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Bandwidth Enhancement of a D-Crescent-Shaped Monopole Patch Antenna for Wireless Applications

Kablosuz Uygulamalar için D-Hilal Şekilli Tek Kutuplu Yama Anteninin Bant Genişliğinin Artırılması

[1]Cem GÜLER, **[2]Sena Esen BAYER KESKİN**

[1]Kırklareli University, Department of Lüleburgaz Faculty of Aeronautics and Astronautics, Kırklareli, Türkiye
[2]Kırklareli University, Department of Electrical and Electronics Engineering, Kırklareli, Türkiye

[1]cemguler@klu.edu.tr, [2]senakeskin@klu.edu.tr

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ABSTRACT

A low-profile monopole patch antenna is proposed for wireless communication purposes, covering PCS1900, UMTS, LTE2300, LTE2500, ISM, and WLAN bands. The antenna features a novel double-crescent-shaped (D-Crescent-Shaped) patch with a partial ground plane to enhance bandwidth. Resonating at 2.4 GHz for ISM applications, the antenna, constructed on FR-4 dielectric, exhibits a proportional bandwidth of 38%, covering 1.91 GHz to 2.81 GHz. The design achieves a low-profile configuration with dimensions of 36.88×44.85 mm², featuring a thickness of 1.6 mm. The proposed antenna has a return loss of -56.1 dB and a directivity gain of 2.21 dBi. The proposed antenna, with its low-profile design, ease of manufacturing, and improved bandwidth and return loss, is well-suited for wireless communication applications across widely-used frequency ranges like PCS, UMTS, LTE2300, LTE2500, ISM, Wi-Fi, Bluetooth, and 4G LTE.

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ÖZET

Bu çalışmada, çok yönlü kablosuz iletişim uygulamaları için PCS1900, UMTS, LTE2300, LTE2500, ISM ve WLAN bantlarını kapsayan düşük profilli bir mikroşerit yama anten önerilmektedir. Anten, bant genişliğini artırmakamacıyla kısmi bir toprak düzlemine sahip yeni bir çift hilal şekilli (D-Hilal Şekilli) yamaya sahip olacak biçimde tasarlanmıştır. ISM uygulamaları için 2,4 GHz'de rezonansa giren ve FR-4 dielektrik malzeme üzerine inşa edilen anten, 1,91 GHz ila 2,81 GHz'i kapsayan %38'lik oransal bant genişliği sergilemektedir. Tasarım, 36,88×44,85 mm² boyutları ve 1,6 mm kalınlığı ile düşük profile sahip bir konfigürasyondan oluşmaktadır. Antenin geri dönüş kaybı -56,1 dB ve yönlülük kazancı 2,21 dBi'dir. Önerilen anten, düşük profilli tasarımı, üretim kolaylığı ve gelişmiş bant genişliği ve geri dönüş kaybı ile PCS, UMTS, LTE2300, LTE2500, ISM, Wi-Fi, Bluetooth ve 4G LTE gibi yaygın olarak kullanılan frekans aralıklarında kablosuz iletişim uygulamaları için çok uygundur.

ORCID ID: [1]0000-0002-6631-7559
[2]0000-0001-8309-3393

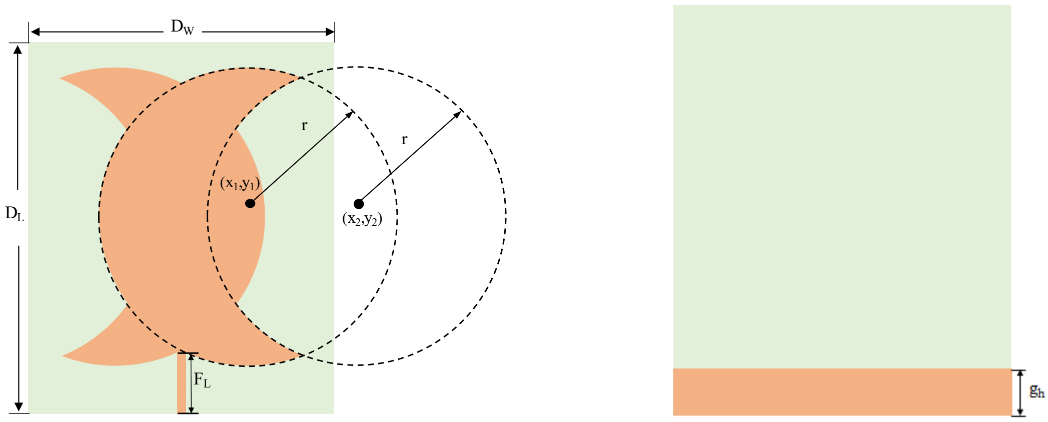
1. INTRODUCTION

Wireless communication systems have become indispensable in various areas, aiming to facilitate our lives in recent years. Particularly in domains such as smart home systems, autonomous vehicles, and healthcare applications, they play a significant role due to their ability to be easily integrated into mobile devices, providing extensive coverage, ensuring communication security, and enhancing efficiency. Communication systems have various frequency bands to optimize communication performance and improve user experience. Among these bands, Personal Communications Service (PCS), Universal Mobile Communication System (UMTS), LTE2300, LTE2500, Industrial, Scientific and Medical (ISM), Wi-Fi, Bluetooth, and 4G LTE are the most used frequency bands [1,3]. Considering the wide frequency bands used for wireless communication, it is crucial for adequately designed antennas to operate effectively and optimize signal quality. Antennas perform essential functions such as transmitting, receiving, and directing signals, thereby influencing the performance of wireless devices [4]. Different types of antennas can be found in the literature when wide frequency bands are used for wireless communication. This variety includes antenna designs specifically created to fulfill different application needs. Examples of these antenna types include Yagi antennas [5,6], dipole antennas [7,8], spiral antennas [9,10], helical antennas [11], horn antennas [12,14], and microstrip patch antennas [15,17]. Microstrip patch antennas are favored in antenna design due to their advantageous characteristics such as cost-effectiveness, lightweight construction, ease of integration, and energy efficiency. Nonetheless, they are also subject to certain limitations [18]. For instance, limitations exist regarding limited bandwidth and directivity gain. Under certain circumstances, these drawbacks may limit the performance of communication and result in physical limitations such antenna size. To improve directivity gain, expand bandwidth, and boost patch antenna efficiency, research and development are therefore continuing. Among various techniques employed to improve patch antenna bandwidth, increasing the thickness of the dielectric layer or reducing the dielectric constant is a common approach. However, these methods yield only a modest 10% increase in bandwidth, necessitating alternative techniques [19-20]. Additionally, feeding techniques also impact the bandwidth of microstrip patch antennas. A study found that the aperture-coupled feeding method resulted in the highest bandwidth, followed by proximity feeding, microstrip feeding, and finally, coaxial feeding [21]. Because of its ease of feeding compatibility and suitability for low-profile designs, microstrip feeding is chosen in this investigation. Using a shorting pin is an additional technique for expanding bandwidth. When a 50×50 mm^2 circular microstrip patch antenna with a shorting pin was used, the bandwidth was increased by an astounding 135%. As a result, the bandwidth was attained at 171.4 MHz with a -27.96 dB return loss. Furthermore, the antenna design produced a 0.6502 dBi directivity gain [22]. However, using a shorting pin introduces additional production challenges and costs. Another method involves using a Near Zero Index Metamaterial, which increased the bandwidth by 90 MHz in a study conducted in 2022 [23]. However, the use of metamaterials introduces frequency dependence and manufacturing difficulties. A rectangular microstrip patch antenna, which operates at a resonance frequency of 2.39 GHz inside the S-band, is another antenna that has been discussed in the literature. With measurements of 75.85×7.23×1.6 mm^3, it is made of FR-4 material. A bandwidth of 58 MHz and a return loss of -38.86 dB were achieved by this design [24]. Another study presented a rectangular microstrip patch antenna on an FR-4 material with 76×59×1.6 mm^3 dimensions. With a frequency centering at 2.4 GHz, the antenna displayed a proportional bandwidth of 2.91%. The antenna used a partial ground plane with a directivity gain of 4.7 dBi to obtain a return loss of -44.78 dB [25]. In 2023, a study was carried out to build a circular microstrip patch antenna with dimensions of 80×80×1.6 mm^3 with FR-4 material. The antenna was specifically developed to operate at a resonance frequency of 2.36 GHz. Through extensive testing and analysis, the antenna demonstrated impressive performance characteristics. The antenna demonstrated a return loss of -25.72 dB, suggesting effective power transmission between the feed line and the antenna. Moreover, it attained a commendable bandwidth of 48 MHz, enabling the transmission and reception of a broad spectrum of frequencies [26]. For S-band applications, a planar inverted F antenna (PIFA) was presented in another study. With a bandwidth of 301 MHz between 2.202 GHz and 2.504 GHz, the suggested antenna obtained a return loss of -21 dB. The antenna was 140×70×1.365 mm^2 and had a directivity gain of 5.62 dBi [27]. In a study conducted in 2023, a triangular microstrip patch antenna design composed of a 49×45 mm^2 patch on an RT/Duroid 5880 substrate was presented. The antenna exhibited electrical characteristics such as a bandwidth of 64.5 MHz, a return loss of 1.39 VSWR, and an antenna gain of 4.77 dB [28]. Partial ground plane usage for microstrip patch antennas enables increased bandwidth, improved efficiency, and easy integration with integrated circuits [29-30].

This paper introduces a microstrip-fed planar single-polarized antenna with a low-profile structure that can effectively support multiple mobile wireless standards, providing good return loss below -56.1 dB at a central resonance frequency of 2.4 GHz and seamless communication capability between 1.91 GHz and 2.81 GHz. A partial ground plane is preferred as a bandwidth enhancement method. The antenna design is subjected to simulation, fabrication, and testing to assess its performance against simulated outcomes. Both numerical analysis and practical experimentation are employed to evaluate the efficacy of the antenna design.

2. ANTENNA DESIGN

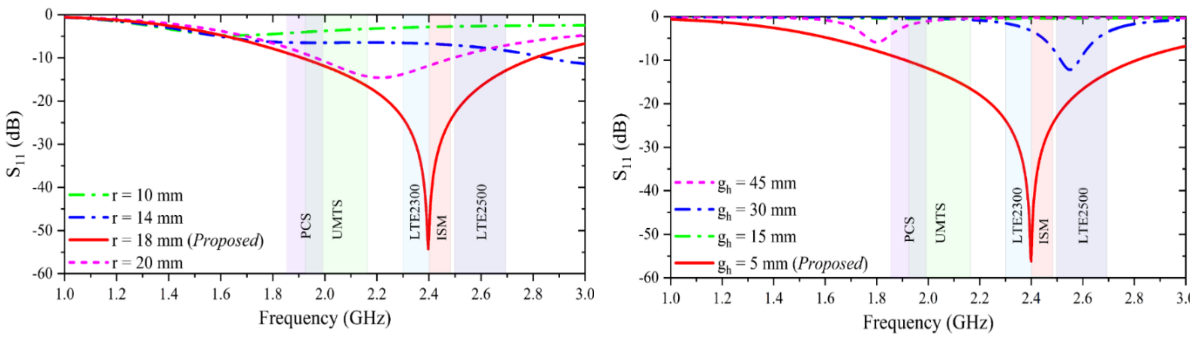
The proposed antenna operates at a frequency of 2.4 GHz, adhering to IEEE 802.11 b/g/n standards, and covers various frequency bands including PCS, between 1.85–1.99 GHz, UMTS ranging from 1.92-2.17 GHz, LTE2300 from 2300-2400MHz, LTE2500 spanning 2500-2690MHz, ISM covering 2.40-2.485 GHz, as well as Wi-Fi, Bluetooth, and 4G LTE. The proposed antenna is fabricated using FR-4 material, characterized by a relative dielectric constant (εr) of 4.3 and a loss tangent (tan δ) of 0.02. The antenna dimensions are 36.88x44.85 mm² with a thickness of 1.6 mm. Choosing FR-4 dielectric material ensures cost-effectiveness and extensive industrial applicability. The antenna configuration comprises a microstrip feed line, a patch formed by the intersection of two mirror-image replacement structures on the front face, and a partial ground plane. The patch and front face are shown in detail in Figure 1 (Figure 1a), and the length of the partial ground plane on the back is shown in Figure 1b.



a) b)

Figure 1. Proposed antenna length parameter values a) Top view, b) Bottom view.

In this study, the crescent shape is derived through the geometric intersection of two circles, each centered at distinct coordinates, denoted as (x_1, y_1) and (x_2, y_2). The crescent shape emerges as the outcome of the overlapping area shared by these two circles as shown in Figure 1a. Subsequently, a mirror-image transformation is applied to this initial crescent shape, followed by an overlapping procedure, resulting in the creation of the D-Crescent-Shape patch geometry. The microstrip antenna's upper face is made up of a feeding line and a patch that are intended to match an impedance of 50 ohms. The lengths of the radiating patch optimization graphs for the designed antenna are presented in Figure 2. The optimization of the radius (r) of the circles centered at (x_1, y_1) and (x_2, y_2) forming the crescent patch shape, is illustrated in Figure 2a to enable radiation at 2.4 GHz. A partial ground plane is utilized in the antenna design. Figure 2b demonstrates the optimization of the ground surface height (g_h), conducted to enhance the microstrip patch antenna's performance within the 2.4 GHz ISM band. This optimization process focused on improving impedance matching, radiation pattern, and overall antenna efficiency by carefully adjusting the ground plane's height. To satisfy the demands of wireless communication applications across the industrial, scientific, and medical domains, it was necessary to optimize the antenna's performance and ensure effective operation within the designated frequency band. The antenna's transmission line and the partially ground plane are soldered with a SMA connector to enable measurement.



a) b)

Figure 2. Optimization of the designed antenna a) radius (r), b) ground plane height (g_h).

The antenna's length measurements are shown in Table 1.

3. RESULT AND DISCUSSION

This section includes both computational and experimental analysis of the proposed d-crescent-shaped monopole patch antenna. The CST Microwave Studio program yielded the antenna's performance parameters, which are given. The measurements of the S_{11} reflection coefficients of the fabricated patch antenna are conducted by using

E5063A Vector Network Analyzer. The S_{11} parameter is a crucial statistic that verifies the antenna's efficient operation. Figure 3 shows the results of the proposed antenna simulation and measurements.

Table 1. Proposed antenna physical dimensions

Parameters	Size(mm)	Parameters	Size(mm)
D_L	44.85	r	18
D_W	36.88	(x_1, y_1)	(8,1.42)
F_L	7.47	(x_2, y_2)	(21.3,1.42)
g_h	5		

The antenna reaches 900 MHz in bandwidth. The measurement of an antenna's efficiency in transmitting an RF signal to its intended recipient is called return loss or reflection coefficient. The antenna being studied demonstrates a return loss of -56.1 dB. With only slight discrepancies likely stemming from manufacturing imperfections in the prototype, the experimental data closely align with the expected outcomes.

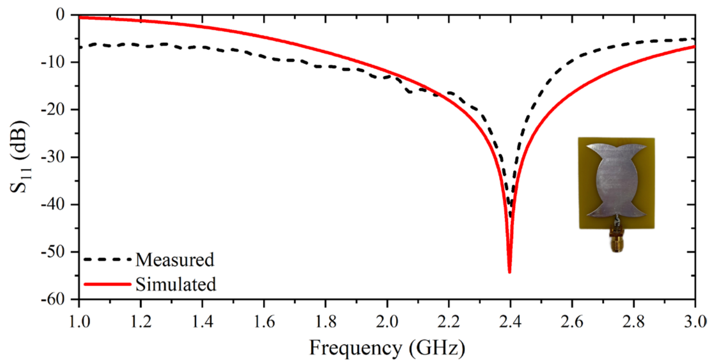


Figure 3. Reflection coefficient of the antenna.

A metric called "directivity" is used to measure how much energy an antenna emits in a certain direction. The ratio of the intensity in the direction of highest radiation to the average intensity distributed over all directions is what it represents. Based on simulation results, the directivity gain graph of the antenna constructed in this work is shown in Figure 4, which is shown in three dimensions at the central frequency. According to the collected results, the suggested antenna at 2.4 GHz achieves a directivity gain of 2.21 dBi.

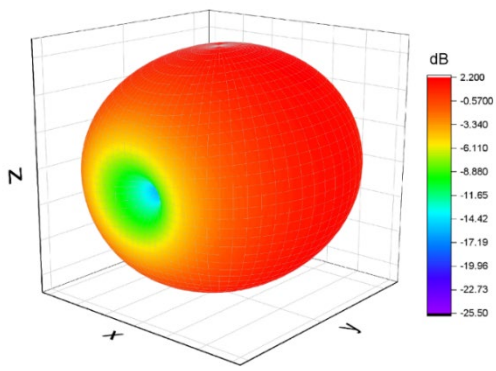


Figure 4. 3D directivity gain graph at center frequency of the proposed antenna.

A radiation model is a graphical representation of the way electromagnetic radiation propagates through space. This model shows the varying signal strength of the antenna in different directions. Figure 5 shows the simulated radiation characteristic of the D-crescent shaped antenna for φ=0° and φ=90°. In case of phi=0, half power beamwidth (HPBW) is determined as 68.4°, while in case of phi=90, it is determined as 86.5°.

At the 2.4 GHz resonance frequency, the maximum surface current amplitude of the planned antenna, as indicated in Figure 6, is 32.7 dB (A/m). Concentrations of surface currents are seen along the patch's borders and where it meets the feed line. These results show that the antenna's surface current distribution satisfies the design goals and performs well at the targeted frequency.

The proposed antenna's gain variation with respect to frequency is depicted in Figure 7. At the 2.4 GHz resonance frequency, the design produces 2.21 dBi gain. The directionality gain value fluctuates between 2.17 dBi and 2.69 dBi in the region between $S_{11} < -10$dB and 1.91 GHz to 2.81 GHz, as shown in Figure 7. The data indicates that the antenna performs well in terms of directivity at the center frequency and has potential uses in wireless communication.

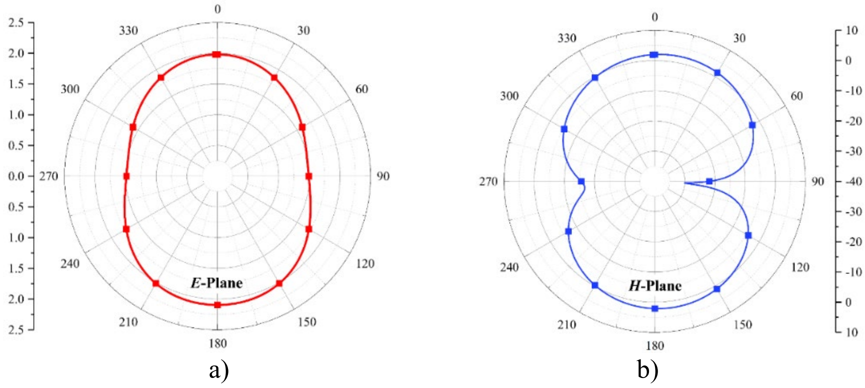


Figure 5. 2D graph of the proposed antenna radiation pattern. a) E - plane a) H – plane.

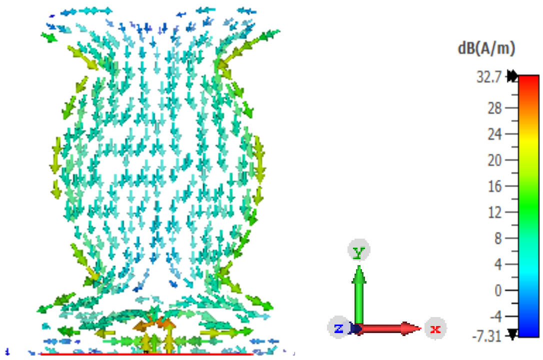


Figure 6. Surface current distribution of the proposed antenna.

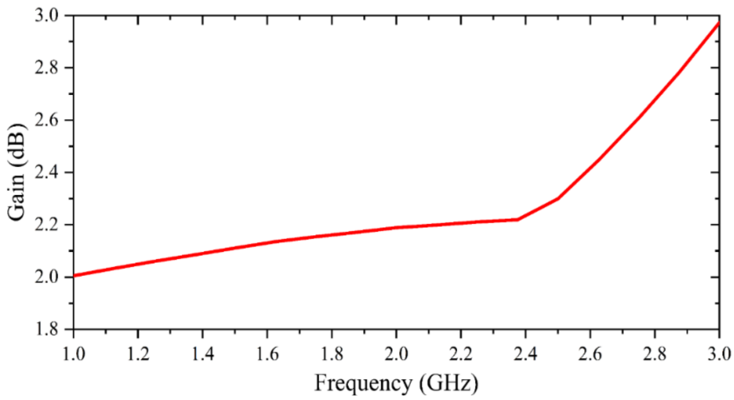


Figure 7. Directivity-gain of the antenna.

The efficiency of the proposed antenna in transmitting radio frequency signals is evaluated through the Voltage Standing Wave Ratio (VSWR), depicting the impedance mismatch between the antenna and the transmission line. Figure 8 illustrates the frequency-dependent VSWR graph, revealing a value of 1.008 within the 2.4 GHz center frequency band. This result indicates the performance of the antenna at the central frequency, underlines its suitability for efficient deployment in wireless communication applications.

Table 2 presents a comparison of the antenna with the literature from the studies conducted at the 2.4 GHz band. The table shows that the suggested reference antenna provides better values than research in the following areas found in published literature. Alternatively, the study that is being offered shows an antenna that is much smaller, measuring only 36.88×44.85×1.6 mm³. It achieves an impressive 56.1 dB return loss, 900 MHz bandwidth at 2.4 GHz, and 2.21 dBi gain. This significant reduction in size and frequency operation demonstrates the potential for compact and efficient antenna design in high-frequency applications. Its small size and efficiency make it suitable for integration into wireless sensor networks (WSNs) for environmental monitoring and industrial automation, as well as Internet of Things (IoT) devices for smart homes and industrial applications. Furthermore, its potential integration into smartphones, tablets, and portable devices could enhance wireless connectivity for everyday communication and location-based services.

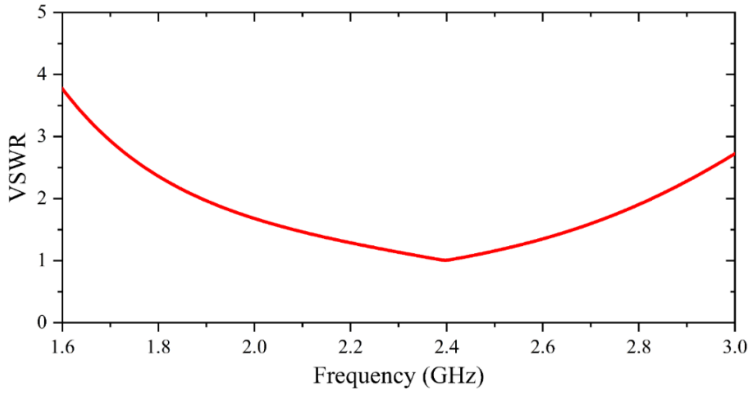


Figure 8. VSWR graph showing the standing wave ratio of the antenna.

Table 2. Analyzing the proposed antenna in relation to previous research

Ref.	Res. Freq	Antenna dim. (mm^3)	Bandwidth	Return loss (dB)	Direc. Gain (dBi)
[24]	2.4	75.85×57.23×1.6	58 MHz	-38.86	6.8 dBi
[25]	2.4	76×59×1.6	70 MHz	-44.78	4.702 dBi
[26]	2.36	80×80×1.6	48 MHz	-25.72	2.97 dBi
[27]	2.35	140×70×1.365	301 MHz	-21.875	5.62 dBi
[28]	2.4	49×45×1.575	64.5 MHz	-15.7	4.77 dB
This Work	2.4	36.88×44.85×1.6	900 MHz	-56.1	2.21 dBi

4. CONCLUSION

The growing need for next-generation antennas with high bandwidth, low profile, and affordability has resulted in substantial advancements in wireless and mobile communication, as this study demonstrates. This increase in demand extends to commonly utilized frequency ranges including 4G LTE, Wi-Fi, Bluetooth, ISM, PCS, UMTS, LTE2300, and LTE2500. Improving the bandwidth and return loss of a low-profile antenna is the primary goal of this research project. To do this, a novel patch geometry with a partial ground plane is introduced. The proposed antenna, which is made with a 1.6 mm FR-4 dielectric substrate, shows a center frequency of 2.4 GHz and a broad bandwidth of 38%. It can operate between 1.91 GHz and 2.81 GHz. The antenna also exhibits a gain of 2.21 dBi and a reflection coefficient of -56.1 dB. Our suggested design is a good choice for a range of wireless communication system applications because of its noteworthy qualities, which include high bandwidth, simplicity, and ease of manufacture. The antenna's compact size and efficiency enable its seamless integration into wireless sensor networks (WSNs) designed for environmental monitoring and industrial automation tasks. Similarly, it finds utility in Internet of Things (IoT) devices tailored for smart homes and industrial settings, offering reliable connectivity across various frequency bands. Moreover, its potential inclusion in smartphones, tablets, and portable devices presents opportunities to support wireless connectivity for daily communication needs and location-based services, ensuring across multiple frequency bands.

Author's Contributions:

All authors contributed equally. All authors read and approved the final manuscript.

Statement of Conflict of Interest:

The authors declare that they have no competing interests.

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