Bandwidth Enhancement of a Tri-Band Slotted Microstrip Patch Antenna

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Manuscript received: October 16, 2023 / Revised: November 15, 2023 / Accepted: November 20, 2023

ABSTRACT

A tri-band microstrip patch antenna, designed for 5G applications, has been developed in this work. The antenna, with dimensions of $6 \times 4 \times 0.508$ mm3, was simulated using CST Microwave Studio 2019. The proposed design used a rectangular patch with a dielectric constant of 2.2 and a dielectric loss tangent of 0.001. The antenna dimensions were optimized using the Design of Experiments (DOE) method. Slotting the patch achieved a minimum return loss of up to -25 dB for each band, with the largest bandwidth of 2.78 GHz. Additionally, the influence of the antenna cutting slot on antenna properties is analyzed to show the trade-off between slot width and reflection coefficient (S11) parameter value.

KEYWORDS: Design of Experiments (DOE); patch antenna; tri-band; CST Microwave Studio

1 Introduction

The antenna is an essential part of a communication system since it is the device that transmits electromagnetic waves into free space and reverses that process (Balanis, 2016, Chen et al., 2020). Multiband antennas are crucial for mobile communication due to their ability to operate in various frequency bands with just one antenna (Chen et al., 2020, Elkorany et al., 2022, Mathew et al., 2015, Sharma et al., 2018). They are capable of supporting many frequency-operated devices at once, including Wi-Fi, WLAN bands (802.11 b/n/g), WiMAX (IEEE 802.16) and the 5th Generation (5G) applications (Al-Saeedi et al., 2021, Ramahatla et al., 2022, Ullah et al., 2018).

Wireless communication has significantly advanced in the past decade, necessitating the use of various antennas, including small, broadband, and multifrequency types, for fast data transfer. There are different types of antennas such as spiral antennas, dipoles, monopoles, etc. Microstrip patch antenna satisfies such requirements. Microstrip patch antennas are low profile, easy to construct, lightweight, cost-effective, comfortable on surfaces, simple, and manufactured using printed circuit boards. The microstrip patch antenna can meet multiple frequency requirements without using separate antennas, making it a challenging task for designers to design antennas with broadband characteristics (Masroor et al., 2021, Ngoc, 2020). A microstrip antenna, on the other hand, has a restricted bandwidth (Balanis, 2016). Several methods have been used to increase the bandwidth of microstrip antennas such as the dual feed line technique (Alam et al., 2021), using parasitic elements (Wang and Zhu, 2021), using a holey superstrate (Asaadi and Sebak, 2017), stacking of patches (Kewei et al., 2013) and fractal-based geometries (Reddy and Sarma, 2014) allowing them to operate in multiple frequency bands. One popular method for enhancing the bandwidth and gain of microstrip patch antennas is through patch-etching. For instance, T-shaped, H-shaped, and U-slotted patch microstrip patch antennas are studied (Ngoc, 2020, Li et al., 2020, Shaw et al., 2018).

Abdullah et al. designed a triple band antenna for energy harvesting, demonstrating acceptable performance in VSWR and return loss, but operating only in licensed frequency bands (Abdullah et al., 2022). AlShaikhli et al. (2022) proposed a triple band antenna for WiMAX, UAV drone data link systems, and WLAN applications. The antenna's design focuses on ground layer slits for enhanced electrical characteristics. The authors in Elkorany et al. (2022) proposed a planar microstrip patch antenna (MPA) with two F-shaped resonators for three-band operations, offering higher gain and radiation efficiency with a small fractional bandwidth.

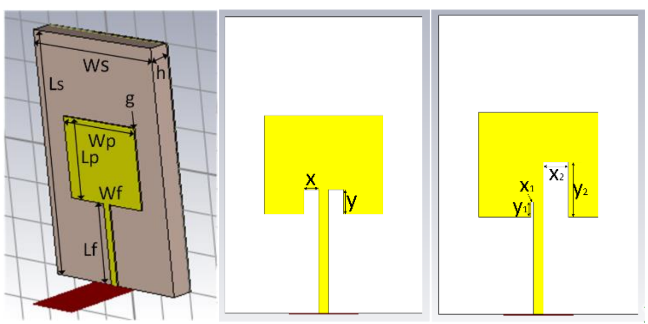
Recently, the growing number of smartphone subscribers and Internet of Things (IoT) devices demands large capacity and faster data rates, which the 4th Generation (4G) technology cannot provide. Therefore, the 5G technology uses multiple antennas at transceivers to increase channel capacity without increasing frequency bandwidth or transmitted power. Researchers are motivated to explore the electromagnetic spectrum of the unused millimeter-wave (30-300 GHz) for high data rate transmission due to the low latency and high-quality transmission demands of 5G applications. This is because the available bandwidth in this spectrum is widely available and can be exploited for high-speed data transmission. A variety of antenna designs have been developed for 5G applications in recent times (Saad and Mohamed, 2019, Imran et al., 2018, Dadgarpour et al., 2017, Kadhim et al., 2023).

In this paper, a microstrip planar antenna is proposed. The patch cuts enable multiband operation with improved bandwidth for each band. The antenna that is being proposed has the ability to operate at three different frequency bands, namely 28GHz, 38GHz, and 54GHz. This suggests antenna can be applied in 5G mobile communications. Additionally, methods for experimental design are utilized to ascertain the most suitable dimensions for the antenna.

The paper is structured as follows: Section 2 describes the recommended antenna geometry and method DOE to obtain the optimal dimensions. Proposed simulation results are discussed in Section 3, while Section 4 presents conclusions.

2 Methodology for Designing Antennas

The antennas proposed in this study are based on conventional rectangular patch antennas. They are slotted in different ways to achieve better control over the radiation behavior. Figure 1 shows the geometry of the proposed antennas in process. The original antenna is built on a rectangular Roger substrate.



(a) (b) (c)

Figure 1. Geometrical representation of designs: (a) the original rectangular patch antenna, (b) symmetrical slotted antenna, (c) asymmetrical slotted antenna

A microstrip patch antenna is made up of an active radiating patch on one side of a dielectric substrate and a ground plane on the other. The microstrip line feeding technique is used for feeding. Although there are other feeding techniques available, they do not offer easy impedance matching. However, with microstrip line feeding, impedance matching can be easily controlled by adjusting the width of the line.

In general, the dimensions of a microstrip antenna are typically calculated using equations found in Balanis (2016).

The well-known formulae used to calculate the dimension of this antenna are listed below.

Resonance frequency:

$$f_r = \frac{c}{2W\sqrt{(\varepsilon_r + 1)/2}} \tag{1}$$

where ε_r —dielectric constant, c is the speed of the light.

Width of the patch:

$$W_p = \frac{c}{2f_r\sqrt{(\varepsilon_r + 1)/2}} \tag{2}$$

Effective dielectric constant:

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\left(\frac{h}{W}\right)}}\right] \tag{3}$$

Length of the patch:

$$L_p = \frac{c}{2f_r\sqrt{\varepsilon_e}} - 0.824h\left[\frac{(\varepsilon_e + 0.3)\left(\frac{W}{h} + 0.26h\right)}{(\varepsilon_e - 0.258)\left(\frac{W}{h} + 0.26h\right)}\right] \tag{4}$$

Length of the ground plane

$$L_s = 6h + L_p \tag{5}$$

Width of the ground plane

$$W_s = 6h + W_p \tag{6}$$

Based on these calculation results, this paper focuses on optimizing the antenna dimensions to meet specific goals. Design of experiments (DOE) was invented by Ronald A. Fisher in the 1920s and 1930s (Fisher, 1960), is applied in this work. DOE is a mathematical methodology used for planning, conducting, and analyzing experiments, a branch of applied statistics, to study systems, processes, or products (Durakovic, 2017). The purpose is to find antenna sizes with return loss parameters that satisfy the condition of less than -25 and at resonant frequencies in the 5G frequency bands. The dimensions of the designed antenna are optimized using the DOE method.

Table 1. Dimensions of the original rectangular patch antenna (mm)

Ws	Ls	Wp	Lp	Wf	Lf	h	g
4	6	2.4	2	0.2	2	0.508	0.035

3 Results and Discussion

The optimization of antenna dimensions is carried out using DOE. The CST Studio Suite 2019 software was used to design and simulate the results of the designed microstrip patch antenna. From this, the study can derive the most optimal parameter set for each type of antenna. The performance of microstrip patch antennas is evaluated based on various radiation parameters including the resonant frequency (how close it is to the desired frequency band), reflection coefficient (S11), bandwidth, number of bandwidths, gain, directivity, Voltage Standing Wave Ratio (VSWR).

Error! Reference source not found. presents the performance result obtained from the conventional rectangular patch antenna in terms of the reflection coefficient (S11) parameter value.

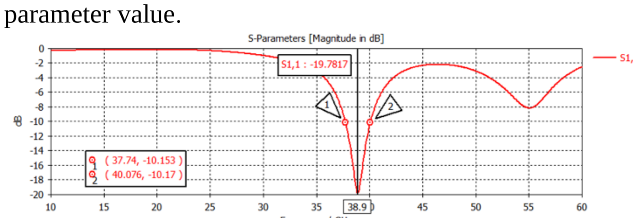


Figure 2. Reflection coefficient (S11) parameter value with respect to resonant frequency for the conventional rectangular patch antenna

The design exhibits resonance at 38GHz, which is a target frequency for 5G. To be more precise, this antenna achieves a resonant frequency very close to 38GHz (accurately at 38.9 GHz). It has a low reflection coefficient value of -19.7dB and a bandwidth of 2.4 GHz. However, this design has only single-band. Visualizing the current is an important aspect of gaining a better understanding of the physics involved and serves as a starting point for future optimization. The surface current of the original antenna is depicted in Figure 3.

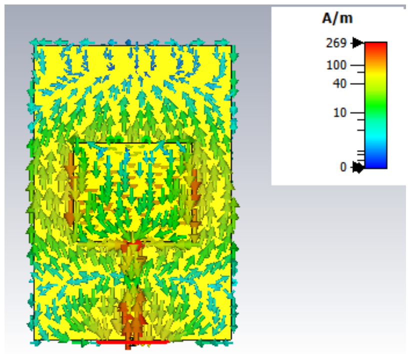


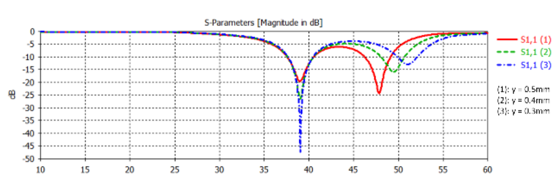
Figure 3. The surface current of the original antenna at the resonant frequencies

Figure. 3 displays the surface current, which shows that the strongest current flows between the edges of the patch. Research can be conducted to change the antenna parameters by modifying the shape and adding apertures in these important regions of the patch to obtain special properties. Furthermore, two options are suggested to achieve compatibility with 5G and improve results in multi-bandwidth.

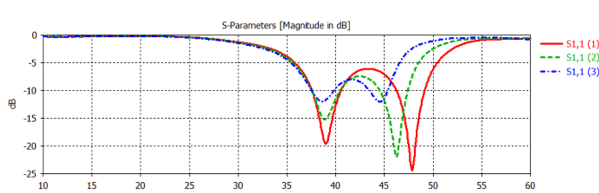
A symmetrical slotted antenna

In this design, the patch has been slotted symmetrically while maintaining all of the original parameters as shown in Figure 1b. The optimal slotted parameters can be determined using the DOE method. In this case, the optimal slotted size is received as x= 0.3mm and y = 0.5mm.

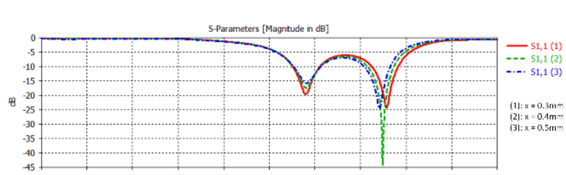
The frequency-dependent reflection coefficient (S11) parameter value for the symmetrical slotted antenna with variations in x or y is illustrated in Figure 3.



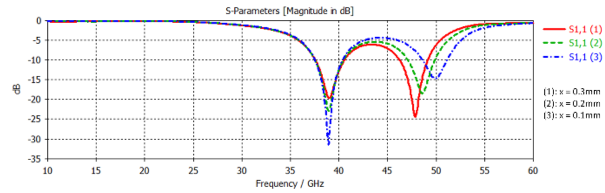
(a) Keeping all parameter in the an original design, fix the value of x, decreasing y



(b) Keeping all parameter in the an original design, fix the value of x, increasing y



(c) Keeping all parameter in the an original design, fix the value of y, increasing x



(d) Keeping all parameter in the an original design, fix the value of y, decreasing x

Figure 4. The reflection coefficient (S11) parameter value of the symmetrical slotted antenna at different frequencies: (a) decreasing y, fixed x; (b) increasing y, fixed x; (c) increasing x, fixed y; (d) decreasing x, fixed y.

It should be noted that the reflection coefficient (S11) parameter value is obtained at double frequency bands. Additionally, Figure 3 illustrates a trade-off between reflection coefficients of the two frequencies by modifying slotted parameters. Based on the observations, it is evident that the reflection coefficient (S11) parameter value in those two frequency bands is a trade-off for each other, regardless of whether the x or y values or both are changed. Thus, the antenna can operate efficiently in two frequency bands. By determining the optimal x and y values using the DOE method, a target reflection coefficient (S11) parameter value of -25 dB can be achieved.

Asymmetrical slotting antennas were studied by altering the slot dimensions on each side of the patch while retaining original antenna parameters. This is illustrated in Figure 1c. The optimal slotted dimensions for the asymmetrical antenna are x1=0.01mm, y1=0.3mm, x2=0.5mm, and y2=1.1mm, obtained using the DOE approach. Figure 5 displays the reflection coefficient (S11) parameter value.

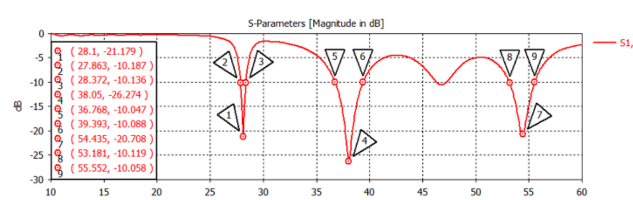
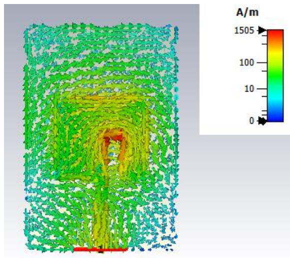


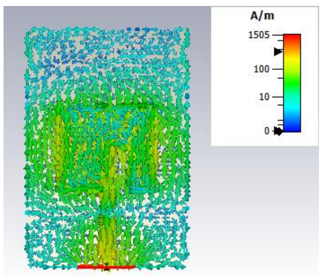
Figure 5. Three bandwidths of proposal antenna

In Figure 5 it can be observed that the simulated reflection coefficient of the antenna indicates that the antenna resonates well in three frequency bands. Table 2 lists the values of coefficients such as bandwidth, the reflection coefficient (S11) parameter value and gain of each resonant frequency band of the proposed antenna.

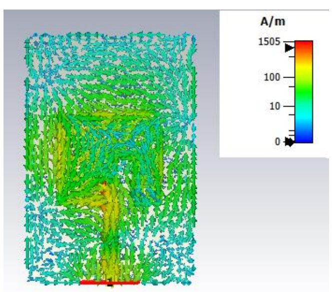
The current distribution of the symmetrical slotted antenna is displayed in Figure 6. When the original antenna is cut, the current on the patch is concentrated in the patch, which results in a reduction in the current flowing under the patch in the asymmetric antenna (about 8 A/m) as compared to the original antenna (about 40 A/m). This indicates that the impact on the patch can change the antenna characteristics and enable it to operate in multiple frequency bands.



(a) 28.11GHz



(b) 38.09 GHz



(c) 54.45 GHz

Figure 6. The surface current of the symmetrical slotted antenna at the resonant frequencies ((a) 28.11GHz; (b) 38.09 GHz, (c) 54.45 GHz)

The radiation pattern is another potential aspect that may be utilized to deduce the real nature of an antenna. The simulated two- and three-dimensional (2D, 3D) realized gain of the asymmetrical slotted antenna at three frequency bands are shown in Figures. 7, 8, 9.

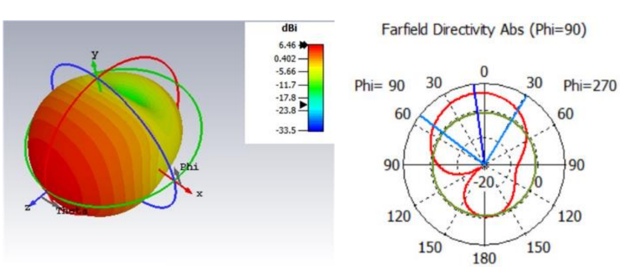


Figure 7. The radiation pattern for the proposal antenna at 28GHz in 3D (left) and in 2D (right)

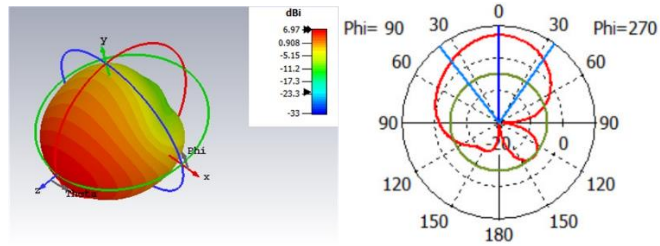


Figure 8. The radiation pattern for the proposal antenna at 38GHz in 3D (left) and in 2D (right)

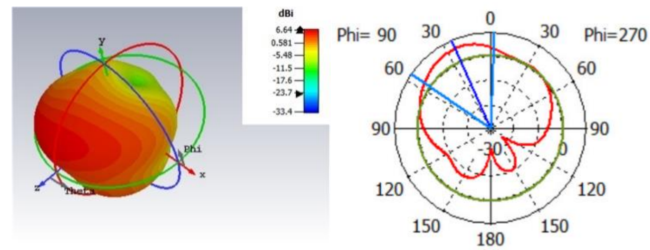


Figure 9. The radiation pattern for the proposal antenna at 54GHz in 3D (left) and in 2D (right)

These Figures 7, 8, 9 show that the antenna's maximum gains occur at almost zero degrees azimuthal angle and have a value of roughly 6.5 dB. It should be noted that the asymmetrical slotted antenna can be seen radiating in an almost omnidirectional pattern. Its main lobe, which contains the majority of its energy, is shown by red pixels. Significantly, the yellow and green pixels in these figures represent a small quantity of energy. Table 2 presents a comparison between the design of this work and the existing ones.

Table 2. The comparison of our proposed antenna with existing designs

	Frequency (GHz)	BW (GHz)	S11 (dB)	Gain (dB)
Imran et al. (2018)	38	1.94	-15.5	6.9
	54	2	-12	7.4
Darboe et al. (2019)	27.95	0.85	-13.48	8.37
Abdelaziz and Hamad (2019)	10	0.343	-25.8	5.67
	28	0.761	-24.9	9.33
	38	1.5	-32.9	9.57
Elfatimi et al. (2018)	28	0.921	-23.81	8.05
	38	1.05	-17.09	8.28
This work	28.11	0.51	-20.97	6.46
	38.09	2.78	-25.99	6.97
	54.45	2.38	-20.65	6.64

It is evident that this work offers better bandwidth and the reflection coefficient (S11) parameter value than Imran et al. (2018), while maintaining similar gain values. Although its gain is about 1.5 times lower, this designed antenna has a bandwidth up to 3 times wider than others. It is important to note that only the specific antenna design is capable of operating on the tri-band frequency of the 5G network.

4 Conclusion

In this work, a slotted microstrip patch antenna is designed for 5G wireless communication. The antenna provides a tri-band of 28GHz, 38GHz, and 54GHz frequencies that are all used in 5G communication. The microstrip antenna has a gain of 6.46, 6.97, and 6.64 for 28GHz, 38GHz, and 54GHz, respectively. To obtain the optimal dimensions of the designed antenna, the DOE method is used. This antenna has up to three times wider bandwidth than reference antennas. Furthermore, the effect of the antenna cutting slot on antenna attributes is carried out to demonstrate the trade-off between slot width and the reflection coefficient (S11) parameter value.

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