KSÜ Mühendislik Bilimleri Dergisi, 27(4), 2024
Araştırma Makalesi

KSU J Eng Sci, 27(4), 2024
Research Article

Kahramanmaras Sutcu Imam University
Journal of Engineering Sciences

Geliş Tarihi : 13.06.2023
Kabul Tarihi : 18.09.2024

Received Date : 13.06.2023
Accepted Date : 18.09.2024

INVESTIGATION OF THE EFFECTS OF DIFFERENT FEED LINE STRUCTURES ON UWB ANTENNA PERFORMANCE BY CHARACTERISTIC MODE ANALYSIS

FARKLI BESLEME HATTI YAPILARININ UWB ANTEN PERFORMANSI ÜZERINE ETKILERININ KARAKTERISTIK MOD ANALIZI ILE İNCELENMESI

Miraç Dilruba GEYIKOĞLU[1] (ORCID: 0000-0003-2399-4741)

[1] Atatürk University, Electrical - Electronics Engineering, Erzurum, Türkiye

*Sorumlu Yazar / Corresponding Author: Miraç Dilruba GEYIKOĞLU, dilruba_mdk@hotmail.com

ABSTRACT

This study investigates the effect of various feed topologies on the parameters of a novel ultra-wideband (UWB) antenna using characteristic mode analysis. The proposed design is guided by characteristic mode analysis, commencing with a basic square structure. Initially, a closed-form estimate of the resonance frequencies of the primary modes is provided for the square-shaped structure. Subsequently, the characteristic modes that resonate in the frequency spectrum are modified by introducing symmetrical square slots. To excite these modes and achieve a wideband antenna that encompasses the relevant spectrum, the geometry of the feeding line is altered and its effects are examined. The study incorporates two fundamental feed line geometries: tapered and traditional feed impedance lines. The proposed UWB antennas are fabricated and measured to validate their performance. According to the measurement results a wide impedance bandwidth of 147.82% at -10 dB reference ((0.9–6 GHz)) and stationary radiation patterns across the operating frequency band are obtained for the tapered feed line. The results demonstrate a significant advantage of the tapered feed line over the traditional impedance line. The results for the fabricated prototypes exhibit high similarity to the simulated results. The findings confirm the applicability of the mode analysis method.

Keywords: Characteristic modes analysis, UWB antenna, traditional feed line, tapered feed line

ÖZET

Bu makalede, farklı besleme topolojilerinin yenilikçi bir UWB anteninde performans üzerindeki etkisi, karakteristik mod analizi kullanılarak araştırılmaktadır. Önerilen tasarım, basit bir kare yapıdan başlayarak karakteristik mod analizi ile yönlendirilmiştir. İlk olarak, kare biçimli yapı için birincil modların rezonans frekanslarının kapalı form tahmini sağlanmıştır. Daha sonra, simetrik kare yuvalar eklenerek frekans spektrumunda rezonans durumda olan karakteristik modlar değiştirilmiştir. Bu modları uyarmak ve ilgili spektrumu kapsayan geniş bantlı bir anten elde etmek için besleme hattının geometrisi değiştirilmiş ve etkileri incelenmiştir. İki temel besleme hattı geometrisi, konik ve geleneksel besleme empedans hattı içermektedir. Önerilen UWB anteninin performansını doğrulamak için prototipleri üretilmiş ve gerçek zamanlı ölçümleri yapılmıştır. Ölçüm sonuçlarına göre, konik besleme hattı için -10 dB referansta (0,9–6 GHz) %147,82'lik geniş bir empedans bant genişliği ve çalışma frekans bandında sabit radyasyon desenleri elde edilmiştir. Sonuçlar, geleneksel empedans hattına göre konik besleme hattının açık avantajını göstermektedir. Üretilen prototiplerin sonuçları, simüle edilen sonuçlara son derece benzerlik göstermiştir. Sunulan sonuçlar, mod analizi yönteminin uygulanabilir olduğunu kanıtlamaktadır.

Anahtar Kelimeler: Karakteristik mod analizi, UWB anteni, geleneksel besleme hattı, konik besleme hattı

ToCite: GEYIKOĞLU, M. D., (2024). INVESTIGATION OF THE EFFECTS OF DIFFERENT FEED LINE STRUCTURES ON UWB ANTENNA PERFORMANCE BY CHARACTERISTIC MODE ANALYSIS. *Kahramanmaraş Sütçü İmam Üniversitesi Mühendislik Bilimleri Dergisi*, 27(4), 1117-1127.

INTRODUCTION

In the rapidly evolving wireless communication landscape, the utilization of antennas, which constitute a critical component of communication systems, has increased substantially in wireless applications such as Wi-Fi, WiMax, WLAN, LTE, 4G, and 5G. To adapt to available technology and integrate into emerging technologies, antennas must possess broadband properties. Broadband antennas also exhibit high data rates, stable radiation patterns, and compatibility with increased impedance bandwidth in practical applications. Various structures, including spiral antennas (Tran and Le, 2019), conical antennas (Dastranj and Bornapour, 2019), and log-periodic antennas (Amini and Oraizi, 2015), have been employed to achieve wide impedance bandwidth. However, these antennas (Tran and Le, 2019; Amini and Oraizi, 2015) often possess complex and sizable geometric structures. These characteristics present challenges in manufacturing and device integration. Due to their simple construction, patch antennas have been extensively studied, and their impedance bandwidths have been expanded using techniques such as slot coupling feed (Singh et al., 2020) and U-shaped slot feed (Ghimire and Choi, 2019). An alternative approach to designing wideband antennas is characteristic modes analysis (CMA) (Perli and Rao, 2019; Mohanty and Behera, 2021; Jabire et al., 2021). Characteristic mode theory provides profound insights into the potential propagation properties that occur on conductor structures. Desired antenna properties are obtained through systematic analysis of resonance modes on radiating elements. For each characteristic mode, information regarding mode resonance and resonance behavior is derived from characteristic angle, eigenvalue, and modal significance parameters. The antenna's characteristic modes are dependent on the size and structure of the radiating element. Characteristic mode theory has recently been applied to various antenna designs (Khan and Chowdhury, 2020). It is a frequently employed method for creating additional resonances (Behdad, and Sarabandi, 2004; Lu and Zhu, 2014), size minimization (Azadegan and Sarabandi, 2003), generating circular polarization (Mir et al., 2022), and increasing bandwidth (Bohannon and Bernhard, 2014; Lin and Chu, 2018).

In the working procedure, firstly, the main construction of the radiated factor is optimized at the design frequency, and the natural resonance modes are estimated. Secondly, a suitable supply shape is selected to activate the requested modes (Cabedo-Fabres et al., 2007). Furthermore, including the feeding construction alters the antenna radiating geometry and the characteristic modes, subsequently affecting the radiated mode. The mode analysis of the feed structure can be examined for changes in antenna performance parameters without modifying the main radiation pattern. One of the primary design objectives for high bandwidth is 50-50 impedance matching. Numerous miniaturization and matching techniques have been reported in the literature. These techniques include feed gap optimization (John and Ammann,2005), beveling technique (Ammann, 2001), ground plane slots and DGS (Chakraborty et al. 2012), multiple feed configurations and orientations (Ul Haq et al.2018). Additionally, the effect of dielectric substrate and antenna dimensions on input impedance and radiation beam width in tapered antennas is presented in (Srifi et al. 2011). Techniques such as exponential tapering (Manohar et al. 2013) and triangular tapering (Manohar et al. 2013) are utilized to increase the impedance bandwidth.

In this study, a novel ultra-wideband antenna with an omnidirectional radiation pattern is proposed, and its effects are presented in the literature by analyzing it in three different scenarios with CMA: 1) the antenna structure before including the feed structure (obtaining the overall antenna configuration), 2) the antenna operating parameters after including the traditional linear feed, and 3) the antenna operating parameters after including the tapered line feed. The following two benefits are achieved with the proposed method: first, the influence of feed structures is taken into account, and second, the CMA solved from the radiation and scattering problem is consistent, which provides the possibility of optimizing antenna radiation and scatter performance with the same CM set. All simulations are performed using CST Microwave Studio. The remainder of this paper is organized as follows. In Section II, the antenna configurations and an analysis of their CMA are presented. Section III describes the measurement results. Finally, section IV presents the results of this study.

CHARACTERISTIC MODE ANALYSIS

In recent years, characteristic mode analysis has been used to present the natural modes of the radiation structure in the field of antenna engineering. CMA is independent of material properties and feed type. By means of the impedance matrix, the eigenvalue problem is solved and the characteristic modes are obtained (Eq. 1). These eigenvalues potentially provide physical information about antenna structure and analysis (Shu and Zhang, 2022).

$$X(J_n) = \lambda_n R(J_n) \quad (1)$$

Here, the real and imaginary parts of the impedance matrix are denoted by R and X, respectively. By solving this equation, n. for mode is obtained eigenvalue λ_n and characteristic current (J_n). If the eigenvalue is zero at any frequency point, that frequency is considered resonance. The eigenvalue is used to comment on the energy and diffusion efficiency of the modes. There are two important parameters in CMA;

1) Modal Significance (MS): This shows how close all modes are to resonance at all frequencies. It reaches a maximum value of 1 at the resonant frequency λ_n. It decreases as the eigenvalue increases which is defined as (Eq. 2) (Shu and Zhang, 2022);

$$MS_n = 1/(1 + j(\lambda_n)) \tag{2}$$

2) Characteristic angle (α_n); the phase difference between the Eigen current and Eigen fields is modeled by the characteristic angle. If the characteristic angle is 180, there is an effective radiator condition and is calculated by (Eq. 3) ;

$$\alpha_n = 180^o - \tan^{-1}(\lambda_n) \tag{3}$$

In case of resonance, λ_n = 0, *MS*=1 ve α_n = 180^o (Shu and Zhang, 2022)

Antenna Design

The proposed antenna designs are shown in Figure 1. The current distribution is directed to the outer frame, by adding 3 symmetrical slots on a simple square monopole (Antenna 1). The square monopole structure is calculated with traditional equations (Balanis, 2016). The effect of the added slots is followed through the CMA. More modes need to be excited to achieve higher impedance matching at lower frequencies. For this reason, a ring was formed on the patch (Singh et al., 2022). The traditional feed line is added to the main configuration structure (Antenna 2). Additionally, the rectangular ground structure helps achieve 50- ohm impedance matching and a wider bandwidth. The next step converts the traditional feed line structure to a tapered line structure feed. This causes improved impedance matching (Antenna 3). The tapered feed line is calculated with E q. 4 and 5 (Manohar et al. 2013). Where L_f is the feed height, r_c is the effective area of the tapered feed line, gap is the feed gap and k is the regulation coefficient, which was experimentally selected as 1.18 for a dielectric layer with a dielectric constant ($\varepsilon_r = 4.4$). The gap between the ground plane and the radiating patch plays an important role in impedance matching. The result will be an antenna with UWB characteristics. The geometry parameters of the proposed antenna are given in Table 1.

$$f = \frac{7.2}{(L_f + r_c + gap\,) x\ k}\ GHz \tag{4}$$

$$r_c = \frac{(\frac{w_{f2} + w_{f3}}{2})}{2\ x\ \pi} \tag{5}$$

Table 1. The Geometry Parameters of the Proposed Antenna

Parameters	L_1	L_2	L_3	L_f	W_g	W_{g1}	W_{g2}	W_1	W_2	W_{f1}	W_{f2}	W_{f3}
Dimensions (mm)	4	35.9	3.5	4.4	0.5	1.5	0.05	17.5	35.5	0.38	0.38	0.12

Feed Structure Modifications

The feed structure is an important design factor in antennas (Adams et al., 2022). It contributes to the performance analysis as the choice of feed affects radiation, power transfer, and impedance matching. In this study, Characteristic Mode Analysis (CMA) studies are presented for tapered and traditional impedance feed line geometries. The objective is to examine the changes in antenna performance parameters with CMA by combining the antenna configuration with the feed lines. Initially, CMA analysis is performed on Antenna 1. The surface current distribution, modal significance, characteristic angle, and radiation pattern for the first four modes are examined, respectively. According to the 0.707 modal significance resonance condition, four distinct resonance points have formed in Antenna-1 within the bandwidth range (Figure 2-a). At 0.707 *MS*, it corresponds to the half-power bandwidth. Above this threshold value, the antenna is considered to radiate significant modes.

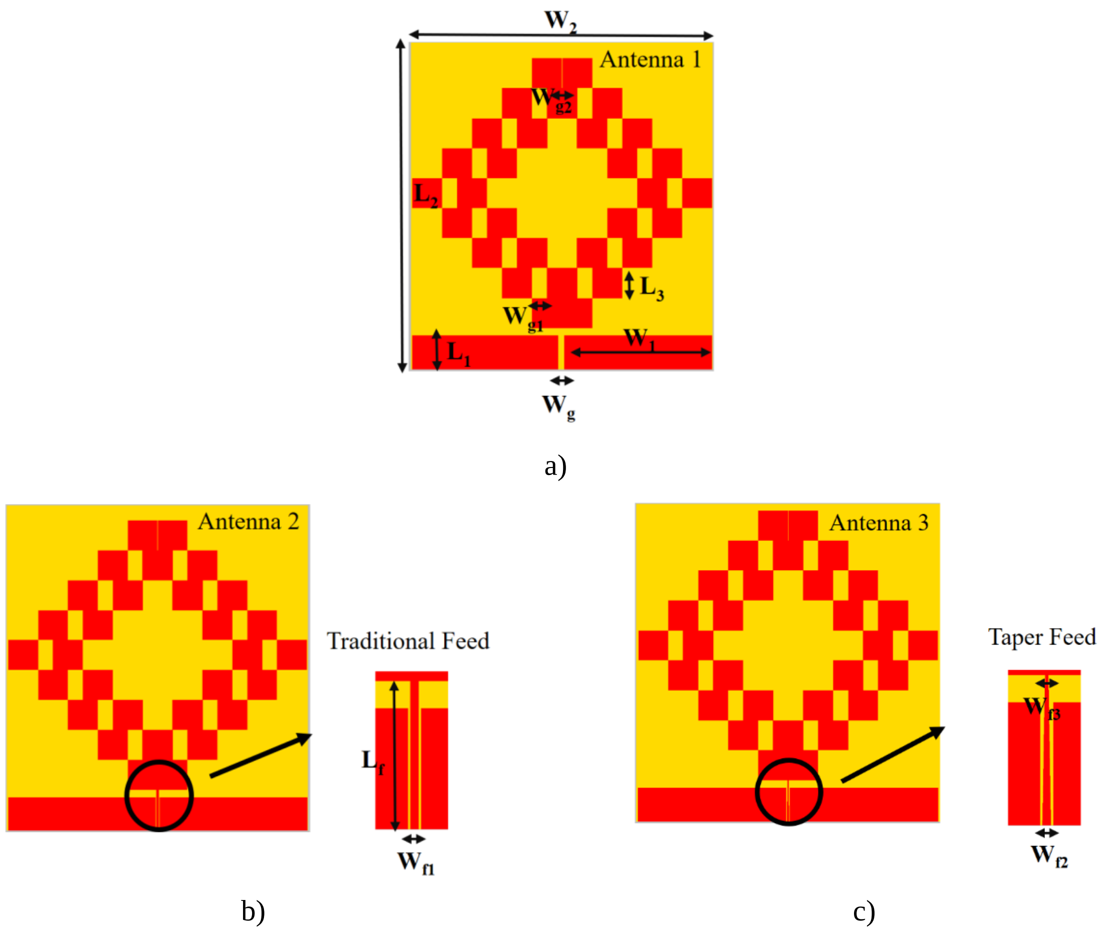


Figure 1. Geometry of Antennas a) Antenna 1, b) Antenna 2, and c) Antenna 3

Examining α_n graph of Antenna-1 (Figure 3-a), four different resonance formations have been observed at points consistent with MS. Additionally, the surface current distribution and radiation patterns are by these four resonances (Figure 4-a).The traditional feed (Antenna 2) and tapered feed (Antenna 3) have been added to the main configuration (Antenna 1), respectively, and the changes made to antenna characteristics have been examined. According to the *MS* results, with the addition of the traditional feeding structure (Figure 2-b), it has been observed that the bandwidth increased in the resonances. Examining the α_n graph of Antenna-2 (Figure 3-b), it has been observed that the dominant modes increased the bandwidth to the 3-6 GHz range. The linearly varying surface current distributions also showed variations in radiation patterns (Figure 4-b). For Antenna 3, when examining the *MS* (Figure 2-c) and α_n (Figure 3-c) graphs, it is observed that resonance frequency occurs in the range of 0.9-6 GHz. A wide bandwidth has been obtained through the Antenna-3 structure. A higher efficiency radiation pattern has been obtained with circularly varying surface current distributions (Figure 4-c).

MEASUREMENT RESULTS

The prototypes of the proposed antennas are produced on FR-4 ($\varepsilon_r = 4.4, h = 1.55\ mm$) substrate using a PCB scraper, and real-time measurements are taken. The produced antenna prototypes are given in Figure 5. The antenna parameters are measured with an N9928A Field Fox vector network analyzer in a semi-anechoic chamber (Figure 6). The reflection coefficient, efficiency, peak gain, and axial ratio parameters are examined. The results are given in Figure 7 and Figure 8, respectively. According to these results, the antenna fed with the tapered feed line shows a perfect resonance with 147.82% BW at -10 dB reference. In addition, gain between 1.2-6.9 dB and efficiency above 85% are measured. According to the axial ratio values, it is linear polarization. It is seen that the simulation and measurement results are compatible. In addition, the radiation patterns obtained for 2.45 GHz are given in Figure 9.

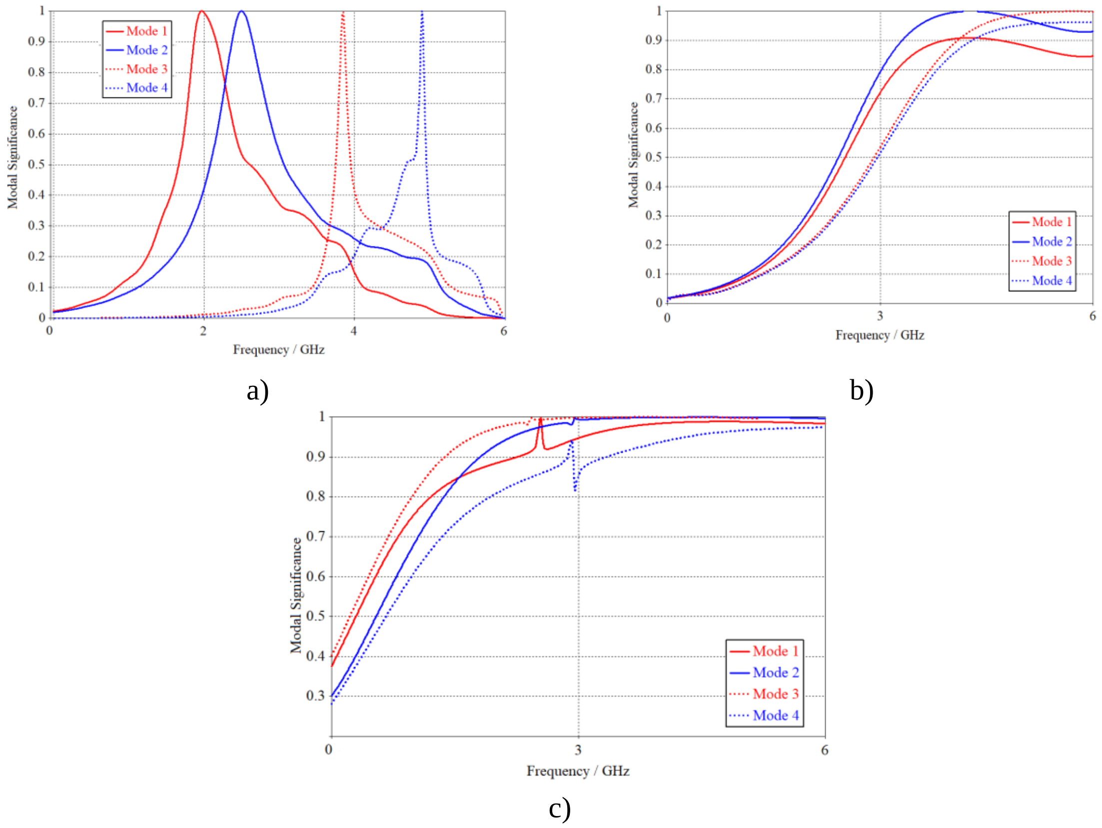


Figure 2. The *MS* of CMA Analysis Results for Four Modes a) Antenna 1, b) Antenna 2, c) Antenna 3

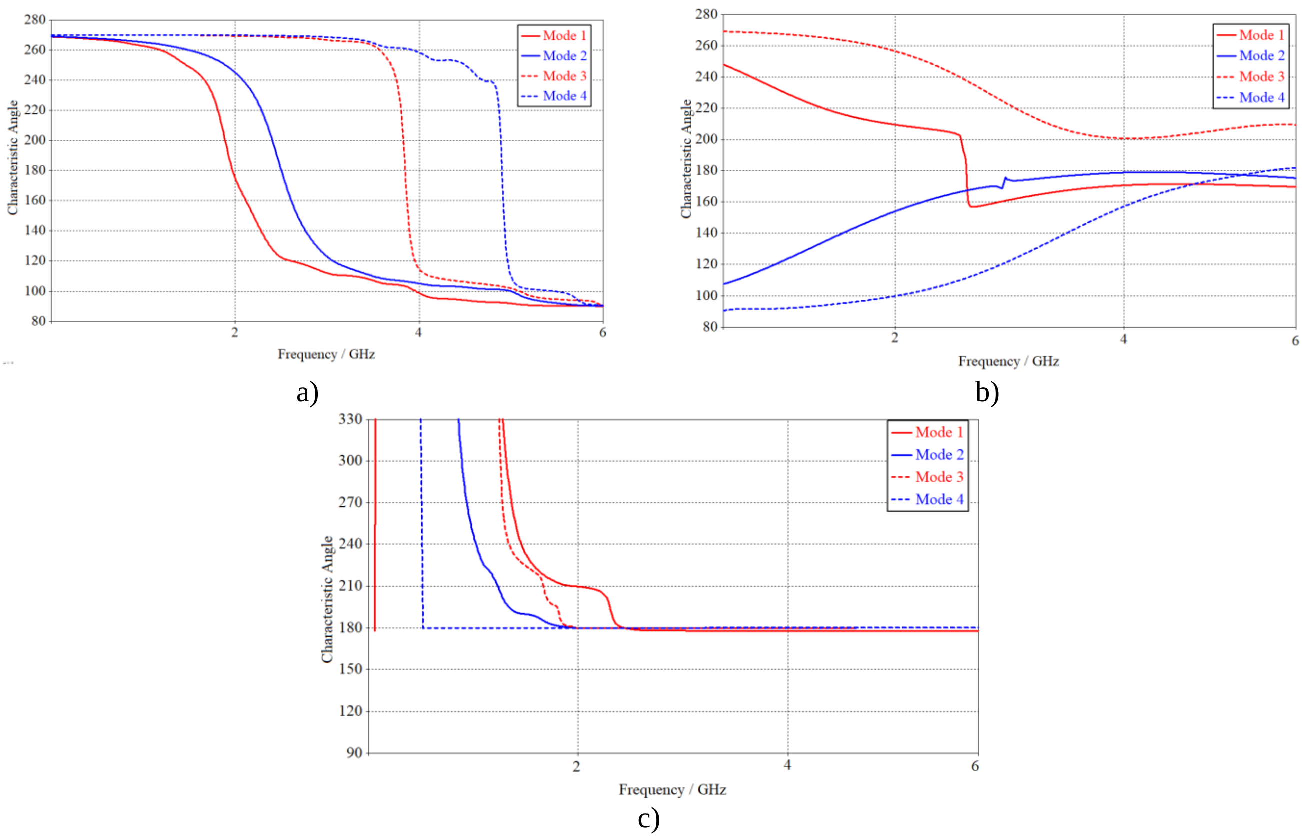
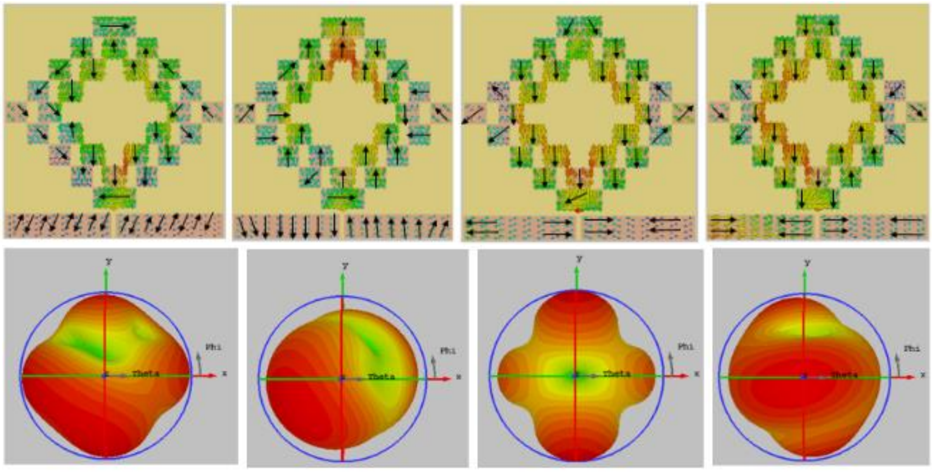
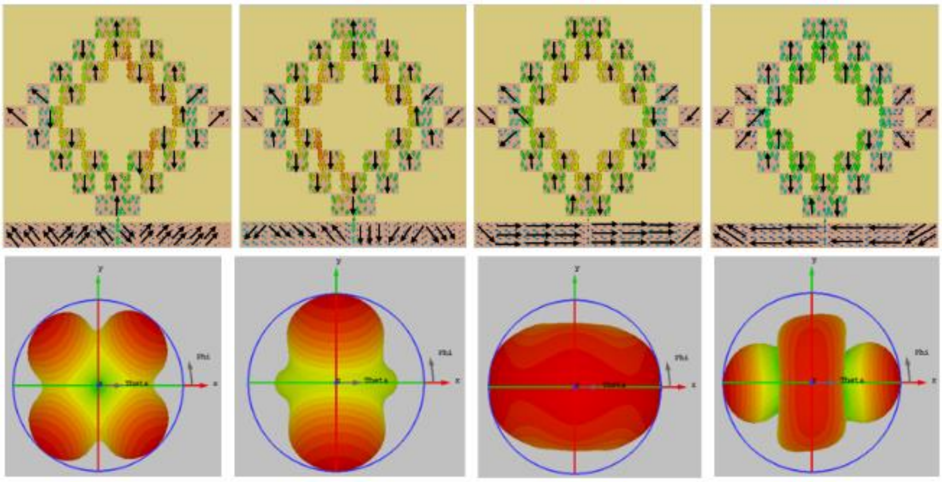


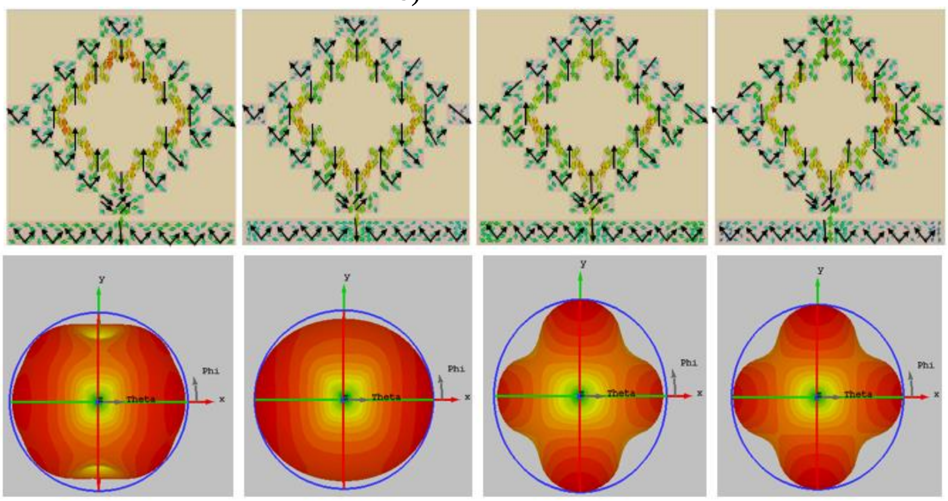
Figure 3. The α_n of CMA analysis results for four modes a) Antenna 1, b) Antenna 2, c) Antenna 3



a)



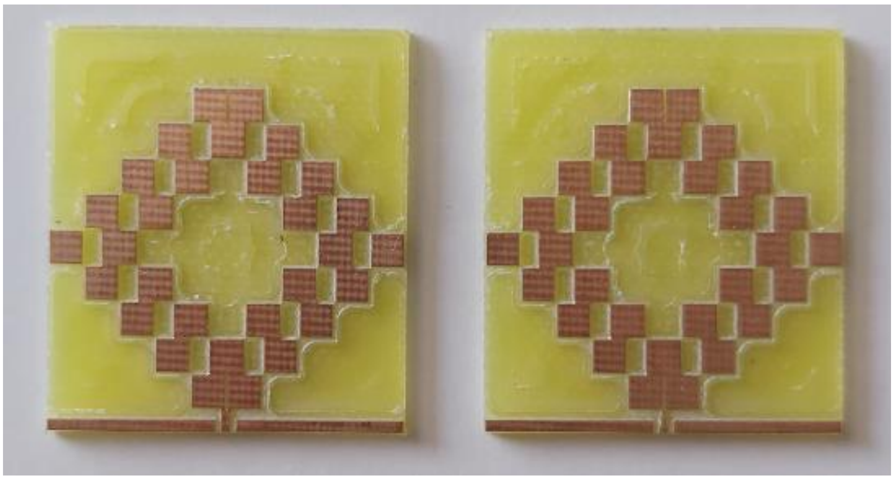
b)



c)

Figure 4. The Radiation Patterns and the Surface Current Distributions Results of CMA Analysis a) Antenna 1, b) Antenna 2, c)Antenna 3

The effects of conventional and tapered feed line structures on the radiation pattern are examined. The conventional feed line has a unidirectional radiation pattern in the xz plane, while the tapered feed line, the side lobe, and the back lobe levels decrease and an omnidirectional radiation pattern occurs. The cross-pol level of the conventional feed is higher in the xz plane, while the cross-pol level increases with the tapered feed. In the yz plane, while there is a unidirectional radiation pattern with a back lobe in the conventional feed, an omnidirectional radiation pattern is obtained with the decrease of the unwanted lobes in the tapered feed line. In addition, a stable radiation pattern is observed in both E-Field (xz) and H-Field (yz) planes for the 0.6-9 GHz frequency range. The results clearly show the advantage of the tapered feed line over the traditional feed line. In addition, it has been observed that the electrical performance of the antennas does not decrease due to the application of different feed line topologies. The difference in the results is due to the effect of the supply cable.



Antenna 2 Antenna 3

Figure 5. Prototypes of the Fabricated Antennas

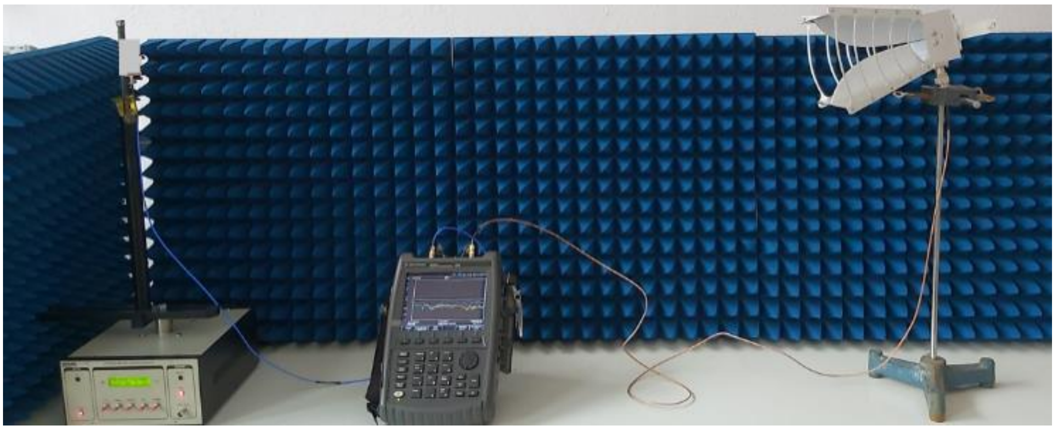


Figure 6. The Semi-Anechoic Chamber Measurement Environment

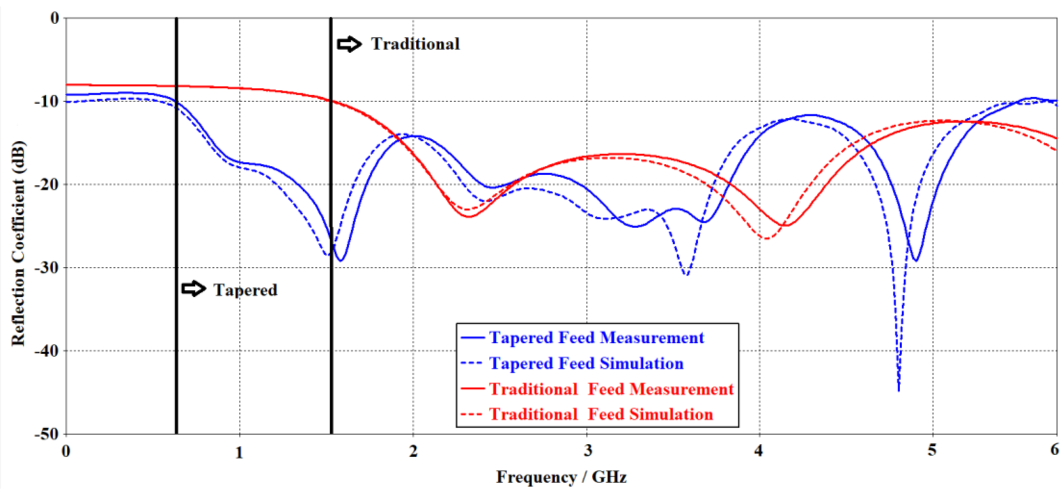


Figure 7. The Simulation and Measurement Result in terms of the Reflection Coefficient

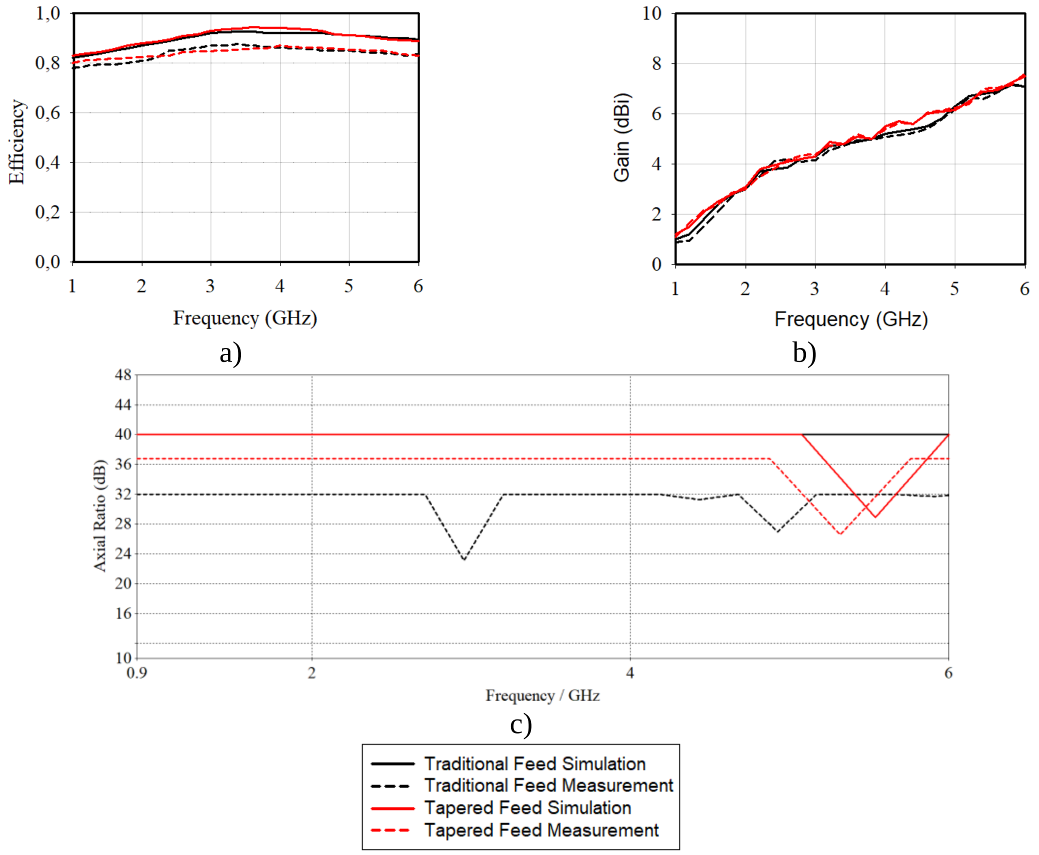


Figure 8. The Results in terms of a) the Efficiency, b) the Gain, c) the Axial Ratio

The comprehensive performance comparison of the proposed antenna with similar studies is given in Table 2. According to the literature, the effects of different feed structures such as conventional, tapered, exponential, and multi-section feed lines on different antenna configurations have been investigated. As can be seen, some of the designs have a bandwidth-limit effect despite having high gain and efficiency values. In other designs, the bandwidth is above the ultra-wide range, but empirical background theory has been preferred for different feed line investigations. On the other hand, the proposed antenna configuration provides communication in the sub-6 GHz band, which has a widespread use area. To investigate the effects of conventional and tapered feed line structures on antenna performance, CMA analysis, which is a more precise approach rather than a heuristic or trial-and-error approach, has been used.

Table 2. Performance Comparison of the Proposed Antenna with Studies on Different Feed Structures

	This work	**Manohar et al. 2014**	**Ul haq et al.2018**	**Aktar et al. 2020**	**Newton et al.2022**	**Firmansyah et al .2023**
Frequency (GHz)	0.9-6	2.5-80	3.1-10.6	3.1-10.6	3.3-3.65	14.65-22.7
Bandwidth	Ultra wideband	Super wideband	Ultra wideband	Ultra wideband	Narrowband	Wideband
Peak Gain (dBi)	6.9	5.9	4.1	10.2	7	9.5
Efficiency (%)	85	-	95	-	86	98.2
Background Theory	CMA	Heuristic	Heuristic	Heuristic	CMA	Heuristic
Method Feature	Comparison of the conventional and tapered feed lines	Comparison of the exponential and tapered feed lines	Comparison of the Stepped-impedance and multi-section taper feed lines	Comparison of the balun antenna and Step Constant Tapered feed line	Comparison of the conventional and stepped feed lines	Investigation of the quasi tapered feed line

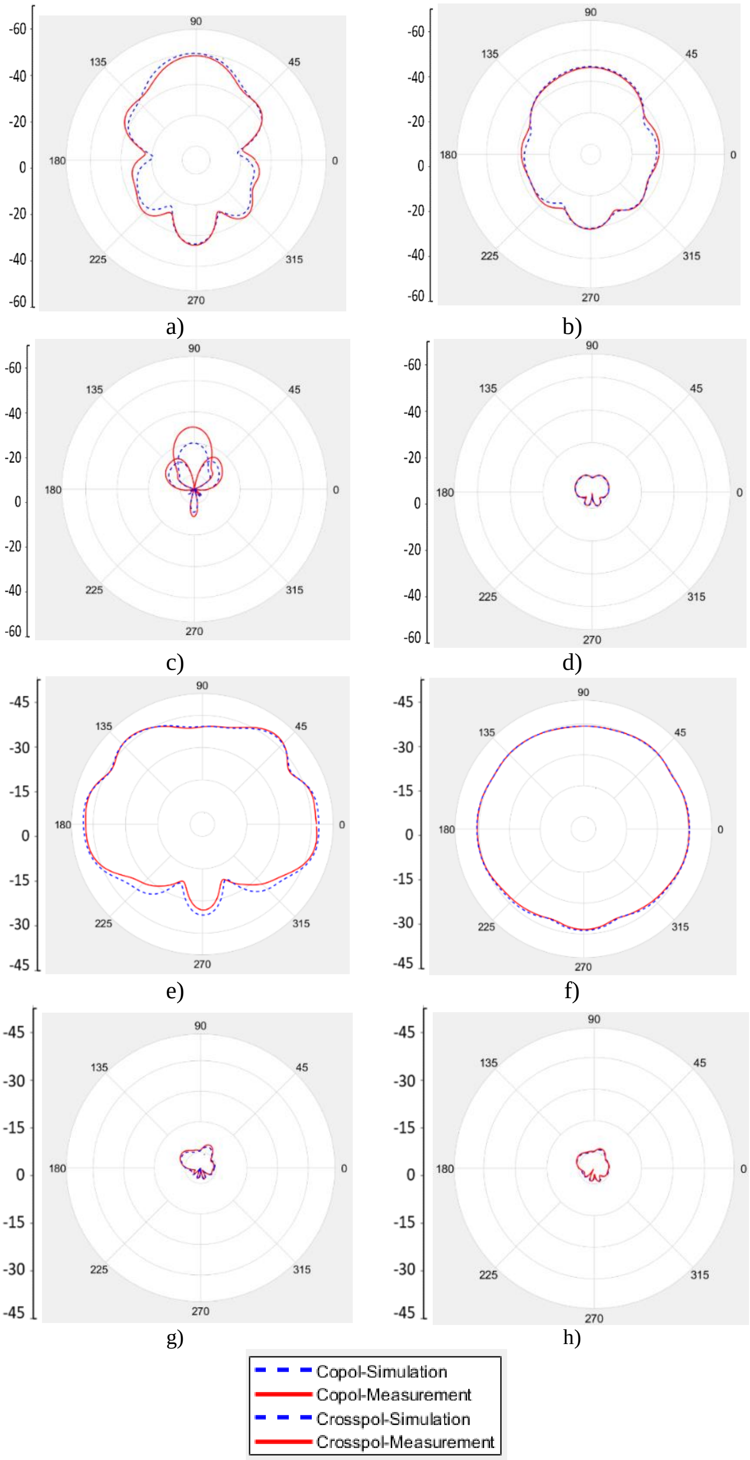


Figure 9. The Simulation and Measurement Result in terms of the Radiation Pattern for the 2.45GHz Frequency. a) XZ Plane Co-Pol Antenna 2 (Traditional Feed), b) XZ Plane Co-Pol Antenna 2 (Tapered Feed), c) XZ Plane Cross-Pol Antenna 2 (Traditional Feed), d) XZ Plane Cross-Pol Antenna 2 (Tapered Feed), e) YZ Plane Co-Pol Antenna 3 (Traditional Feed), f) YZ Plane Co-Pol Antenna 3 (Tapered Feed) g)YZ Plane Cross-Pol Antenna 3 (Traditional Feed), h) YZ Plane Cross-Pol Antenna 3 (Tapered Feed)

CONCLUSION

This article proposes a compact novel ultra-wideband (UWB) antenna. The effects of the feed line geometry are presented. The influence of different feed line structures on the modes was analyzed by characteristic mode analysis (CMA) without altering the main radiation structure. Two distinct feed line topologies are employed: traditional feed line and tapered feed line. The proposed antenna is fabricated with two different feed line structures, and the simulation results are validated. It is observed that parameters such as S11, efficiency, gain, and radiation pattern demonstrate high agreement between the results. The findings indicate the superiority of the tapered feed line over the traditional feed line. Furthermore, it has been noted that the electrical performance of the antennas does not deteriorate due to the application of different feed line topologies. The proposed novel UWB antenna may be a suitable candidate for 5G wireless communication systems, as it encompasses the Sub-6 GHz frequency range.

REFERENCES

Adams, J. J., Genovesi, S., Yang, B., & Antonino-Daviu, E. (2022). Antenna Element Design Using Characteristic Mode Analysis: Insights and research directions. *IEEE Antennas and Propagation Magazine*, *64*(2), 32-40.

Aktar, M., Rana, M. M., Sarker, N., & Hossain, M. S. (2020). Comparative analysis on antenna balun and feeding techniques of step constant tapered slot antenna. *Journal of Sensor Technology*, *10*(3), 31-45.

Ammann, M. J. (2001). Control of the impedance bandwidth of wideband planar monopole antennas using a beveling technique. *Microwave and Optical Technology Letters*, *30*(4), 229-232.

Amini, A., & Oraizi, H. (2015). Miniaturized UWB log-periodic square fractal antenna. *IEEE Antennas and Wireless Propagation Letters*, *14*, 1322-1325.

Azadegan, R., & Sarabandi, K. (2003). A novel approach for miniaturization of slot antennas. *IEEE Transactions on Antennas and Propagation*, *51*(3), 421-429.

Balanis, C. A. (2016). Antenna theory: analysis and design. John Wiley & Sons.

Behdad, N., & Sarabandi, K. (2004). Coupled Sectorıal Loop Antenna (Csla) For Ultra-Wıdeband Applıcatıons. *This Technıcal Report Has Been Revıewed And Is Approved For*, *15*, 159.

Bohannon, N. L., & Bernhard, J. T. (2014). Design guidelines using characteristic mode theory for improving the bandwidth of PIFAs. *IEEE Transactions on Antennas and Propagation*, *63*(2), 459-465.

Cabedo-Fabres, M., Antonino-Daviu, E., Valero-Nogueira, A., & Bataller, M. F. (2007). The theory of characteristic modes revisited: A contribution to the design of antennas for modern applications. *IEEE Antennas and Propagation Magazine*, *49*(5), 52-68.

Chakraborty, M., Rana, B., Sarkar, P. P., & Das, A. (2012). Size reduction of a rectangular microstrip patch antenna with slots and defected ground structure. *International Journal of Electronics Engineering*, *4*(1), 61-64.

Dastranj, A., & Bornapour, M. (2019). UWB planar conical horn-shaped self-complementary bow-tie antenna. *Journal of Communication Engineering*, *8*(1), 20-33.

Firmansyah, T., Praptodiyono, S., Permana, J., Alam, S., Supriyanto, T., Paramayudha, K., ... & Kondoh, J. (2023). Modeling of quasi-tapered microstrip antenna based on expansion-exponential tapered method and its application for wideband MIMO structure. *AEU-International Journal of Electronics and Communications*, *169*, 154745.

Ghimire, J., & Choi, D. Y. (2019). Design of a compact ultrawideband U-shaped slot etched on a circular patch antenna with notch band characteristics for ultrawideband applications. *International Journal of Antennas and Propagation*, *2019*.

Jabire, A. H., Ghaffar, A., Li, X. J., Abdu, A., Saminu, S., Alibakhshikenari, M., ... & Limiti, E. (2021). Metamaterial base design of compact UWB/MIMO monopoles antenna with characteristic mode analysis. *Applied Sciences*, *11*(4), 1542.

John, M., & Ammann, M. J. (2005). Optimization of impedance bandwidth for the printed rectangular monopole antenna. *Microwave and Optical Technology Letters*, *47*(2), 153-154.

Khan, M., & Chowdhury, M. (2020). Analysis of modal excitation in wideband slot-loaded microstrip patch antenna using theory of characteristic modes. *IEEE Transactions on Antennas and Propagation*, *68*(11), 7618-7623.

Lin, J. F., & Chu, Q. X. (2018). Increasing bandwidth of slot antennas with combined characteristic modes. *IEEE Transactions on Antennas and Propagation*, *66*(6), 3148-3153.

Lu, W. J., & Zhu, L. (2014). Wideband stub-loaded slotline antennas under multi-mode resonance operation. *IEEE Transactions on Antennas and Propagation*, *63*(2), 818-823.

Mir, R., Dashti, H., & Ahmadi-Shokouh, J. (2022). Design and analysis of circularly polarized circular patch antenna with multiple shorting pins using characteristic mode theory. *AEU-International Journal of Electronics and Communications*, *146*.

Mohanty, A., & Behera, B. R. (2021). Characteristics Mode Analysis: A review of Its Concepts, Recent Trends, State-of-the-Art Developments and Its Interpretation with a Fractal UWB MIMO Antenna. *Progress In Electromagnetics Research B*, *92*.

Manohar, M., Kshetrimayum, R. S., & Gogoi, A. K. (2014). Printed monopole antenna with tapered feed line, feed region and patch for super wideband applications. *IET Microwaves, Antennas & Propagation*, *8(1)*, 39-45.

Newton, M. E., Ma, K., Luo, Y., Yan, N., & Tang, B. (2022). Dual-mode wideband slotted patch antenna using characteristic mode analysis and low-cost SISL technology. *Microwave and Optical Technology Letters*, *64(3)*, 583-588.

Perli, B. R., & Rao, A. M. (2019). Characteristic mode analysis of wideband microstrip antenna. *Progress In Electromagnetics Research C*, *97*, 201-212.

Shu, J., & Zhang, Y. (2022). Design of a liquid crystal beam-steerable antenna with characteristic mode analysis. *IET Microwaves, Antennas & Propagation*, *16*(1), 29-36.

Singh, A., Mehra, R. M., & Pandey, V. K. (2020). Design and optimization of microstrip patch antenna for UWB applications using Moth–Flame optimization algorithm. *Wireless Personal Communications*, *112*(4), 2485-2502.

Singh, G., Kanaujia, B. K., Pandey, V. K., & Kumar, S. (2022). Quad-Band multi-polarized antenna with modified electric-inductive‒ capacitive resonator. *International Journal of Microwave and Wireless Technologies*, *14*(1), 65-76.

Srifi, M. N., Podilchak, S. K., Essaaidi, M., & Antar, Y. M. (2011). Compact disc monopole antennas for current and future ultrawideband (UWB) applications. *IEEE Transactions on Antennas and Propagation*, *59*(12), 4470-4480.

Tran, H. H., & Le, T. T. (2019). Ultrawideband, high-gain, high-efficiency, circularly polarized Archimedean spiral antenna. *AEU-International Journal of Electronics and Communications*, *109*, 1-7.

Ul Haq, M. A., Koziel, S., & Cheng, Q. S. (2018). Miniaturisation of wideband antennas by means of feed line topology alterations. *IET Microwaves, Antennas & Propagation*, *12(13)*, 2128-2134.