna design **(Darweesh and Yetkin, 2018).** Bandwidth enhancement in UWB antennas can be obtained through the integration of configuration modifications, Advanced material usage, and advanced feeding techniques. Among these methods, reconfiguring the antenna geometry by using etched slots, such as embedding U-slots, H-slots, or circular slots, has been verified effectively. These slots lead to additional resonant frequencies, which widens the bandwidth of resonant frequency while maintaining the antenna's miniaturized size **(Rafique et al., 2014; Mishra et al., 2022; Chair et al., 2005).** The technique to create wider bandwidth operation modes is reducing the effective permittivity by employing air gaps, which improves electromagnetic (EM) field propagation and enhances impedance matching. Moreover, defected ground structures (DGS) and partially grounded surfaces are highly effective in attenuating surface waves, which results in enhanced radiation efficiency and broader bandwidths **(Suvarna et al., 2021)**. The most prominent methods are designs inspired by metamaterials, such as split-ring resonators (SRRs) and materials with near-zero refractive index (NZRI). These elements are used to control the propagation of electromagnetic waves and adjust their resonant behavior, enabling the generation of additional operating states and contributing to a significant expansion in bandwidth and an overall improvement in the antenna's radiation performance **(Anitha et al., 2024).** Similarly, dielectric resonators (DRs) and dielectric substrate layers are employed as an effective tool to produce a controlled and regulated resonant effect, in addition to their prominent role in directing electromagnetic fields towards the intended direction of radiation. These Techniques improve the impedance features and overall radiation efficiency of antennas while assisting in extended bandwidth **(Gupta et al., 2023; Huda et al., 2023)**. Antenna array configurations employable (PBG) structures operate as EM filters that reject undesired modes coherent interference among antenna radiators to enhance radiation features over a wider bandwidth range. In addition, the techniques of frequency-selective surfaces (FSS) and photonic band control the operational bandwidth **(Matta et al., 2024).** Regardless of the intrinsic wideband property of many planar and monopole antennas, obtaining a continuous and stable impedance bandwidth through the whole UWB frequency range remains a demanding task. Practical restrictions such as impedance mismatch at spectrum range edges, surface-wave excitation, radiation pattern distortion, and increased losses often limit the achievable bandwidth. Therefore, extensive research attempts have been focused on evolving bandwidth improvement techniques that can mitigate these challenges without considerably increasing antenna size and with low fabrication complexity **(Hota et al., 2019).** Between 2018 and 2025, a significant number of studies have concentrated on bandwidth enhancement in UWB antennas by employing advanced design techniques. These techniques comprise radiator structure modification, ground-plane engineering methodology, enhanced feeding techniques, and the embedding of electromagnetic configurations such as frequency-selective surfaces (FSS), defected ground structures (DGS), metamaterials, and fractal geometries designs. Geometry-based strategies and ground modifications have been shown to excite multiple resonant frequencies, therefore widening the impedance bandwidth **(Yadav and Baudha, 2020; Ibnyaich et al., 2021**). In parallel, FSS- and metamaterial-aided designs have shown the capability to enable simultaneous enhancement of bandwidth and gain by regulating the electromagnetic environment surrounding the design antenna **(Darweesh and Yetkin, 2018; Swetha and Naidu, 2020; Al-Gburi et al., 2020)**. Although various review papers have focused on UWB antenna implementations in a wide meaning, a focused and systematic investigation of broad bandwidth techniques presented in recent years is still essential. In particular, a systematic classification of enhancement techniques and a comparative analysis of their performance are essential to guide future antenna design attempts, especially based on the accelerated development of combined and optimization-aided by techniques **(Din et al., 2023; Bouchachi et al., 2024)**. This review paper presents an extensive review of bandwidth enhancement techniques applied to UWB antennas during

2018 to 2025. **Fig. 1** presents a theoretical timeline chart that demonstrates the evolution of research directions in bandwidth improvement techniques for ultra-wideband (UWB) antennas over the duration from 2018 to 2025. This approach, published studies were examined and classified according to the main design techniques implemented to improve impedance bandwidth. These techniques include structural modification of the radiating patch, ground-plane design, and optimization of feeding configurations, and the use of electromagnetic structures such as defected ground structures (DGS), frequency-selective surfaces (FSS), metamaterial elements, and fractal geometries. The time-based arrangement presented in the figure demonstrates the research direction observed in the surveyed literature and illustrates how different design approaches have gradually developed and evolved over recent years.

The main contributions of this work are summarized as:

- A methodical classification of bandwidth enhancement techniques based on design concepts and physical mechanisms behaviors.
- A comparative evaluation of standard UWB antenna designs existing in recent literature.
- An important analysis of design challenges, trade-offs, and future study paths for wideband UWB antennas.

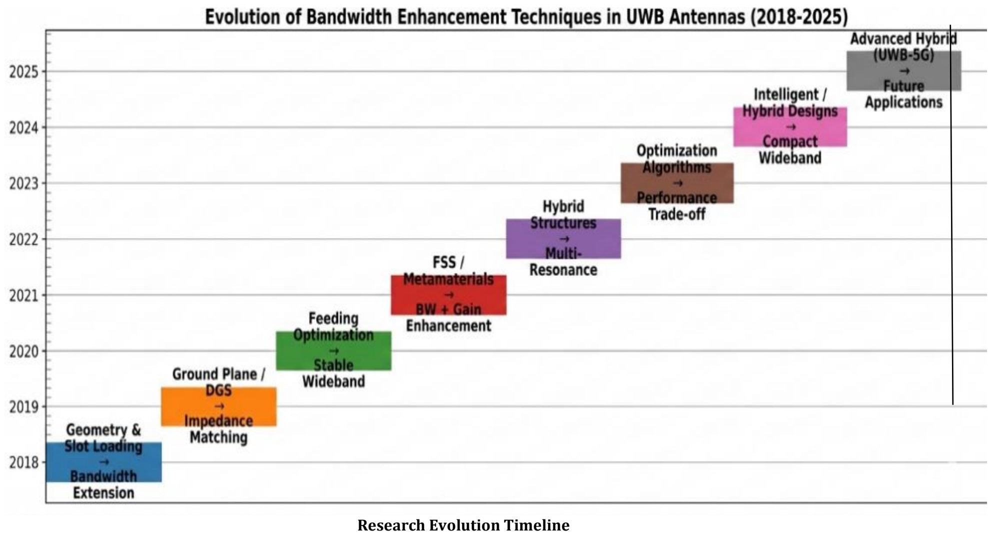

Figure 1. Evolution of Bandwidth Enhancement Techniques in UWB Antennas (2018–2025).

The previous figure discusses the developments in technologies related to bandwidth enhancement during the period between 2018 and 2025, as the detected ground plane (DGS) technology increases the effective length by adding these slots to the ground layer in planar antennas, creating multiple paths, which leads to the appearance of more than one resonance frequency, and these frequencies overlap to form a wide frequency band. Similarly, metamaterials and Frequency-Selective Surfaces (FSS) are considered examples of electromagnetic structures that reshape the effective electromagnetics surrounding the antenna, thereby improving radiation performance and impedance matching, which leads to an improvement in bandwidth. Therefore, understanding the essential electromagnetic processes is important for designing high-efficiency UWB antennas that obtain a wide bandwidth while preserving acceptable radiation efficiency and consistent radiation properties.

3. FUNDAMENTALS OF ULTRA-WIDE-BAND ANTENNAS

The Ultra-wideband operation is determined by regulatory bodies, for example, the Federal Communications Commission (FCC), which indicates that UWB technology must demonstrate that the bandwidth or a fractional bandwidth greater than 500 MHz or exceeding 20%, respectively. For antenna designers, this demand contributes to attaining an input reflection coefficient |S11| below −10 dB across a wide frequency response, typically from 3.1 GHz to 10.6 GHz for largely commercial UWB applications. The fractional bandwidth (FBW) is generally given by Eq. (1):

$$FBW = \frac{f_H - f_L}{f_c} \times 100\% \tag{1}$$

Where

f_H : Upper cutoff frequency.

f_L : Lower cutoff frequency.

f_c : Center frequency.

Attaining a high FBW while sustaining stable antenna performance is the main aim of UWB antenna design, specifically in compact printed geometries **(Mishra and Beg, 2022)**. While impedance bandwidth is the Key parameter in UWB antenna design, various other performance factors are strongly associated with bandwidth enhancement techniques. These consist of radiation pattern stability, gain fluctuation within the operating range, radiation efficiency, and time-domain performance. Stable radiation characteristics in UWB antennas generally reflect the preservation of stable radiation behavior over the operating bandwidth. Major evaluation factors contain radiation pattern distortion, cross-polarization levels, gain change over frequency, and radiation efficiency. Keeping these factors within allowable limits provides dependable antenna performance for wideband communication systems. Extremely wide operating bands attained through extensive geometrical alterations may produce degraded radiation patterns or reduce efficiency, specifically at higher frequencies. Furthermore, wideband technology is generally based on short-duration waveforms; therefore, antenna designs minimize signal interference and group delay variation within the operating range. Various recent research works have emphasized that optimized bandwidth improvement techniques should not only broaden the impedance bandwidth but also preserve stable radiation behaviors and reasonable time-domain behavior **(Nejdi et al., 2023).**

4. CLASSIFICATION OF BANDWIDTH ENHANCEMENT TECHNIQUES IN UWB ANTENNAS

4.1 Geometry-Based Techniques for Bandwidth Enhancement

Surface patch modification refers to one of the most efficient and widespread methods for improving the bandwidth of UWB antennas. By reshaping the geometry of the radiating element as shown in **Fig. 2**, multiple resonant patterns can be generated and combined to achieve continuous wideband operation. Modified planar shapes based on slots have been extensively analyzed due to their ability to precisely control surface current distribution and edge band performance **(Sandi et al., 2021; Al-Yasir et al., 2020).** Additionally, slot and stub loading techniques have shown their ability to enhance bandwidth performance by adjusting the current distribution on the patch **(Bhatia and Sharma, 2020; Yoo and Son, 2020).** As proven, compact dual-antenna elements with a geometry designed for the radiating element achieve an improvement in impedance bandwidth while maintaining stable radiation behavior **(Tan et al., 2019)**. Moreover, unconventional shapes for radiating elements, such as leaf-like, artistic, and circular shapes, have been introduced to significantly expand the operating range without increasing the antenna dimensions **(Kumar et al., 2019; Guebgoub et al., 2022)**. These designs rely on gradual impedance variations and effective current paths to improve matching within the frequency range of UWB antennas. Fractal-based shapes further improve bandwidth by increasing the effective electrical length of the radiator **(Devana et al., 2022)**. Circular and hybrid fractal antennas based on Peano curves and Sierpinski carpet configurations have shown excellent bandwidth performance. Integrated with high gain, preparing them compatible for compact UWB systems.

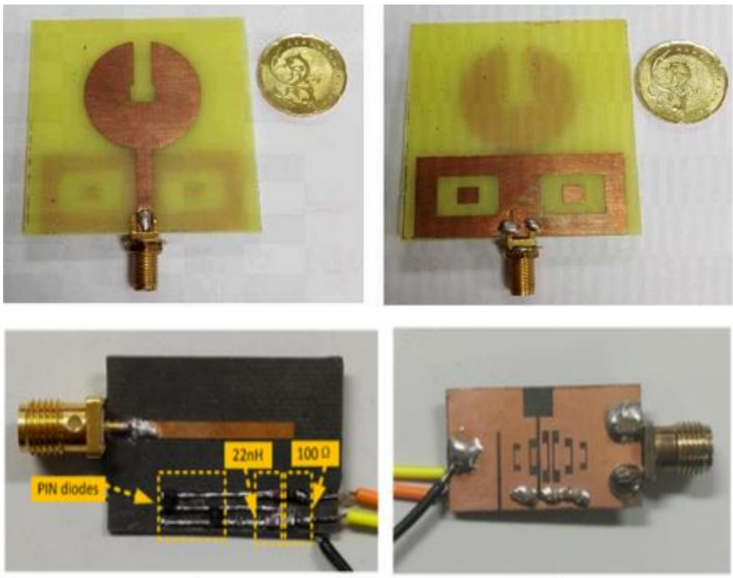

Figure 2. Examples of geometry-based bandwidth enhancement techniques in UWB antennas, including shaped radiators, slot loading, and fractal geometries **(Tan et al., 2019; Yang et al., 2019)**

4.2 Ground Plane Optimization and Defected Ground Structures

Ground plane optimization is another effective technique for bandwidth enhancement in UWB antenna design. Partial ground planes and defected ground structures (DGS), as shown in **Fig. 3,** are commonly adopted to reduce surface waves and insert additional resonant paths **(Kim and Nam, 2020; Ankush et al., 2018)**. The ground planes with corrugated and ladder-shaped have been demonstrated to substantially improve impedance bandwidth by adjusting the coupling between the radiator and the ground plane **(Baudha and Yadav, 2019)**. Furthermore, ground planes with different complicated geometries such as mace-shaped and slotted shapes, have shown enhanced wideband effectiveness by rearranging surface currents and optimizing impedance matching across a wide frequency range. Recent research has merged DGS with optimization approaches to improve bandwidth and radiation efficiency **(Babu and Anuradha, 2021)**. Specifically, the application of grey wolf optimization (GWO) allowed methodical adjustment of ground parameters, leading to improved bandwidth behavior without intensive manual optimization. These results emphasize the efficacy of ground plane modification as a cost-effective and easy-to-fabricate bandwidth enhancement technique.

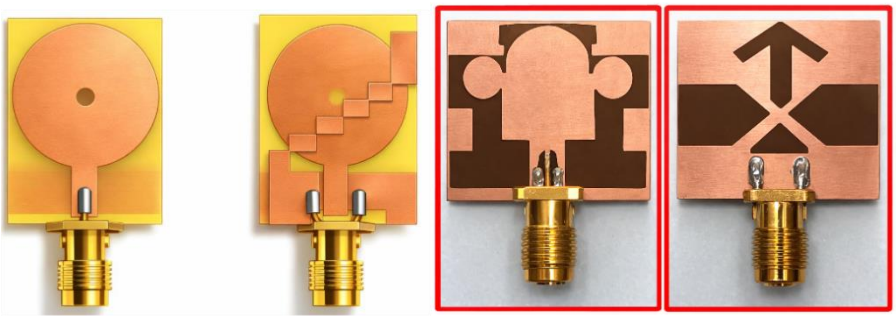

Figure 3. Typical ground-plane optimization techniques for bandwidth enhancement in UWB antennas **(Hota et al., 2019; Baudha and Yadav, 2019)**

4.3 Feeding Techniques for Wideband Operation

Feeding technique optimization plays a key contribution to improve impedance bandwidth in UWB antennas as shown in **Fig. 4**. Coplanar waveguide (CPW) feeding technique has achieved substantial wide adoption due to its inherent wideband behaviors, minimized radiation losses, and ease of merging with planar configurations **(Alqaisy et al., 2025; De et al., 2021).** Ultra-wideband (UWB) hybrid antennas that feeding is through common planar wave (CPW)with adjustment of the feeding dimensions, enabled obtaining a wider frequency range and achieving impedance matching **(Suraj and Gupta, 2020)**. Similarly, microstrip-feed line antennas have garnered significant research attention and have been extensively studied, particularly in planar and miniaturized designs for UWB applications **(Patel and Shah, 2020).** Cautious feedline optimization and impedance conversion techniques have allowed microstrip-fed antennas to accomplish wide bandwidth range while preserving stable radiation patterns, leading them to be appropriate for DS-UWB and mobile applications **(Sarkar et al., 2021)**. These studies verify that feeding optimization, when combined with structural alterations, is crucial for attaining reliable wideband behavior.

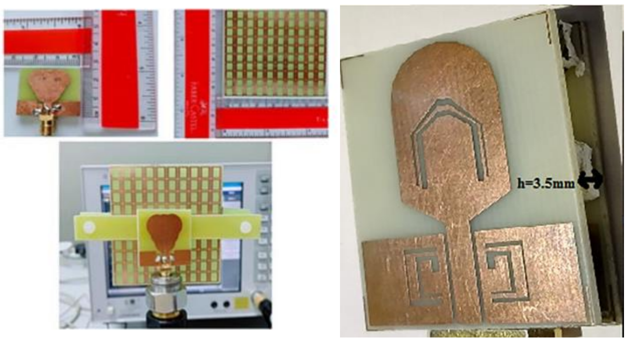

Figure 4. Common feeding techniques used to improve impedance bandwidth in UWB antennas **(Suraj and Gupta, 2020; Al-Gburi et al., 2020)**.

4.4 Parasitic Elements and Electromagnetic (EM) Structures

The embedding of parasitic elements and EM structures has been developed as an effective technique for improving bandwidth and gain concurrently, as shown in **Fig. 5**. Frequency-selective surfaces (FSS), when utilized as reflecting or Upper dielectric layers, improve impedance bandwidth by strengthening supportive interference and controlling radiation performance **(Pandhare et al., 2022).** Dual-layer and single-layer FSS structures have been demonstrated to considerably improve bandwidth and gain in UWB antennas, specifically for optimized-performance and ground penetrating radar (GPR) applications **(Kundu et al., 2018)**. Metamaterial-based designs have also proved significant improvements in bandwidth by controlling the efficient permittivity and permeability of the antenna surroundings **(Jairath et al., 2022; Rahman et al., 2025; Aucapina et al., 2018).** Such structures allow enhanced impedance, matching and bandwidth improvement without a considerable increase in dimensions.

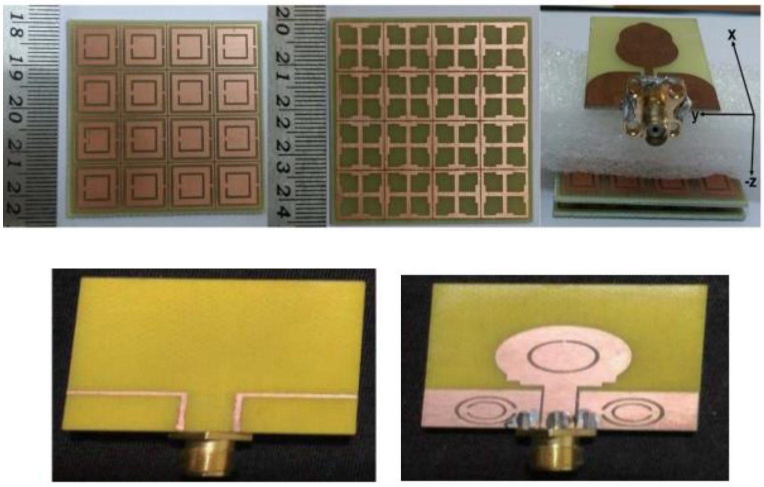

Figure 5. Bandwidth enhancement using electromagnetic structures such as FSS, metamaterials, and dielectric resonators **(Swetha and Naidu, 2020; Kundu et al., 2018)**

Moreover, hybrid antenna structures that integrate dielectric resonators with metallic patches employ multiple resonator-mode excitation techniques to achieve a broader operating spectrum, providing an effective solution for bandwidth enhancement in compact UWB antennas **(Song et al., 2019).** Metamaterial-based structures and frequency-selective surfaces (FSS) are broadly employed to improve antenna performance. Metamaterial-inspired designs primarily enhance bandwidth by altering the equivalent electromagnetic characteristics around the antenna and enabling additional resonant modes **(Saeidi et al., 2019; Dihaji et al., 2024**). In comparison, FSS designs are often utilized to improve antenna gain by acting as reflective surfaces that enhance radiation directivity. Consequently, metamaterials are commonly associated with bandwidth improvement, while FSS structures are particularly effective for gain improvement

4.5 Hybrid and Optimization-Assisted Technique

Recent studies indicate a developing attention in Hybrid bandwidth improvement that merged multiple design methods. By combining geometry alteration with ground plane design and EM structures as shown in **Fig. 6**, hybrid structures exhibit improved bandwidth performance relative to single-technique approaches. Optimization-supported techniques, including biologically motivated algorithms, have further improved bandwidth by methodically regulating key parameters **(Sarkar et al., 2023).** Hybrid fractal configurations, which merge self-similar geometries with engineered ground configurations, have exhibited enhanced bandwidth performance while preserving compact dimensions and high gain. These Techniques represent a promising approach for future UWB antenna development **(Attioui et al., 2025).** Optimization-based antenna design methods, including grey wolf optimization, evolutionary algorithms, and particle swarm optimization, have been broadly applied to improve bandwidth performance by automatically tuning antenna parameters. Although these methods can considerably improve antenna properties, they usually require iterative computations that increase both computational complexity and overall design time **(Elajoumi et al., 2019)**. In contrast, traditional techniques such as simple geometric modification or ground-plane adjustment require less computational processing, but their effect on performance enhancement may be relatively restricted. Consequently, hybrid design strategies combine various techniques in order to achieve improved antenna performance while maintaining an acceptable computational cost **(Sohi and Kaur, 2020; Akinola et al., 2019).**

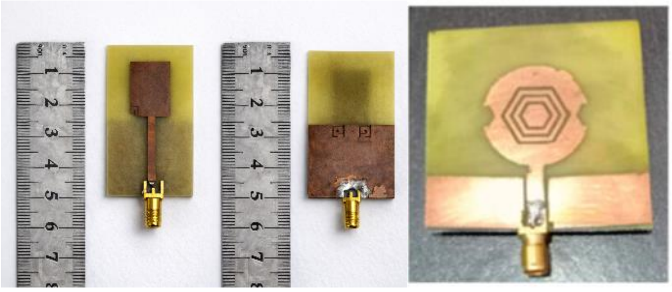

Figure 6. Hybrid and optimization-assisted UWB antenna designs for enhanced bandwidth performance **(Bouchachi et al., 2024; Singh et al., 2025)**

4.6 Band-Notched Techniques

Despite the key objective of UWB antenna design being to reach a broad impedance bandwidth, most practical applications demand the elimination of narrowband interference from surrounding wireless networks. The band-notched behavior is usually implemented using slots, stubs, or resonant structures, without negatively affecting the wide operating bandwidth. Many studies have shown that well-designed notch configurations can be integrated with wideband performance, achieving controllable frequency rejection while maintaining the performance of UWB antennas **(Abbas et al., 2020)**. Notch techniques, as shown in **Fig. 7**, which rely on slots and resonant elements, also provide precise control over the center frequency and bandwidth of the rejected bands. Multi-notch and reconfigurable designs have significantly improved flexibility, allowing antennas to respond to changing interference environments while preserving wide impedance bandwidth behavior **(Hammache et al., 2020; Chao et al., 2022)**. These observations demonstrate that bandwidth improvement and interference reduction can be accomplished in parallel through optimized resonant configurations.

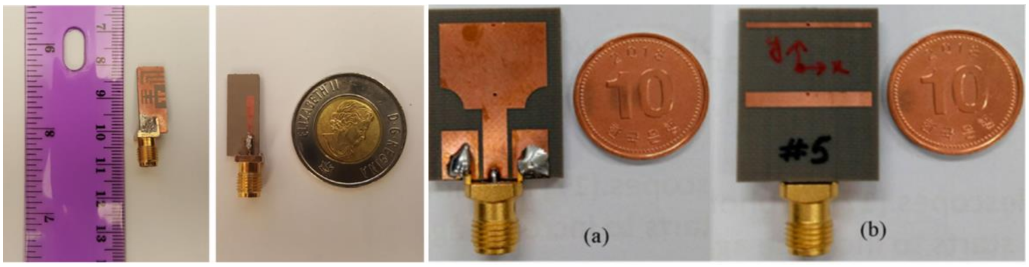

Figure 7. Illustration of band-notched mechanisms integrated within UWB antennas while preserving wide bandwidth **(Abbas et al., 2020; Hammache et al., 2020).**

4.7 MIMO-UWB Antennas Techniques for Bandwidth Enhancement

Multiple-input multiple-output (MIMO) ultra-wideband antennas are broadly used to enhance transmission channel capacity and improve link stability in advanced wireless systems. For example, compact MIMO configurations and parasitic structures improve impedance bandwidth and radiation stability **(Liu et al., 2015; Kareemulla and Kumar, 2023).** However, obtaining a broad impedance bandwidth while maintaining low mutual coupling between antenna elements persists as a design challenge. Multiple techniques have been presented to solve this issue, including slot modification of the radiating patch, ground-plane engineering using defected ground structures (DGS), and the use of decoupling structures to increase isolation and impedance matching. These approaches allow MIMO-UWB antennas to maintain wide bandwidth and reliable radiation performance in compact antenna systems **(Öztürk and Çimen, 2025**). A compact ultra-wideband MIMO antenna is shown in **Fig. 8**, formed of multiple radiating elements engineered to obtain a wide impedance bandwidth and improved isolation between antenna ports.

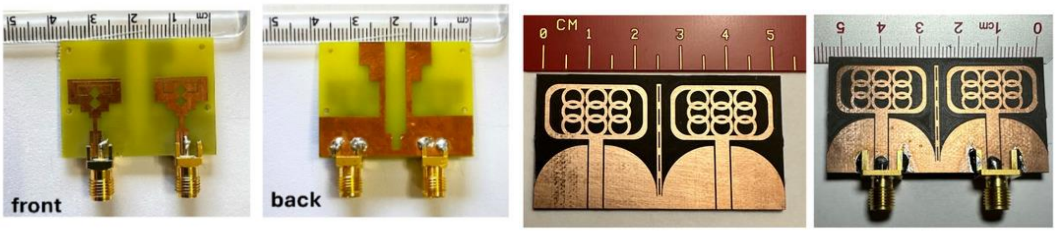

Figure 8. Example of a compact ultra-wideband MIMO antenna prototype **(Öztürk and Çimen, 2025; Kiani et al., 2023)**

5. COMPARATIVE ANALYSIS OF REPORTED UWB ANTENNAS

A comparative study of illustrative UWB antenna designs reported between 2018 and 2025 is presented in **Table 1.** The comparison emphasizes the efficiency of various bandwidth improvement methods in terms of operating bandwidth, gain, size, and design complexity. Geometry-based and ground-plane engineered approaches offer low-complexity and compact solutions, while FSS, metamaterial, and hybrid-based techniques achieve bandwidth and gain improvement at the expense of higher structural complexity. This study shows the possibility of combining multiple techniques in order to improve radiation performance in terms of achieving ultra-wide bandwidth, enhancing gain, and reducing size summarized in **Table 1.** It was analyzed that an antenna that relies on a single method to improve the frequency range, such as modifying the shape of the radiating element or adjusting the ground structure, achieves a frequency range of 110% to 130%, with a gain ranging from 3 to 5 dBi. For example, **(Nejdi et al. 2023)** antenna with circular polarization achieved a bandwidth of 113%, while the antenna proposed by **(Yadav and Baudha 2020)** achieved a bandwidth of 118% with gain improvement using a lightning-shaped ground plane technique. On the other hand, designs that use the damping feature with DGS work on significantly improving performance, the bandwidth of a defective ground structure (DGS) antenna optimized using the Grey Wolf Algorithm **(Bouchachi et al., 2024)** reaches about 162%. Similarly, the hybrid fractal configuration **(Attioui et al., 2025)** provides broadband performance with a gain of approximately 6.8 dBi isotropic.

Table 1. A Comparison of published UWB antenna designs between 2018 and 2025

Ref.	Antenna Type/	Size (mm× mm)	Bandwidth (GHz) Enhancement Technique	Gain (dB)	S11 (dB)	Beamwidth (°)	Key Contribution
(Darweesh and Yetkin, 2018)	Microstrip patch antenna	36 × 38	2.6 – 20 (138%) Metamaterial loading	5.6	−28	90	Simultaneous gain and bandwidth enhancement
(Kundu et al., 2018)	Leaf-shaped printed antenna	44× 44	3–14.64 (114%) Dual-layer FSS reflector	8.7	-25	80–90	Bandwidth and gain enhancement for GPR applications
(yang et al., 2019)	Compact slot antenna	17× 8	3.05-12 (118.9%) Slot engineering + band-edge selectivity	4.8	-30	85	Enhanced bandwidth with controllable band-edge behavior
(Tan et al., 2019)	Modified planar antenna	55× 56	2.2-12 (138%) Geometry modification	6.6	-27	N/A	Low-cost wideband antenna on FR-4 substrate
(Song et al., 2019)	Hybrid Dielectric Resonator patch antenna	17.6× 33.6	3.2-10.96 (109.6%) Dielectric resonator hybridization	2	-40	N/A	Multi-mode excitation for a wide bandwidth
(Baudha and Yadav, 2019)	Planar antenna	15 × 20	2.4-11.4 (130.4%) Corrugated ladder ground plane	3.5	-23	90	Ground-plane engineering for BW extension
(Hota et al., 2019)	Compact planar antenna	20×20	2.7-11 (121.16%) Modified radiator + ground	3.34	-40	N/A	Simple structure with enhanced bandwidth
(Abbas et al., 2020)	Rectangular UWB antenna	16 × 25	3.1–12.5 (120.5%) Tunable notch structures	4.5	-29	N/A	Wide bandwidth with controllable notched band
(Swetha and Naidu, 2020)	Printed antenna	53.15 × 53.15	3.16 – 15 (130.3%) FSS reflector	4.9-10.9	-10	N/A	Gain and bandwidth enhancement via FSS
(Al-Gburi et al., 2020)	Artistic monopole antenna	61×61	3.05–11.9 (118.4%) Single-layer FSS reflector	9.68	-46	N/A	Compact size with wide bandwidth and gain
(Yadav and Baudha, 2020)	Circular patch antenna	14×18	3.1 -12.13 (118%) Mace-shaped modified ground	3.2	-30	90	Bandwidth enhancement using ground modification
(Hammache et al., 2020)	Slot antenna	20.25 × 8	2.65 -11.05 (122.2%) Triple band-notched slots	4.5	-20	**85° – 95°**	Wideband operation with interference suppression
(Suraj and Gupta, 2020)	CPW-fed antenna	35.4 × 26.6	2.85 -11.45 (120.3%) Quad-notch + geometry tuning	4.2	< −10	80° – 95°	Enhanced bandwidth with stable radiation

(Sarkar et al., 2021)	Low-profile patch antenna	50 × 40	72% Feed optimization + geometry	5.08	< −10	85–95	Wide bandwidth suitable for DS-UWB
(Ibnyaich et al., 2021)	Pentagonal planar antenna	30 × 17.59	2.66-10.82 (121%) DGS implementation	4.5	-28	90	Bandwidth enhancement via defected ground
(Mishra and Beg, 2022)	Miniaturized patch antenna	30 × 30	3.1-10.6 (109.5%) Size reduction + matching optimization	3.3	-26	90	Compact wideband antenna
(Anand et al., 2022)	Stacked microstrip antenna	27 × 30	3.34-12.59 (116%) Stacked configuration	4.5-8	< −10	N/A	Multiple resonances for bandwidth extension
(Chao et al., 2022)	Miniaturized antenna	59.98×43.83	1.3-11.6 (159.7%) Tunable double band-notch	5.8	-50	N/A	Wide bandwidth with reconfigurable notches
(Din et al., 2023)	FSS-based antenna	30 × 30	3.3–10.8 (159.7%) Integrated FSS structure	3 - 8.1	-53	N/A	Significant bandwidth and gain enhancement
(Nejdi et al., 2023)	Circular fractal antenna	40 × 24.5	2.83–10.16 (113%)Fractal geometry	2.47 - 7.73	-45	N/A	Wide bandwidth with high gain
(Parveen et al., 2024)	Printed planar antenna	10×16	3.6 -14.6(120.9%) Geometry optimization	3.96	< −10	90	Simple printed structure for wideband operation
(Bouchachi et al., 2024)	Planar antenna	47×35	2.38–22.5(162%) DGS + GWO optimization	6.5	< −10	N/A	Intelligent optimization for bandwidth enhancement
(Attioui et al., 2025)	Hybrid fractal antenna	40 × 30	3.05-11.9 (118%) Peano & Sierpinski fractal hybrid	6.8	< −10	90°	Enhanced bandwidth via hybrid fractal design
(Öztürk and Çimen, 2025)	UWB MIMO antenna	38 × 38	3.1-10.6 (109%) Geometry optimization + isolation	5.4	< −10	95	Wide bandwidth with MIMO configuration

6. CHALLENGES AND DESIGN TRADE-OFFS

Despite the advancement in technologies and the improvement of bandwidth, the challenges faced by designers still exist, as increasing the bandwidth often leads to complexity in design and manufacturing, which results in a decrease in radiation efficiency. Many of these techniques enable the addition of resonant frequencies, which leads to bandwidth expansion but negatively affects radiation performance. For example, structures loaded with slots work to increase bandwidth expansion, but due to the formation of surface currents around the slots, the antenna's radiation performance decreases. Achieving a balance between achieving a wide bandwidth and maintaining radiation characteristics is extremely important in UWB antenna design, according to published studies, where antennas with bandwidth values reaching approximately 120% show radiation efficiency ranging between 70% and 90%, depending on the properties of the dielectric substrate and an increase in complexity during design. Studies have also shown that techniques such as defective ground structures (DGS) and slot techniques like U and H slots increased and improved the bandwidth, but they led to a change in the radiation path, resulting in unwanted radiation that reduced antenna performance and distorted the radiation pattern. These are considered additional losses, and they also led to increased complexity during design and manufacturing. Techniques using stacked patches as well as frequency selective surfaces (FSS) and metamaterials have achieved an increase in bandwidth but have led to an increase in substrate thickness, and consequently to increased complexity during manufacturing **(Darweesh and Yetkin, 2018).** Achieving an ultra-wideband (UWB) antenna frequency range while maintaining radiation pattern characteristics remains a challenge for researchers and designers. Consideration must be given during design to balancing the attainment of wideband frequencies with maintaining the radiation pattern and reducing complexity in terms of design and manufacturing. In addition to presenting the current challenges, this review offers a methodical and trend-focused evaluation related to bandwidth improvement techniques for UWB antennas published between 2018 and 2025. By analyzing the progression from geometry-based and ground-layer alterations in the direction of hybrid and optimization-based designs, this study illustrates the principal trade-offs among bandwidth enhancement, design complexity, fabrication cost, and radiation behavior. The present approach supports identifying unresolved constraints regarding current techniques and provides practical observations for achieving optimized and effective UWB antenna configurations compatible for developing applications.

7. CONCLUSIONS

This paper offered a comprehensive review of bandwidth enhancement techniques in ultra-wideband antennas published between 2018 and 2025. Geometry modification, ground plane design, feeding optimization, and the integration of electromagnetic configurations such as FSS, metamaterials, and fractal geometries were determined as the most high-performance strategies for achieving a wide impedance bandwidth. Comparative analysis demonstrated that hybrid and optimization-assisted designs provide enhanced performance by balancing bandwidth, gain, and compactness. The observations offered in this review act as a valuable reference for researchers and engineers intending to design high-efficiency UWB antennas for future wireless applications. Future studies on bandwidth enhancement for UWB antennas are predicted to progressively utilize merged and intelligent design approaches that integrate multiple enhancement techniques within a single system. Algorithmic optimization strategies, such as data-driven and intelligent methodologies, are predicted to perform an increasing role in expediting the design workflow and enhancing wideband behavior while minimizing manual adjustment. In addition, the advancement of reconfigurable and responsive UWB antennas able to adaptively tuning their operating bandwidth and suppression properties will become more significant to handle diverse and time-varying system demands. Furthermore, achieving stable and wide-range behavior across the entire bandwidth of ultra-wideband (UWB) antennas, while simultaneously maintaining consistent and uniform radiation patterns and good time-domain response, remains a significant scientific and engineering challenge that attracts the attention of both researchers and designers, and requires continued research efforts to find effective practical solutions. These trade-offs collectively highlight the importance of adopting balanced design methodologies that combine bandwidth optimization with consideration of the practical constraints associated with implementation and manufacturing phases, ensuring the development of efficient designs applicable in real-world environments.

Credit Authorship Contribution Statement

Hafsa Amer Jassim: Visualization and draft writing, discussion and linguistic review. Heba Ahmed Jassim: Conducting and analyzing results and Zahraa Khduair Taha: proofreading

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper**.**

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مراجعة حول تقنيات تحسين عرض النطاق في الهوائيات المستوية فائقة الاتساع(UWB)

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الخلاصة

أصبحت الهوائيات فائقة الاتساع (Ultra-Wideband – UWB)عنصرًا أساسيًا في تطبيقات الاتصالات اللاسلكية المتقدمة، نظرًا لقدرتها على توفير نطاقات ترددية واسعة للغاية المطلوبة من أجل تحقيق الاتصال السريع، وأنظمة الرادار، وتقنيات الاستشعار، وتطبيقات التصوير المختلفة. ومع ذلك، فإن تحقيق عرض نطاق ممانعة واسع ومستقر مع الحفاظ في الوقت ذاته على تصغير أبعاد الهوائي، وكسب مقبول، وخصائص إشعاع مستقرة ما يزال يمثل تحديًا تصميميًا جوهريًا أمام الباحثين والمصممين. وفي السنوات الأخيرة، تزايدت الجهود البحثية بصورة ملحوظة لتطوير تقنيات تحسين عرض النطاق بهدف التغلب على هذه التحديات. تقدم هذه الورقة البحثية مراجعة علمية شاملة لأبرز تقنيات تعزيز عرض النطاق المستخدمة في تصميم الهوائيات فائقة الاتساع، وذلك بالاعتماد على الدراسات المنشورة خلال الفترة الممتدة بين 2018و2025. وقد جرى تصنيف هذه التقنيات بصورة منهجية إلى عدة محاور رئيسية تشمل :التقنيات المعتمدة على هندسة الشكل الهندسي للهوائي، وتعديل مستوى الأرضي(Ground Plane) ، وتحسين طرق التغذية، بالإضافة إلى دمج التراكيب الكهرومغناطيسية المتقدمة مثل هياكل الأرضي المعيبة (Defected Ground Structures – DGS)، والأسطح الانتقائية للتردد (Frequency-Selective Surfaces – FSS)، والمواد الميتا (Metamaterials)، والهندسيات الكسرية (Fractal Geometries) علاوةً على ذلك، تستعرض الدراسة التقنيات الهجينة وتقنيات التصميم المدعومة بخوارزميات التحسين لما لها من دور متزايد الأهمية في تحقيق أداء عريض النطاق عالي الكفاءة. كما تم تقديم تحليل مقارن لعدد من النماذج التطبيقية الممثلة بهدف توضيح الأداء المحقق، والمزايا التصميمية، وكذلك الموازنة بين المكاسب والقيود المرتبطة بكل تقنية. وفي الختام، تسلط هذه المراجعة الضوء على أهم التحديات البحثية القائمة والاتجاهات المستقبلية التي من شأنها دعم تطوير وتصميم هوائيات فائقة الاتساع محسّنة تلبي متطلبات تطبيقات الاتصالات اللاسلكية في الأجيال القادمة.

الكلمات المفتاحية: الهوائيات فائقة الاتساع(UWB) ، تحسين عرض النطاق، عرض نطاق الممانعة، هيكل الأرضي المعيب (DGS)، تصميم الهوائيات الهجينة