Improved Millimeter Wave Patch Antenna for Next-Generation and Beyond Networks

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This paper presents an optimization of a compact, ultra-wideband (UWB) rectangular microstrip patch antenna (MSPA), tailored for next-generation mm-wave wireless applications. The proposed UWB antenna offers significant enhancements in gain and bandwidth. It achieves an impressive bandwidth of 36 GHz, covering the V-band (40–75 GHz), essential for high-capacity satellite communication, as well as the 61.25GHz ISM band and most of the 60GHz WiGig band. Simulations performed using CST MW Studio 2021 demonstrate that the antenna achieves a maximum efficiency of 93.3% at 44.2 GHz and a minimum efficiency of 63.1% at 66.2 GHz. A maximum realized gain is 10.2 dB at 55.8 GHz, with the lowest realized gain being 4 dB at 65 GHz. These results underscore the antenna's suitability for future 5G handheld devices and other high-frequency applications. Comparative analysis with existing designs is provided, highlighting the proposed antenna's superior performance metrics.

Keywords: 5G, Mm-Wave, Ultrawideband, V-Band, Wireless Communication

Introduction:

The annual data traffic in wireless networks is experiencing an unprecedented surge, increasing by 40% to 70% each year. This exponential growth suggests that wireless networks will need to provide up to 1000 times more capacity in coming years than they currently do. To meet this rapidly escalating demand, an implementation of fifth-generation (5G) systems, which offer peak throughput capabilities of multiple gigabits per second (Gb/s), is seen as a crucial solution for future communication applications [1][2][3].

However, sub-6 GHz frequency bands, which are currently widely utilized for wireless communication, suffer from limited channel capacity and restricted bandwidth. These limitations have prompted researchers and engineers to explore the underutilized millimeter-wave (mm-wave) spectrum for 5G wireless communication systems [4], [5]. The mm-wave spectrum, with its higher frequency bands, provides significantly more bandwidth and capacity, making it an essential component in addressing the ever-growing data demands of modern networks.

Deployment of 5G technology is vital not only for supporting exponentially increasing data rates and accommodating the growing number of connected devices with low power consumption and high reliability but also for enhancing the capabilities of emerging technologies. Applications such as smart cities, the Internet of Vehicles (IoV), and virtual reality (VR) will benefit significantly from the high-speed, low-latency, and robust communication provided by 5G networks [6].

However, this progress is fraught with issues that hinder the efficient implementation of mm-wave communications, such as atmospheric absorption that reduces the signal strength and path loss that reduces the length of the communication link. Special bands in the range of mm-wave include Higher frequency bands including mobile communications and usage of the ISM band ranging from 61- 61. 5 GHz [7], [8]. There was heavily rising interest in performance and new applications of mobile phones and WiGig or 60 GHz Wi-Fi, so the primary goal in designing the antennas was to increase the gain and bandwidth. WiGig currently operates in the 57 GHz to 71 GHz spectrum and includes the existing IEEE 802. 11ad Wi-Fi standard up to the prospective one IEEE 802. 11ay and facilitates the devices to communicate at multi-gigabit speed [9]. This wide frequency operation and high data rate becomes important for the development of wireless technologies and satisfies the increasing demand for higher speed and reliable data transfer.

Microstrip Patch Antennas have been widely acknowledged often because of their low profile, low weight, compact size, low cost, plus simplicity in fabrication. These attributes make MPAs appropriate for planar and non-planar structures particularly when used to further the development of 5G technology. For example, there are slots, which can help to increase gain, as well as efficiency [10]. To enhance the performance, some strategies including slot integration, antenna arrays, defective ground plane structures, and the incorporation of metamaterials have been incorporated [11]. For example, the MPA configuration that included two vertical slots was suggested for the C-Band frequencies and the studies indicated successful results [12]. Likewise, detailed research on planar antennas revealed that it was possible to attain a gain of 14. 22dB at a frequency of 44. 8GHz and a gain of 9. 9db at 67. 8GHz and using linear array configuration [13]. Also, another patch antenna design has been proposed and has offered a bandwidth of 1.318 GHz, return loss of -19. 5 dB, and resonant frequency of 24.85GHz [14]. Another design included a rectangular single-patch antenna that was fed by a notch in the microstrip line; it was specifically for 5G [15]. These enhancements show the possibilities and viability of MPAs in fulfilling the tough challenges of today's wireless communication links.

In the work [16], there is described a design of four array antennas with circular polarization and SIW configuration. This design gave an axial ratio bandwidth of 14% and a gain of 15. 9 dBi. When it comes to the evolution aspect, one must bear in mind that AR bandwidth is narrower in case of circularly polarized (CP) antennas Though, SRT has been introduced in prior research [17], [18] to overcome this shortcoming. Also, this work agrees with the method called the partial ground plane, mentioned in [19], which is found to be effective in enhancing the gain and extending the bandwidth of MSPAs [20].

This paper therefore describes an ultra-wideband rectangular microstrip patch antenna that covers over 95% of the V-bands pertaining to future 5G use. The antenna also works in 61. 25 GHz ISM band and covers the entire operating bandwidth of WiGig which is between 57 GHz to 71 GHz. The last optimized design shows the bandwidth is significantly wider ranging from 38 GHz to 74 GHz covers the V-band frequency range of 40- 75 GHz and, in a way, represents six distinguishable mm-wave bands. This extensive coverage positions the proposed antenna as a versatile solution for high-capacity satellite communication and advanced 5G networks, addressing the comprehensive needs of next-generation wireless technologies.

Objectives and Novelty:

- Design and optimize the performance of a compact UWB MSPA. In order to develop and evolve a small UWB rectangular MSPA antenna for next-generation mm-wave wireless communication systems such as Satellite communication and 5G devices.
- Enhanced Bandwidth and Gain Performance: To achieve a great 36 GHz bandwidth covering important frequency ranges including the V-band, the 61.25 GHz ISM band, and the 60 GHz WiGig band in addition to impressive improvements in gain and efficiency.
- Simulation and Analysis: To be able to perform deeper simulations with CST MW Studio 2021 to test the efficiency of the antenna, realized gain, and bandwidth at several frequencies, and compare the results with recent academic research.
- Lead Assessment of the Suitability of the Antenna for High-Frequency Techniques: To assess the capabilities and fitness of the antenna for next-generation communication systems with high-frequency technology for example use in 5G handheld devices and satellite communication.

This research provides a compact design of a rectangular microstrip patch with bandwidth optimization for upcoming mm-wave wireless technologies, which is presented as a design that provides striking gains in gain as well as bandwidth. The design includes a wide bandwidth of 36 GHz that can cover V-band (40–75 GHz), 61.25 GHz, and most of the 60 GHz WiGig band to guarantee high performance in high-capacity satellite communication and next-generation 5G systems. The major innovation in the design is its emphasis on efficiency maximization (93.3%) and high gain realization (10.2 dB) at relevant frequencies that improve its applicability to high-frequency systems of communications. Compared with existing designs, the proposed antenna shows superior performance highlighting its significance in representing a significant step forward for the development of UWB antennas for advanced wireless systems.

Antenna Design:

The design and measurements of the suggested ultra-wideband antenna are shown in Figure. 1(a) and (b).

The overall dimension of the proposed antenna is chosen as square, which is optimally set to 14×16 mm². The substrate material used by the hardware is Rogers RT5880 high-frequency laminate with a thickness of 0. 508 mm, and patch size is 10×10 mm while made of copper with a thickness of 0. 035 mm, and the ground plane is measured at 14×13.9 mm made of annealed copper, and the partial ground is also included under the patch. In this case, two slots at the two sides of the presented patch enable the antenna to be tuned to the correct frequency. The layout dimensions for this design are listed in the table below; Table I: Layout

Dimensions. Its UWB covers seven bands pertinent to future 5G services and six within the existing bands (42.5–43.5 GHz, 45.5 to 47 GHz, 47.2 to 50.2 GHz, and 50.4 to 52.6 GHz). Moreover, two more bands; 40. 5-42. 5 GHz and 47-47. 2 GHz are recommended for future use as stated in [21].

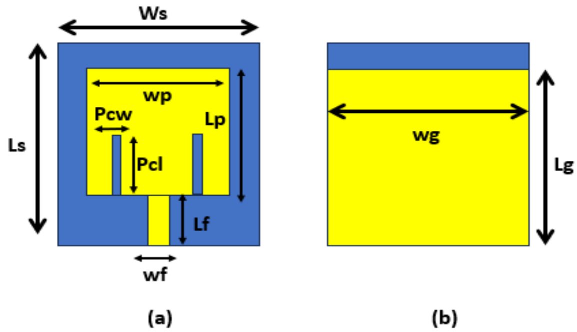

Figure 1. The front and back view of the antenna layout

Table 1. Antenna dimensions detail

Parameters	Description	Values (mm)
Ws	Width of substrate	16
Ls	Length of substrate	14
Hs	Hight of substrate	0.508
Wp	Width of patch	10
Lp	Length of patch	10
Top	Thickness of patch	0.035
Wf	Width of feed	1.505
Lf	Length of feed	4
Wg	Width of ground	14
Lg	Length of ground	13.9
Pcw	Patch cut width	0.4, 0.5, 0.6
Pcl	Patch cut length	4.7

Methodology:

The development of the proposed rectangular microstrip patch antenna based on UWB commenced with a literature review to find out what questions there are as far as the design of mm-wave antennas is concerned. Based on these findings, we came up with a preliminary antenna configuration whose purpose was to attain small size and wide frequency range performance. Thereafter the antenna was modeled and simulated in CST Microwave Studio 2021 in order to find the parameters as return loss, bandwidth, gain, and efficiency. After the simulation was concluded, we sat to review the results to identify the areas which could be improved. Based on the insights from the analysis, further improvement on the design was carried out to improve the performance of the DiD device concentrating on the V-band and WiGig bands. Improvements were then made resulting in improved gain, bandwidth, and efficiency evident in the optimization stage of the methodology diagram.

Results:

The S-parameters of the proposed antenna are depicted in Figure 2 while keeping other parameters of the same as in the previous antennas reported in [22][23], and the current modified antenna]. The antenna presented in the work [22] has a maximum bandwidth of 1.107 GHz and the maximum realized gain is 7.71 dB at 37 GHz. A printed antenna in reference [23] achieves a maximum efficiency of 95. 3%, with a bandwidth of 31.7 GHz while the maximum realized gain is 7.7 dB at the operating frequency of 41.4 GHz. In similar circumstances, both antennas have a VSWR of 3:1 under respective operations, where the impedance bandwidth is regarded at -6 dB from the center value.

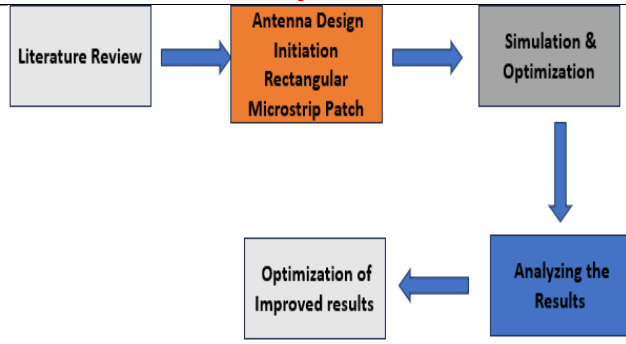

Figure 2. presents the step-by-step methodology for designing and evaluating the proposed ultra-wideband rectangular microstrip patch antenna.

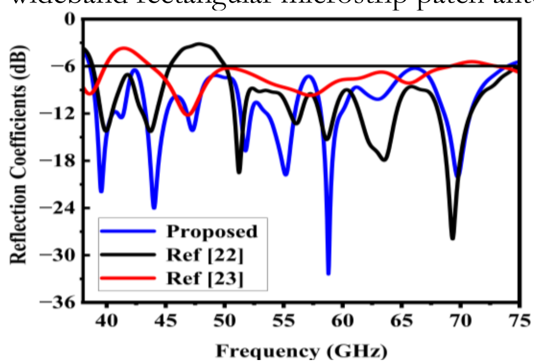

Figure 3. S-parameters of the initially designed antenna without any modifications to its parameters and proposed modified antenna.

To achieve ultra-wideband performance, the dimensions of a patch and ground plane were varied. The specific adjustments and their effects are detailed in the following subsection.

Pcw = 0.4, 0.5, 0.6, Pcl = 4.7, Wg = 14 and Lg = 13.9

The parameters PCL and pcw mean the patch cut length for the desired wavelength and half patch width, respectively, and Wg and Lg mean the width and length of the ground plane of the desired microstrip antenna respectively. Dimension is only maintained at this point is the length and width of the ground as indicated earlier. Changing the patch cut width brings the VSWR improvement in terms of the reflection coefficient manifesting a wider reflection coefficient originating from a dual band. Thus, the optimized values of the patch cut width are 0.4, 0.5, and 0.6 mm only. The reflection coefficient is represented in Figure 3 which shows the reflection coefficient for the different patch cut widths.

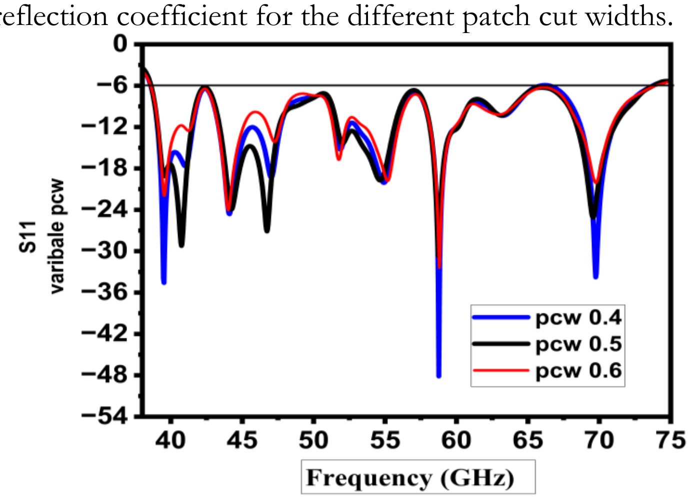

Figure 4. Reflection coefficient of fixed patch cut length and varying patch cut width.

Pcw = 0.6, Pcl = 4.7, Wg = 14 and Lg = 13.9

To achieve the desired ultra-wideband performance, the patch cut width was increased from 0.4 mm to 0.6 mm, while the patch cut length was fixed at 4.7 mm. Additionally, the ground plane width was maintained at 14 mm, but its length was reduced from 14 mm to 13.9 mm. These modifications resulted in an improved reflection coefficient, indicating enhanced ultra-wideband capabilities. The reflection coefficient after these parameter changes is illustrated in Figure 4.

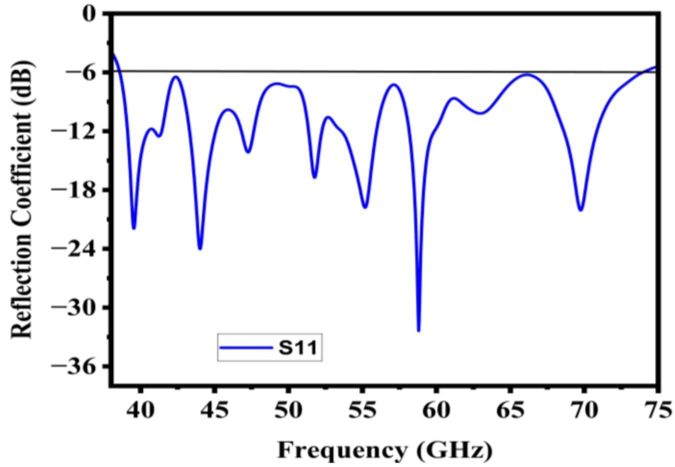

Figure 5. Reflection coefficient of proposed and modified ultra-wideband.

In comparing the proposed antenna design to several works found in literature, there is only one perceived issue with its performance over the previously created designs. However significant advantages include getting higher gain and wider bandwidth of the circuit that uses this technique. This comparison is illustrated in Table II below. The last optimized rectangular microstrip patch is fabricated with ultra-wideband characteristics, which operates over the range of 36 GHz. All this ranges from VHF to microwave and upper microwave frequencies useful for future 5G mobile communication devices. Thus, the proposed antenna occupies an ultra-wideband spectrum that contains a V-band which is vital for the high-capacity satellite communication channel. It also encloses the 61. 25 GHz ISM band along with a major part of the WiGig communication band which ranges from 57 GHz to 68. 36 GHz. Specifying the antenna performance by relying on the efficiency parameters, it is possible to define that the antenna under discussion possesses a maximum efficiency of 9/3%f at 44. 2 GHz and a minimum efficiency of 6/f3%f at 66. 2 GHz. In addition, the maximum realized gain of the antenna is 10. 2 dB at 55. 8 GHz, and the minimum realized is 4 dB at 65 GHz. The gain and efficiency performance attributes are depicted in Figure 5 below. In this study, the surface current distribution of the proposed modified UWB antenna is at 69. 5 GHz as depicted in Figure 6, which proves that 90% of the physical aperture of the antenna resonates in all the frequencies. The recurrent pattern of f radiation at this frequency is shown in Figure 7 below.

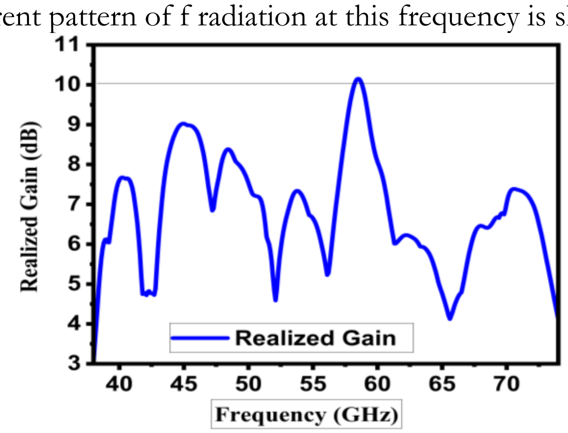

Figure 6. Realized gain of the proposed antenna.

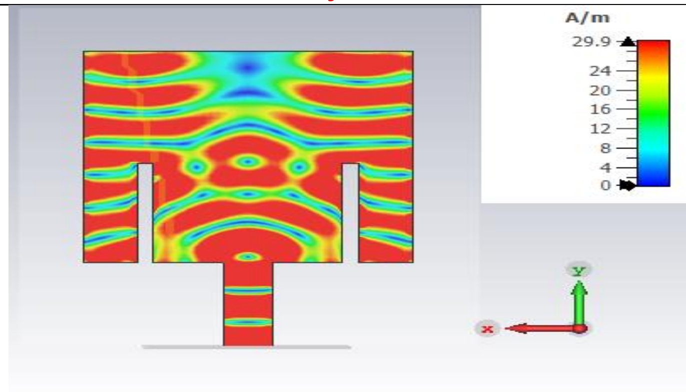

Figure 7. Illustration of the surface current distribution of ultra-wideband Antenna (UWB) at the frequency of 69.5 GHz.

Discussion:

Contrary to existing antennas, the proposed modified UWB rectangular microstrip patch antenna provides superior performance considering bandwidth, gain, and coverage. Unlike the narrow 1.107 GHz bandwidth and 7.71 dB gain provided by [22] and the 31.7 GHz bandwidth and 7.7 dB gain indicated by [23], the proposed antenna has a much wider bandwidth of 36 GHz (38-74 GHz) and a maximum gain of 10.2 dB at 55.8 GHz. By capturing more than 95% of the V-band, the full 61.25 GHz ISM band, and most of the WiGig band, this antenna is ideally designed for 5G and satellite communication applications. Increasing the patch and ground dimensions led to better reflection coefficients and VSWR, which will support effective ultra-wideband operations. The antenna shows outstanding efficiency at 93.3% until the end of the frequency range and high gain stability across the range, which is supported by the surface current distribution showing robust resonance. The results confirm the suitability of the antenna for emerging technologies that require mm-wave performance.

Table 2. Comparative Analysis

Ref	Frequency	Size	Bandwidth (dB)	Gain(dB)
[19]	37 / 54	7.2 × 5 × 0.787	1.5	N/A
[20]	30.5 / 41.5	10 × 10 × 0.762	5.5 / 8.67	5.5 / 6
[22]	37	14 × 16 × 0.508	1.107	7.71
[23]]	15.6 / 24.7 / 41.4	10 × 16.5 × 0.787	3.1 / 1.1 / 31.7	4.6 / 6.95 / 7.7
Prop.	38-75	14 × 16 × 0.508	36	10.2

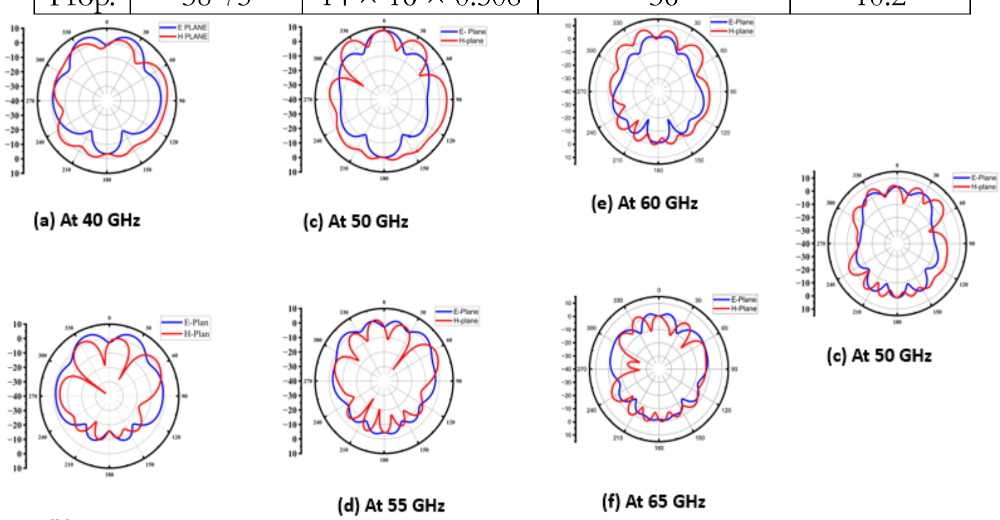

Figure 8. The radiation pattern of a proposed antenna at different frequencies

Conclusion:

In this paper, the proposed modified ultra-wideband antenna represents a significant advancement in antenna design for next-generation mm-wave wireless applications. Despite its larger physical footprint compared to some existing designs, the antenna offers substantial improvements in both gain and bandwidth. It achieves a 36 GHz bandwidth, covering critical frequency bands such as V-band, ISM band, and WiGig band, thereby making it suitable for high-capacity satellite communication and future 5G handheld devices. The antenna demonstrates maximum efficiencies of 93.3% at 44.2 GHz and 63.1% at 66.2 GHz, with a maximum realized gain of 10.2 dB at 55.8 GHz and a minimum of 4 dB at 65 GHz. This research underscores the antenna's potential to meet the demanding requirements of modern communication systems. Future research directions could focus on practical implementation and optimization for real-world applications, thereby contributing valuable insights to the advancement of mm-wave antenna technology. In the future, the proposed antenna will be fabricated and tested after that; the antenna will be reoptimized for higher realized gain and efficiency.

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The authors hereby confirm that the manuscript has not been published previously, nor is it under consideration for publication elsewhere. All authors contributed equally to the research and preparation of this manuscript and are in full agreement with its content.

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