Design and Analysis of a 28 GHz Microstrip Patch Antenna for 5G Communication Systems

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Abstract – *In this paper, a 28GHz microstrip patch antenna (MSPA) design and performance analysis for fifth-generation (5G) communication systems is presented. The antenna is designed using FR-4 substrate material with thickness of 0.244 mm, and dielectric constant (ε_r) of 4.4 to operate at 28 GHz and analyzed using CST (Computer Simulation Technology) simulator. The simulated results show that, the beam-gain of 7.587 dBi, directivity of 7.509 dBi, the radiation efficiency of 98.214 %, and bandwidth of 1.046 GHz. As compared to other similar designs reported in the literature, the proposed antenna shows significantly better bandwidth, beam-gain, return loss, and radiation efficiency. Therefore, the proposed antenna gives a highly competitive performance as related to other works, and also, it is a potential candidate antenna type for 5G communication systems.*

Key Words: Antenna, Bandwidth, Beam-gain, Directivity, Fifth-Generation.

1. INTRODUCTION

Over the past few decades, wireless communication systems have brought a significant impact on the daily lives of human beings. Consequently, nowadays, more and more users connect their devices to the existing networks which are causing a constant increase in data traffic and the need for high-speed networks will keep increasing in the upcoming years. To deal with the ascension of wireless data traffic, the next deployment of wireless communication networks is at a nascent phase, which is stated to be a fifth generation wireless network [1-3].

The emerging 5G communication systems are projected to highly enhance communication capacity by exploiting enormous unlicensed bandwidth specifically, in the millimeter-wave band. It is also expected to be ready to provide and support very high data rates which in turn to a replacement challenge on network requirements as well as in the antenna designs to satisfy the expected data rate and capacity [4-6].

The advancement of wireless communication systems require low-profile antenna types that are capable of delivering astonishing performance over a wide frequency band. With this regard, the MSPA represents a lucid choice for wireless devices due to their low fabrication cost, lightweight and volume, and a low-profile configuration as compared to the other bulky types of antennas. The MSPA is easy and multipurpose in terms of polarization, resonant frequency, pattern, and input impedance. The patch antennas can be attached on the surface of high-performance aircraft, spacecraft, rockets, satellites, missiles, cars, and even hand-held mobile telephones. Therefore, the MSPA acting a substantial role within the fastest-growing wireless communications industry. However, the depth of the substrate material deteriorates the MSPA bandwidth and radiation efficiency, by boosting surface wave and spurious feed radiation laterally through the feeding line. Consequently, undesired cross-polarized radiation is directed by feed radiation effects. Also, the MSPA suffers from losses such as conductor, dielectric, and radiation which results in narrowing the bandwidth and lowering the gain [7-13].

Therefore, because of this performance limitation, the bandwidth of MSPA is narrow; its directivity, gain, and radiation efficiency are low for the futuristic 5G communication systems. Attempting to augment the MSPA performance for 5G communication, different designs have been demonstrated and reported in the scientific literature. Among these, to increase the bandwidth and radiation efficiency, many broadband patch antenna designs are reported in [7-9, 14-16]. Some of these design optimizations includes; the patch with multi-layer substrate integrated waveguide, and multi-patch designs, by incorporating multiple slots on the patch, by employing a defected ground plane, tuning dimension of the patch width, and employing a serial feed of the patch. Similarly, to reduce the feeding network structures and patch edge impedance mismatch, the use of quarter wavelength microstrip feed-line as inset-feed and lumped element to the patch edge were presented in [10, 15, 16].

Generally, by using the above-aforementioned techniques at resonant frequency rectangular patch antenna presented in [19-21, 24] achieves minimum return losses and wide -10 dB impedance bandwidth. Alternatively, due to poor impedance matching at the interfaces, the antenna return loss cited in [6, 8, 18, 22] is large for wireless communication. Besides, the antenna reported in [18-23] has a good beam-gain but the design reported in [6, 10, 22, 24] achieved bandwidth is narrow for 5G applications. In [6, 8, 22, 23] another similar MSPA is presented and achieved a minimum VSWR and better radiation efficiency.

Therefore, from the above summary of obtained simulation results in previous work, we can infer that the demonstrated work is tried to find better functionality in terms of one or two specific performance metrics. In this study, we are motivated to design and analyses a 28 GHz single element rectangular MSPA to see it's feasibility for 5G systems, and also increase all the key performance metrics of the antenna. To ensure this, we have used inset-feed and quarter-wavelength impedance matching techniques, tuning dimensions of the antenna.

The remaining part of the paper is ordered as follows. Section 2 explains the material specification and design methodology of a single element rectangular MSPA. Section 3 discusses the governing equations and design of the proposed antenna. The simulation results and discussion presented in section 4. Lastly, the conclusion is given section 5.

2. MATERIAL SPECIFICATION AND METHODOLOGY

The performance characteristics of the antennas are mainly determined by their shape of physical geometry, dimensions of antenna structures, and the material properties from which they are made. In this study, the rectangular patch shape is selected, because it is easy to design and analyze, and it has wide bandwidth by reason of its broader shape as compared to other types. The physical structure of the examined MSPA is given in Fig - 1. The MSPA is designed using the FR-4 substrate material with, a loss tangent of 0.0025, ε_r of 4.4, and a radiating copper metal thickness of 0.035 mm, which is planned to function at 28 GHz frequency. The MSPA performance is described by its bandwidth, directivity, return loss, gain, and radiation efficiency. To achieve our objective, we have used inset-feed impedance matching techniques, quarter-wavelength impedance transformer, and optimization of the antenna dimensions as methodology.

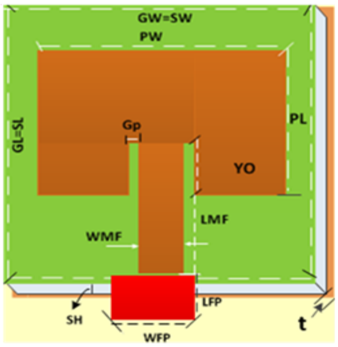


Fig -1. Proposed Inset-feed Rectangular MSPA.

3. GOVERNING EQUATIONS AND DESIGN OF THE PROPOSED MSPA

The overall goal of any antenna design is to achieve specific performance characteristics at a desired operating frequency. The very primary steps to begin the designing of the rectangular MSPA are, choosing the operating frequency, substrate type, and substrate thickness. Moreover, after preliminary design parameters are chosen, dimensioning of the remaining parameters of the antenna structure which are revealed in Fig - 1 is the subsequent step. These include substrate height, width and length of the patch, and ground plane dimensions. Various governing equations are employed to calculate dimensions of rectangular MSPA. Some of the major governing equations are presented as follows.

3.1. Height of the Substrate

The microstrip antenna height is related to substrate thickness or height (SH). The SH material is typically within the range of 0.003 $\lambda_0 \leq SH \leq 0.05\ \lambda_0$. Where, λ_0 denotes free-space wavelength. The substrate height is calculated by [13]:

$$SH = \frac{0.3C}{2\pi Fo\sqrt{\varepsilon_r}} \quad (1)$$

3.2. Patch Width

The patch width (PW) has less effect on the resonant frequency and radiation pattern. But it significantly affects the bandwidth and radiation efficiency of antenna. The PW is calculated by [13]:

$$PW = \frac{C}{2Fo\sqrt{\frac{\varepsilon r+1}{2}}} \quad (2)$$

3.3. Patch Length

During patch antenna design, the particular length of the patch is a critical parameter. Because of its inherent narrow bandwidth of the patch, it controls the resonant frequency. The patch length is sometimes selected within the range of 0.3333 $\lambda_0 < PL < 0.5\ \lambda_0$ [6]. Therefore, the actual patch length (PL) is found by using:

$$PL = PL_{eff} - 2\Delta PL \quad (3)$$

3.4. Length of the Inset

Ideally, at the patch edge, an impedance is high, which is around 300 Ω. However, impedance falls rapidly if the inset position is moved towards the center of the patch. Therefore, to match the patch to the 50 Ω feeder line, the inset length (Y_0) is used which can be calculated using Eq. (4) [17].

$$Yo = \left(\frac{PL}{\pi}\right)\mathrm{Cos}^{-1}\left(\sqrt{\frac{Z_O}{Z_L}}\right) \quad (4)$$

3.5. Feed Point Location

The feed point location to the rectangular MSPA is located in X-Y coordinates as X_f and Y_f respectively. The formula to calculate the feed point locations is given as follows [7].

$$X_f = \frac{PL}{2\sqrt{\varepsilon_{reff}}} \quad (5)$$

$$Y_f = \frac{PW}{2} \quad (6)$$

3.6. Ground Plane Dimension

The ground plane length and width are more than PL and PW completely encapsulate the patch and also the feed line. Because the radiation fields of rectangular MSPA are completely not confined to the patch i.e., a fraction of the field lies outside the physical dimensions of the patch. The ground plane dimensions are often calculated using the equation given below [6, 14].

GL = PL + 6SH (7)

GW = PW + 6SH (8)

3.7. Length Width and of Microstrip Feeder

A microstrip feeder line is positioned between the source and the antenna. The interfaces between the feeder line and antenna occur along microstrip feeder line width. Therefore, the impedance changes with the width of microstrip feeder line (WMF) instead of its length (LMF). Mathematically, the microstrip feeder line dimension are calculated by using the equation given below [14].

$$WMF = \frac{5.98SH \dfrac{1}{\exp\left(\dfrac{ZMFL\sqrt{\varepsilon_r}+1.41}{87}\right)} - t}{0.8} \quad (9)$$

$$LMF = \frac{\lambda_0}{4\sqrt{\varepsilon_r}} \quad (10)$$

Therefore, by substituting the initial design parameters in the above governing equations, the remaining physical dimensions of the proposed rectangular MSPA given in Fig - 1 can be calculated as follows. The substrate height, PW, and PL are calculated by substituting C = 3 * 10^8 m/sec, PL_{eff} = 2.701 mm, ΔPL = 0.1114 mm, ε_r = 4.4, and F_0 = 28 GHz in Eqs. (1), (2), and (3), the dimension of SH, PW, and PL is:

$$SH = \frac{0.9 * 10^8 \text{ m/sec}}{56\pi * 10^9 \text{/sec} * \sqrt{4.4}} = 0.244 \text{ mm}$$

$$PW = \frac{3 * 10^8 \text{ m/sec}}{56 * 10^9 \text{/sec} * \sqrt{2.7}} = 3.26025 \text{ mm}$$

PL = 2.700971 mm – 2(0.111397 mm) = 2.47818 mm

Next, by substituting PL = 2.47818 mm, Z_0 = 50 Ω, Z_L = 121.6749 Ω, PW = 3.26025 mm, and ε_{reff} = 3.93393 in Eqs. (4), (5), and (6), the inset length of the feeder, location of feed point along the X-axis, and Y-axis is found to be;

$$Yo = \left(\frac{2.47818 \text{ mm}}{3.14}\right)\mathrm{Cos}^{-1}\left(\sqrt{\frac{50}{121.6748}}\right) = 0.905498 \text{ mm}$$

$$Xf = \frac{2.47818 \text{ mm}}{3.96682} = 0.624727 \text{ mm}$$

$$Yf = \frac{3.26025 \text{ mm}}{2} = 1.63\text{mm}$$

Lastly, by substituting ZMFL = 45.152 Ω, SH = 0.244 mm, ε_r = 4.4, t = 0.035 mm (standard thickness for copper metal), in Eq. (9) and λ_0 = 10.7143 mm, ε_r = 4.4, in Eq. (10), then the WMF and LMF connected to the edge patch are calculated as:

$$WMF = \frac{1.46 \text{ mm} * \dfrac{1}{\exp(1.251)} - 0.035\text{mm}}{0.8} = 0.4785\text{mm}$$

$$LMF = \frac{10.7143\text{mm}}{8.3905} = 1.27696\text{mm}$$

In the above section, the calculated initial dimensions of the anticipated MSPA using 28 GHz as resonant frequency and a ε_r of 4.4 are provided. The patch is designed using the overall dimension of the proposed MSPA is 4.7245 mm x 3.942177 mm x 0.244 mm. Besides, to legitimately match the impedance of patch antenna and the feed microstrip feeder line, which is 50 Ω, 0.624726 mm is picked for an inset to move the feed location far from the edge. Whereas the gap between the feed line and patch is kept at 0.017761 mm.

The performance of the MSPA is mainly defined by the selected dimensions of the physical structure, in this study the performance effects of the patch width, ground plane, inset gap, and the transmission line width dimensions are analyzed using a repetitive simulation of CST simulator to boost the functionality in terms of beam gain, directivity, bandwidth, and radiation efficiency. The values are altered manually and the effects are observed with the simulator. While tuning the dimension of the antenna parameters, its impact on all the performance metrics is considered by concerning all the performance metrics for the given design. The initially calculated and optimized dimensions of the MSPA are summarized in Table 1.

Table -1. Design parameters of the antenna structure.

Design Parameters	Symbol	Calculated Values (mm)	Optimized Values (mm)
Width of the patch	PW	3.26025	3.3
Length of the patch	PL	2.47818	2.478
Length of microstrip feeder	LMF	2.18245	2.1543
Width of microstrip feeder	WMF	0.4783	0.478584
Inset gap	Gp	0.017761	0.23915
Length of inset feed	Yo	0.905498	0.9054
Width of the substrate	SW	4.7245	8.5
Length of the substrate	SL	3.942177	8.5
Width of a ground plane	GW	4.7245	8.5
Length of a ground plane	GL	3.942177	8.5

4. RESULTS ANALYSIS AND DISCUSSION

In this section, the simulation results and discussions of the proposed rectangular MSPA is presented. To analyze the designed antenna, we simulated the proposed design of MSPA using CST software. To access the features of an antenna, different performance metrics are used. Among them, the bandwidth, gain, directivity, VSWR, and return loss are often utilized. The matching quality between the radiating patch and the feed point is quantified using the magnitude of the return loss. The antenna is matched to 50 Ω feed-line. As indicated in Fig - 2, at the 28 GHz, a return loss of this antenna is -38.86553 dB, and also, the -10 dB return loss bandwidth is 1.046 GHz.

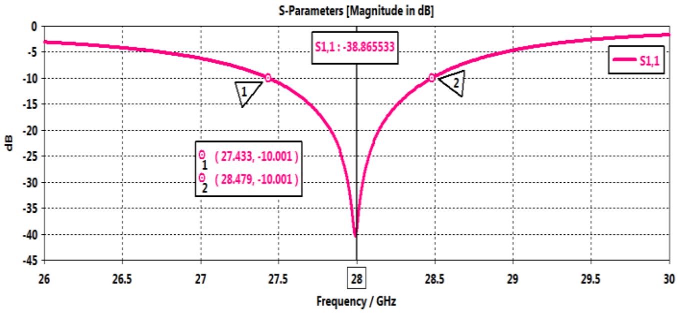


Fig - 2. Return loss versus frequency plot of the antenna.

On the other side, the magnitude of VSWR is also used to quantify the reflection of the power from the antenna to the source. For an ideal transmission line, the magnitude VSWR is one and in the practical scenarios, the magnitude of less than two is acceptable as long as the S11 is less than -10 dB [10, 15]. The simulated VSWR plot of the designed MSPA is revealed in Fig - 3. Therefore, between 27.397 GHz - 28.507 GHz, the magnitude of VSWR is less than two, which is in the acceptable range and 1.02305 at 28 GHz.

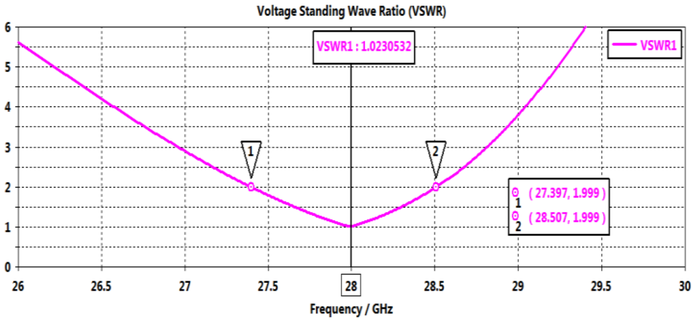
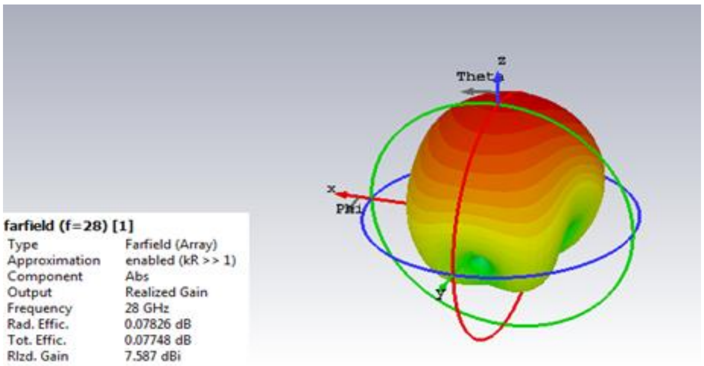


Fig - 3. VSWR versus frequency plot of the antenna.

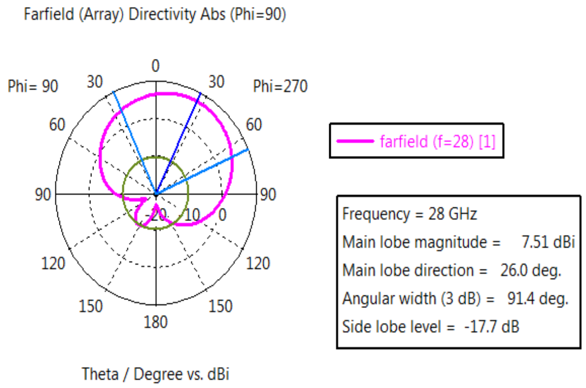
Another parameter that is often used to characterize the MSPA is the radiation pattern. It is the plot of the far-field pattern that shows the angular strength of power radiated from the antenna. It is used to show the directivity and gain of the given antenna at the desired point in space [15]. As given in Fig - 4, the directivity, gain, and radiation efficiency are 7.509 dBi, 7.587 dBi, and -0.07826 dB (98.2141 %) respectively. Similarly, the side lobe level and the half-power beam-width are -17.7 dB and 91.4 degrees respectively as exposed in Fig - 5.



farfield (f=28) [1]

Type	Farfield (Array)
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	28 GHz
Rad. Effic.	0.07826 dB
Tot. Effic.	0.07748 dB
Rlzd. Gain	7.587 dBi

Fig - 4. 3D radiation pattern of the proposed antenna.



Frequency = 28 GHz
Main lobe magnitude = 7.51 dBi
Main lobe direction = 26.0 deg.
Angular width (3 dB) = 91.4 deg.
Side lobe level = -17.7 dB

Fig - 5. 2D radiation pattern of the proposed antenna.

The designed antenna performance is compared with existing similar designs in literature is shown in Table 2. In terms of beam-gain, the proposed design outperforms the designs reported in [10, 18-24]. Similarly, in terms of radiation efficiency, the designed antenna shows better performance than the designs presented in [8, 10, 19, 20, 24]. The VSWR of the studied MSPA is minimum which is much closer to ideal values as compared to design reported in [8, 18, 22, 23]. At the 28 GHz, the examined antenna shows minimum return losses compared to designs reported in [8, 18, 19, 22-24], but it is large as seen with reported in [20, 21]. Finally, the proposed MSPA accomplishes wide bandwidth compared to the designs presented in [10, 22, 24], but it is narrow as compared to designs reported in [19-21]. Therefore, the proposed patch antenna gives a highly competitive performance as equated to other similar antennas reported in the literature.

Table - 2. Performance Comparison of Single MSPA at 28GHz.

Ref.	**S_{11} (dB)**	**GAIN (dBi)**	**VSWR**	**ηrad (%)**	**BW (GHz)**
[8]	-15.35	-	1.79	87.8	-
[10]	-20.53	6.21	1.02	65.6	0.4
[18]	-17.4	6.72	1.28	-	-
[19]	-23.67	6.7	-	81.2	1.150
[20]	-39.37	6.37	1.022	86.73	2.48
[21]	-39.7	5.23	-	-	4.1
[22]	-14.151	6.06	1.488	-	0.8
[23]	-22.2	6.85	1.34	-	-
[24]	-27.7	6.72	1.22	75.875	0.463
This work	***-38.86***	***7.587***	***1.023***	***98.214***	***1.046***

5. CONCLUSIONS

In this paper, design and performance analysis of a 28GHz rectangular MSPA for 5G applications is presented. The proposed MSPA simulation result shows that the return loss, directivity, beam gain, and bandwidth of; -38.86553 dB, 7.509 dBi, 7.587 dBi, and 1.046 GHz respectively. As compared to existing designs reported in the scientific literature, the proposed antenna shows significantly better performance. In this paper, better performance has been achieved because of the introduction of the combined optimization of the parameters, inset-feed and quarter-wavelength impedance matching. Therefore, the designed antenna in this paper is a good candidate antenna type for the 5G millimeter-wave wireless applications.

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