Inset-Feed Rectangular Microstrip Patch Antenna Array Performance Enhancement for 5G Mobile Applications

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Abstract. The advancements in wireless communication systems need a low cost, minimal weight, and low-profile antenna arrays that are capable of providing high performance over a wide frequency band. In this regard, the patch antenna is considered as a candidate antenna type for 5G communication systems. However, the bandwidth of microstrip patch antenna (MSPA) is narrow; its directivity, gain, and radiation efficiency are low. Moreover, attempting to improve the performance of the MSPA by integrating a large number of patch antenna in the array leads to increased mutual coupling and reduced radiation efficiency, and directivity of the antenna. Therefore, to address these challenges, this paper presents the performance enhancement of MSPA array for 5G mobile applications. To achieve this, inset-feed impedance matching techniques, quarter-wavelength impedance transformer, and optimization of the parameters of different MSPA array structures have been simultaneously used. All the studied antenna structures are designed using FR-4 substrate with a dielectric constant of 4.4 to operate at 28 GHz and the performances have been analyzed using a CST antenna simulator. The simulation results show that directivity of the proposed single element, 2×1, 4×1, 4×4, and 8×8 rectangular MSPA arrays are 7.41 dBi, 9.451 dBi, 11.2 dBi, 15.8 dBi, 19.31 dBi; the bandwidths are 572 MHz, 575 MHz, 1394 MHz, 332 MHz, 368 MHz; the radiation efficiency is more than 95% for one-dimensional MSPA arrays and more than 80% for the two-dimensional MSPA arrays. As compared to designs reported in the literature, the proposed antennas show significantly improved performance.

Keywords: Beam-gain · Fifth-generation · MSPA · Millimeter-wave · 28 GHz

1 Introduction

Over the past few decades, the continual development of new generations of wireless communication technology brought a significant impact on the daily

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lives of human beings. Therefore, nowadays more and more users have gotten their devices connected to the networks which are causing a constant increase in data traffic and hastening the need for enormous capacity in the upcoming years. However, the allowable frequency ranges of the existing wireless network generations are too congested. Consequently, this cannot handle the present rapid growth in wireless data and network traffic. Hence, in the near future, the use of the currently unused spectrum is, therefore, being highly encouraged and thus the subsequent next network generation is on emerging stage which is claimed to be fifth-generation of the wireless network [1–3].

The fifth-generation (5G) wireless communication systems are expected to highly enhance communication capacity by exploiting enormous unlicensed bandwidth specifically, in the mm-wave band. It is also expected to be ready to provide and support very high data rates, the maximum amount as 100 times of 4G capacity which results in a replacement challenge on network requirements as well as in the antenna designs to satisfy the expected data rate and capacity [4–7]. The working frequency for the 5G communication systems continues to be being debated but 6 GHz, 10 GHz, 15 GHz, 28 GHz, and 38 GHz bands are among the expected ones. However, the federal communication commission (FCC) approved the allocation of huge bandwidths at 28 GHz, 37 GHz, and 39 GHz [8].

In wireless communication systems, antennas are widely used to transmit or receive electromagnetic energy over the specified frequency ranges. However, the new advancements in wireless communication technology require antennas with a lightweight, and low profile. In this regard, the microstrip patch antennas represent 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 microstrip patch antenna (MSPA) is easy and versatile in terms of resonant frequency, polarization, pattern, and input impedance. The patch antennas may be mounted on the surface of high-performance aircraft, spacecraft, rockets, satellites, missiles, cars, and even hand-held mobile telephones. Therefore, the MSPA plays a significant role within the fastest-growing wireless communications industry. But, the thickness of the substrate material deteriorates the MSPA bandwidth and radiation efficiency, by increasing surface wave and spurious feed radiation along with the feeding line. Consequently, undesired cross-polarized radiation is led by feed radiation effects. Moreover, the MSPA suffers from losses such as conductor, dielectric, and radiation which results in narrowing the bandwidth and lowering the gain [9–13]. Because of this performance limitation, the bandwidth of MSPA is narrow; its directivity, gain, and radiation efficiency are low for the emerging 5G communication systems.

Therefore, attempting to extend the performance of MSPA for 5G communication systems, several designs of single element MSPA has been demonstrated in [8,13–18] using a patch with substrate integrated wave-guide, multi-layer, and multi-patch designs, by incorporating multiple slots on the patch, by employing different impedance matching techniques and a defected ground plane, tuning dimension of the antenna. However, it has been revealed that the radiation pattern of the single antenna is relatively wide and also, its beam gain and directivity are low for futuristic 5G communications. Therefore, to increase the performance of the single-element patch antenna, different sizes of linear MSPA array are demonstrated in [3,10,14–17] by increasing the number of the array element, using proper impedance matching technique, serial microstrip feeding techniques, and tuning the substrate thickness. The proposed linear MSPA improves the performance of single MSPA in terms of beam directivity and gain. But, it produces high side-lobe levels which reduce overall radiation efficiency of the antenna and also, linear antenna array is capable to scan only one-dimensional plane i.e., either the elevation plane or azimuth plane.

Generally, the previous demonstrated works tried to achieve better performance in terms of one or two specific performance metrics, and also the main intention of the studies was only for linear MSPA array. Therefore, in this study, we are motivated to design both linear and planar rectangular MSPA array and enhance the performance in terms of all key performance metrics for 5G communication systems at 28 GHz. To achieve these objectives, we have used inset-feed impedance matching, quarter-wavelength impedance transformer, and design parameters optimization techniques as methodology.

The rest of the paper is organized as follows. Section 2 describes the design concept of; single element, 2×1, 4×1, 4×4, and 8×8 rectangular MSPA array. Section 3 presents the simulation results and discussion of all studied antenna. Finally, Sect. 4 summarizes our concluding remarks.

2 Design of Linear and Planar MSPA Arrays

In this section, we present the design concept of five different structures of MSPA arrays. The first three antenna arrays are one-dimensional and the remaining two antennas are two-dimensional arrays. We start the design concept with a single element MSPA.

2.1 Single Element Inset-Feed Rectangular MSPA

The physical structure of a single element MSPA is shown in Fig. 1. This antenna is designed using the FR-4 substrate with a dielectric constant (ε_r) of 4.4 and a loss tangent of 0.0025. The width of the patch is 3.3 mm and excited using 50Ω microstrip feed-line with width of 0.4783 mm. The over all dimension of this 8.5 mm × 8.5 mm × 0.244 mm and this structures is employed as building block for other MSPA arrays. The performance of the antenna depends on the selection of its design parameters. In this work, our aim is not to show the effect of each parameter of the antenna on its performance. The detail discussion about the effect of the parameters of the antenna on its performance can be found in [12]. The optimized design parameters of this antenna structure are summarized in Table 5 in the Annex. The design parameters are optimized to boost the performance of this patch antenna in terms of beam gain, directivity, bandwidth, and radiation efficiency.

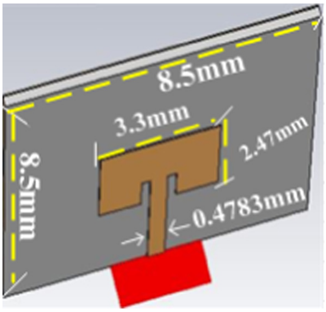

Fig. 1. Proposed single inset-feed rectangular MSPA.

2.2 2×1 Inset-Feed Rectangular MSP Array

The structure of a 2×1 inset-feed rectangular MSPA array is indicated in Fig. 2. The proposed antenna array is designed using 2 rectangular patches arranged in 2×1 formation. In this particular design, a microstrip transmission line of 1:2 power divider is used to feed the two antenna elements. Which is linked with a serial 50Ω microstrip transmission line feed of width 0.4738 mm and later divided into two 100Ω lines having a width of 0.23915 mm. The length of the transmission line is 1.27696 mm and the line widths are adjusted accordingly to optimize the performance trade-offs. The chosen separation distance between the array elements is 5.4 mm and the substrate height is similar to that of single element MSPA. This antenna structure is designed to enhance the performance of the single element rectangular MSPA in terms of its beam gain, directivity, bandwidth, return loss, and VSWR. The optimized design parameters of the proposed 2×1 inset-feed rectangular MSPA array model are reported in Table 6 within the Annex.

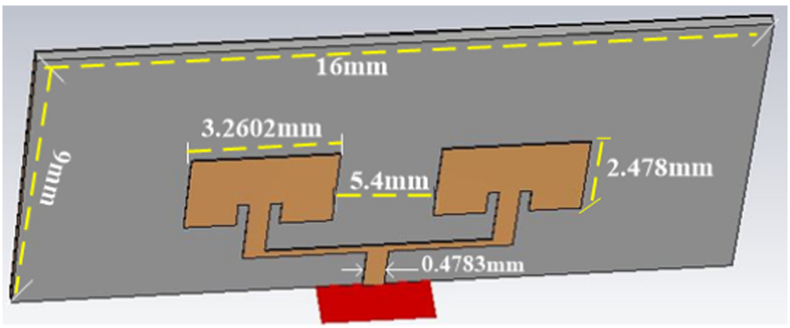

Fig. 2. Proposed 2×1 inset-feed rectangular MSPA array.

2.3 4×1 Inset-Feed Rectangular MSPA Array

A 4×1 inset-feed rectangular MSPA array is designed by connecting two 2×1 arrays as shown in Fig. 3. In the design, successive branching of corporate feed with equal path length to each element has been used to feed all the elements. The last feeder is normalized to 50Ω having a width of 0.4783 mm which is later branched to two 100Ω microstrip lines to feed two antenna elements. Besides, quarter-wave transformers are used for proper impedance matching to connect the patch to the transmission line. The separation distance between the patch is 5.4 mm. The optimized design parameters of the proposed 4×1 inset-feed MSPA array model are listed in Table 7 within the Annex.

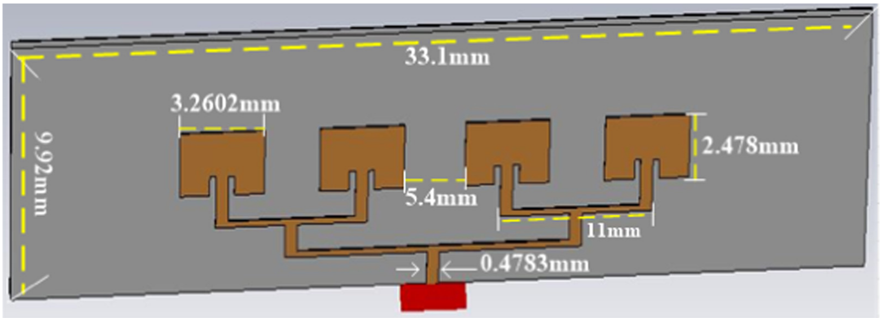

Fig. 3. Proposed 4×1 inset-feed rectangular MSPA array.

2.4 4×4 Inset-Feed Rectangular MSPA Array

The proposed design of 4×4 inset-feed rectangular MSPA array is depicted in Fig. 4. To reduce the return loss of the antenna, a quarter-wave impedance trans-

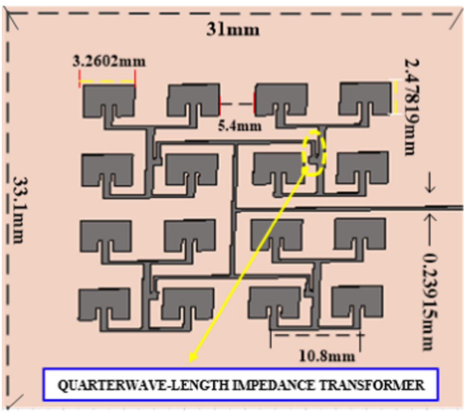

Fig. 4. Proposed 4×4 inset-feed rectangular MSPA array.

former is used. The quarter-wave impedance transformer improves the matching quality of the radiating element and the feeder line. This is the unique feature of our design. The optimized parameters of the proposed 4×4 inset-feed MSPA array are listed in Table 8 in the Annex.

2.5 8×8 Inset-Feed Rectangular MSPA Array

The physical structure of 8×8 inset-feed rectangular MSPA array is indicated in Fig. 5. It is designed to enhance the performance of the above proposed linear MSPA arrays and 4×4 inset-feed MSPA array in terms of their gain, directivity, bandwidth, and scanning dimensions. The structure has 100Ω feeder line impedance. Similar to the 4×4 MSPA array described in the above section, the impedance matching network uses a quarter-wave impedance transformer for better impedance matching. The optimized parameters are width of the patch and microstrip feeder, inset length and width, and ground plane dimension.

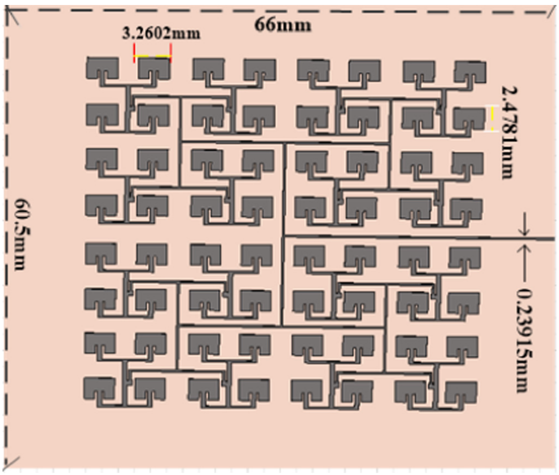

Fig. 5. Proposed 8×8 inset-feed rectangular MSPA array.

3 Simulation Results and Discussion

In this section, we present the simulation result and discussion of five different structures of antenna arrays. We first optimize the performance of a single element MSPA by selecting the suitable parameters and then increase the elements of the antenna array to enhance certain performance parameters. The optimized design parameters that are used for the simulations are listed in the Annex. To analyze the performance of the designed antenna, we simulated the proposed design of MSPA using CST software.

3.1 Single Inset-Feed Rectangular MSPA

The performance characteristics of an antenna is usually described by using different performance metrics like the return loss, bandwidth, VSWR, and beam gain. The return loss is a parameter which is used to indicate the amount of power that is lost to the load and does return as a reflection. Also, it indicates how well the matching between the transmitter and antenna has taken place [13]. For optimum working conditions, the return loss curve must show a dip at the operating frequency with minimum dB value and a flat line throughout other frequency scales. The return loss plot of the studied MSPA is indicated in Fig. 6. From the plot, we observed that at 28 GHz, the return loss of the antenna is 20.24 dB and also, −10 dB impedance bandwidth of the antenna is 572 MHz.

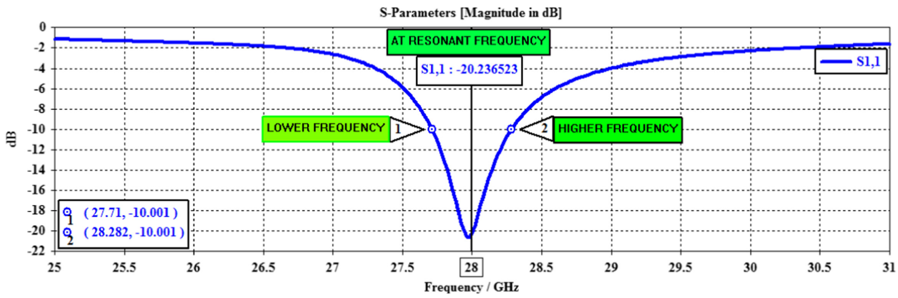

Fig. 6. Return loss versus frequency plot for single inset-feed rectangular MSPA.

The magnitude of VSWR is used to quantify the reflection of the power from the antenna to the source. Therefore, the smaller the VSWR is the better the antenna matched to the transmission line and power delivered to the antenna. For an ideal transmission line, the magnitude of VSWR is one and the acceptable level for practical wireless application should be less than two [12,13]. From Fig. 7, the VSWR of the studied antenna is 1.216. The obtained VSWR indicates that the impedance between the microstrip feeder line and the patch edge of the proposed antenna is well matched to the characteristic impedance by using properly selected dimension of the inset length and width.

Another interesting parameter that characterizes the radiation properties of an antenna and distinguishes one antenna from the other is the radiation pattern [13]. From Table 1, we observe that the designed antenna has a directional radiation pattern with a directivity of 7.404 dBi, a gain of 7.19 dBi, and radiation efficiency of 94.95% and 94.27% respectively. Besides, the side lobe level of the antenna is −12.1 dB and half-power beam width occurred at 72.3 degrees as shown in Fig. 8. The key implication of this result is that the proposed antenna radiates highly towards the desired direction and less in other directions.

The performance comparison of the proposed single radiating element antenna with designs reported in the literature is shown in Table 1. From the

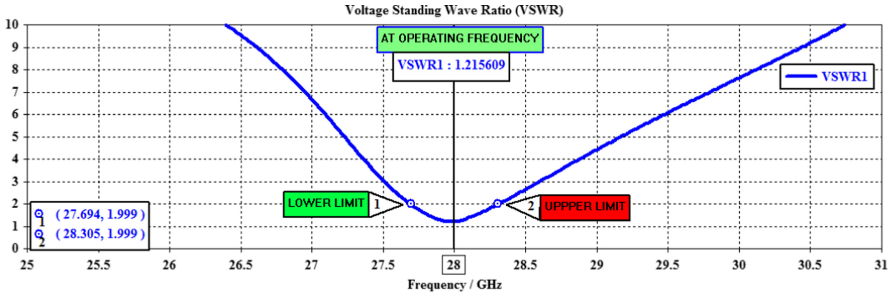

Fig. 7. VSWR versus frequency plot for single inset-feed rectangular MSPA.

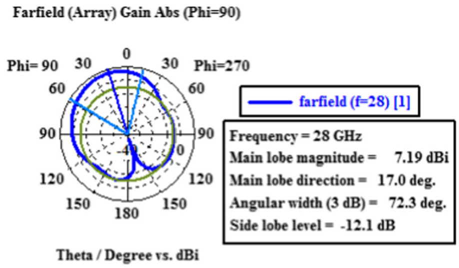

Fig. 8. 2D radiation pattern of single inset-feed rectangular MSPA

table, it is evident that the examined antenna show minimum return losses and VSWR as compared to designs reported in [7,13,18,22], but it is large as seen with antenna presented in [20–24]. In terms of the 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 [10,13,19,20,24]. Finally, the proposed antenna achieves wider bandwidth compared to the design presented in [10,24], but it is narrow as compared to designs reported in [7,19–21]. Therefore, the proposed patch antenna gives a highly competitive performance as compared to other similar antenna reported in the literature.

Where, η_{rad} denotes radiation efficiency, S_{11} denotes return losses, and BW denotes bandwidth.

3.2 2×1 Inset-Feed Rectangular MSPA Array

As indicated in Fig. 9, the return loss of the proposed 2×1 MSPA array is less than −10 dB between 27.755 GHz and 28.33 GHz, and exactly at the resonant frequency, it is −19.886 dB. The obtained return loss is low since the impedance at the last feeding structure of 1:2 microstrip power divider with equal path length is well matched to the characteristic impedance of the feed point through the designed width of the last microstrip feeder line. The −10 dB return loss bandwidth of the antenna is about 575 MHz. The bandwidth of the 2×1 antenna

Table 1. Performance comparison of single MSPA at 28 GHz.Performance comparison of single MSPA at 28 GHz.

Ref.	S_{11} (dB)	GAIN (dBi)	VSWR	η_{rad} (%)	BW (GHz)
[7]	13.48	4.48	1.538	78.9	0.847
[10]	−20.53	6.21	1.02	65.6	0.4
[13]	−15.35	-	1.79	87.8	-
[18]	−17.4	6.72	1.28	-	-
[19]	−23.67	6.7	-	81.2	1.15
[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	−20.24	7.19	1.22	94.95	0.572

array is 3 MHz higher than that of the single element MSPA described in the previous section.

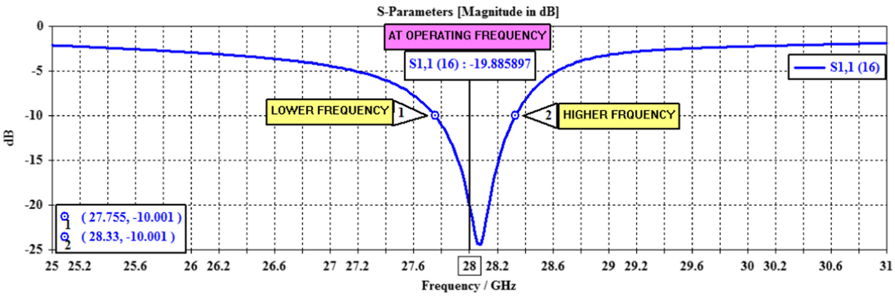

Fig. 9. Return loss versus frequency plot for 2×1 inset-feed rectangular MSPA array.

The VSWR versus frequency plot for 2×1 rectangular MSPA array is shown in Fig. 10. At 28 GHz, the VSWR of the antenna is 1.344 for the optimized design parameters of the antenna. Besides, from Fig. 11, we observe that the side lobe level of the studied array is −16.8 dB, and a half-power beam width of the radiation pattern occurs at 78.9 degrees. The radiation efficiency of the antenna is 96.56%, the directivity is 9.451 dBi, and gain is 9.3 dBi as indicated in Table 2. Generally, the overall performance of 2×1 rectangular MSPA array shows superior performance than the single element antenna described in the previous section.

The summarized comparative analysis of 2×1 antenna array designs reported in the literature is shown in Table 2. From the table, it is evident that the

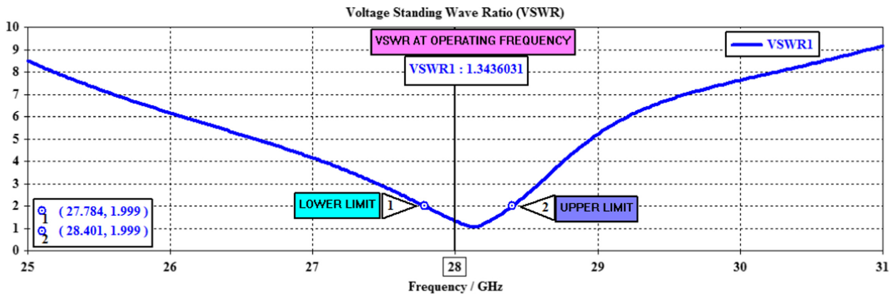

Fig. 10. VSWR versus frequency plot for 2×1 inset-feed rectangular MSPA array.

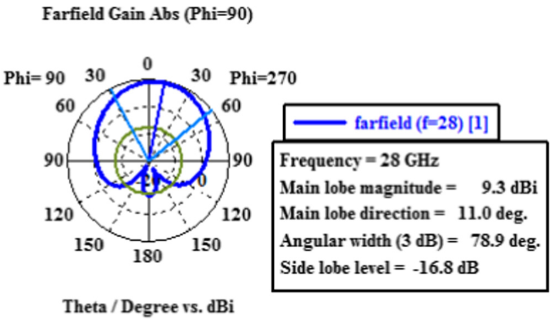

Fig. 11. 2D radiation pattern of 2×1 inset-feed rectangular MSPA array.

proposed antenna has minimum return losses and VSWR as compared to the designs reported in [9,13,22]. The proposed design achieves better radiation efficiency and total radiation efficiency than the design reported in [13,22].

Table 2. Performances comparison of the existing and proposed 2×1 MSPA array.

Ref	Subs. type	F_O (GHz)	S_{11} (dB)	DIR (dBi)	GAIN (dBi)	VSWR	η_{rad} (%)	η_{tot} (%)	BW (MHz)
[9]	ROG	28	−16.65	12	12.4	-	-	-	-
[13]	FR-4	28	−14.7	9.853	-	1.624	92.7	87.77	-
[22]	FR-4	28	−14.8	6.74	6.15	-	86.28	-	-
This work	FR-4	28	−19.886	9.451	9.3	1.344	96.56	92.53	575

Where, η_{rad} denotes radiation efficiency, η_{tot} denotes total radiation efficiency, S_{11} denotes return losses, and BW denotes bandwidth.

3.3 4×1 Inset-Feed Rectangular MSPA Array

The return loss plot of 4×1 inset-feed rectangular MSPA array is shown in Fig. 12. At the resonant frequency, the magnitude of the return loss of the array is about −27.4218 dB, and also, the −10 dB impedance bandwidth of the proposed antenna is 1.394 GHz. As shown in Fig. 13, at 28 GHz, the VSWR of the antenna is 1.1059 which is very close to the ideal values. From the achieved results, it can be observed that the 4×1 inset-feed MSPA array achieved wider bandwidth and minimum VSWR than that of the single patch antenna and 2×1 MSPA array.

The simulated 2D radiation pattern of the 4×1 MSPA array model is shown in Fig. 14. The side lobe level of this antenna is −11.8 dB and the half-power beam width occurred at 72.3 degrees. The designed antenna has the beam gain, directivity, radiation efficiency, and total radiation of 11.06 dBi, 11.2 dBi, 97.41%, and 96.56% respectively as depicted in Table 3. The beam gain and directivity are improved because the number of the array elements has increased from two to four and the radiating array inter-element space has been properly selected in such a way that, the radiation from each array element is added together constructively in the desired direction.

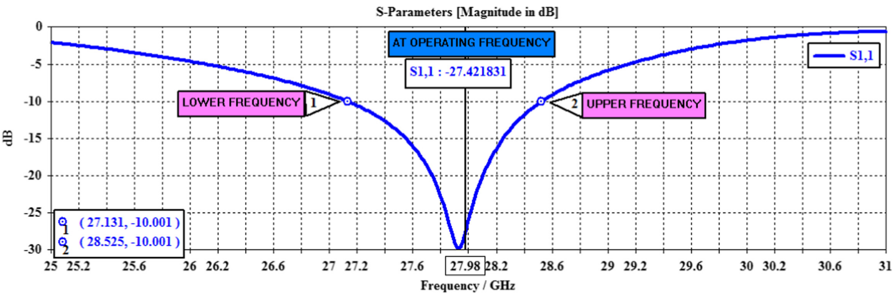

Fig. 12. Return loss versus frequency plot for 4×1 inset-feed rectangular MSPA array.

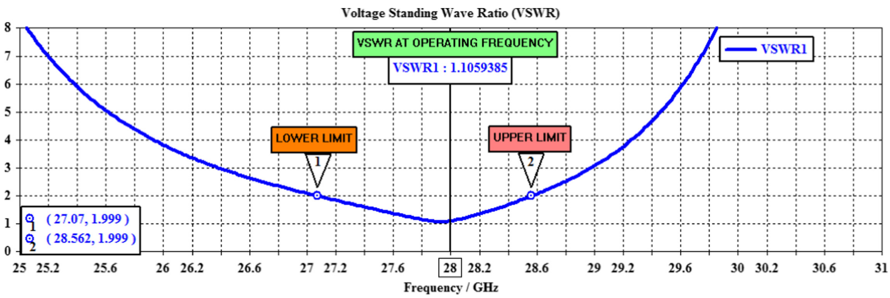

Fig. 13. VSWR versus frequency plot for 4×1 inset-feed rectangular MSPA array.

The performance of the proposed 4×1 MSPA array is compared with the antenna of the same structure reported in the literature. As shown in Table 3, in terms of the return loss, VSWR, and radiation efficiency, the proposed design

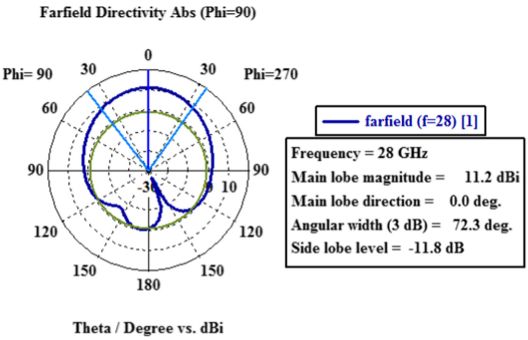

Fig. 14. 2D radiation pattern of 4×1 inset-feed rectangular MSPA array.

Table 3. Performance comparison of the existing and proposed 4×1 MSPA array.

Ref	Subs. type	F_O (GHz)	S_{11}(dB)	DIR (dBi)	GAIN (dBi)	VSWR	η_{rad} (%)	η_{tot} (%)	BW (GHz)
[13]	FR-4	28	−21.4476	11.99	-	1.6502	83.95	78.9	-
[16]	FR-4	28	−17.6	-	-	-	79.9	-	0.540
This work	FR-4	28	−27.4218	11.2	11.06	1.1059	97.41	96.56	1.394

outperforms the design reported in [13,16]. But, in terms of gain and directivity, the design reported in [13] outperforms the proposed antenna.

Where, η_{rad} denotes radiation efficiency, η_{tot} denotes total radiation efficiency, S_{11}, and BW denotes bandwidth.

3.4 4×4 Inset-Feed Rectangular MSPA Array

Fig. 15 shows the return loss plot of the 4×4 inset-feed rectangular MSPA array model. The return loss of the antenna is less than −10 dB between 27.819 GHz and 28.151 GHz. However, at 28 GHz, it is −33.149 dB and the −10 dB working bandwidth of the designed antenna is about 332 MHz. From Fig. 16, it is observed that, at the resonant frequency, the VSWR of the antenna is 1.045 which is very close to the ideal value. Generally, both inset feed and quarter-wave impedance matching techniques with the tuned width of the microstrip transmission line have been used to minimize the impedance mismatch of the proposed antenna at the feed networks and the edge of the patch. As a result, the minimum value of VSWR has been achieved at 28 GHz.

The simulated 2D radiation pattern of the 4×4 MSPA array is shown in Fig. 17. Half-power beam width of the antenna occurred at 25.8 degrees and the side lobe level of 11.1 dB has been achieved from the designed antenna. From Table 4, we can observe that the studied 4×4 rectangular MSPA array shows the radiation efficiency of 86.543%, directivity of 15.8 dBi, and gain of 15.17 dBi.

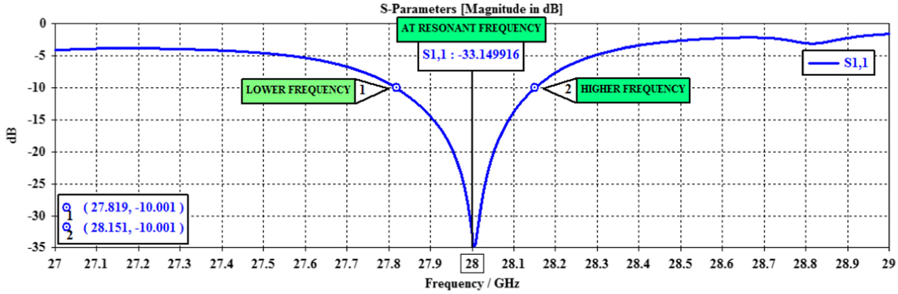

Fig. 15. Return loss versus frequency plot for 4×4 inset-feed rectangular MSPA array.

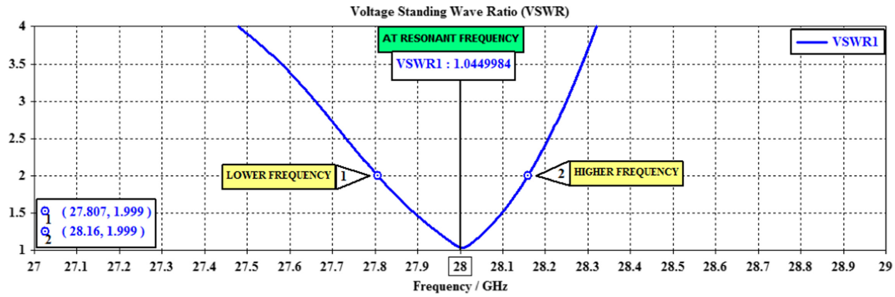

Fig. 16. VSWR versus frequency plot for 4×4 inset-feed rectangular MSPA array.

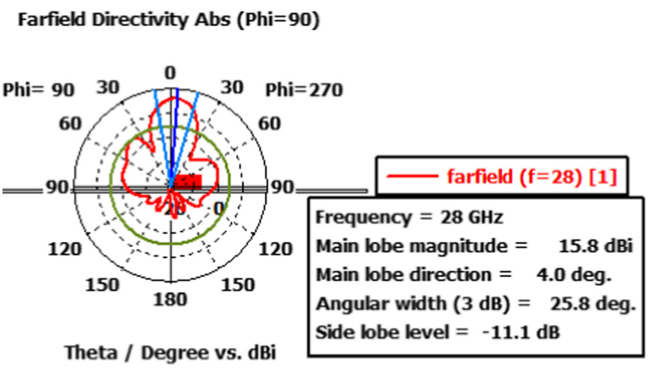

Fig. 17. 2D radiation pattern of 4×4 inset-feed rectangular MSPA array.

3.5 8×8 Inset-Feed Rectangular MSPA Array

The simulated return loss of the proposed 8×8 inset-feed rectangular MSPA array is given in Fig. 18. At the resonant frequency, the return loss of the antenna is −17.749 dB. The −10 dB return loss bandwidth of this antenna is 368 MHz. As compared to the 4×4 antenna array structure, the 8×8 inset-feed rectangular MSPA array achieves wider bandwidth.

Figure 19 shows the VSWR plot of examined 8×8 rectangular MSPA array. From the plot, at the resonant frequency, the VSWR of the antenna is 1.298. On the other side, the side lobe level of this antenna is −10 dB, and the half-power beam width occurs at 12.8 degrees as shown in Fig. 20. As indicated in Table 4, the designed antenna array has radiation efficiency, beam directivity, and gain of 79.73%, 19.31 dBi, and 18.33 dBi respectively. The 8×8 inset-feed MSPA array improves the directivity and gain of 4×4 inset-feed MSPA array by 3.51 dBi and 3.16 dBi.

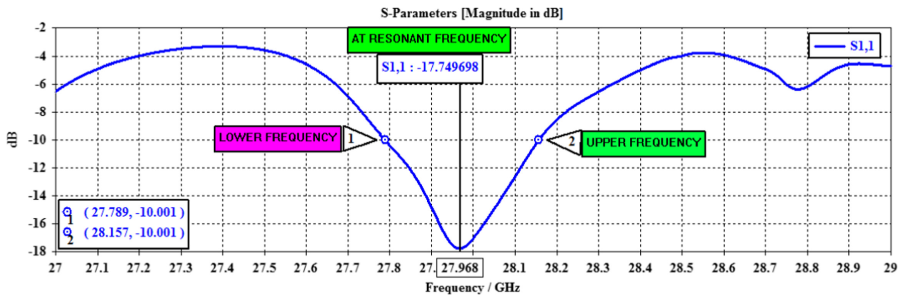

Fig. 18. Return loss versus frequency plot of 8×8 inset-feed rectangular MSPA array.

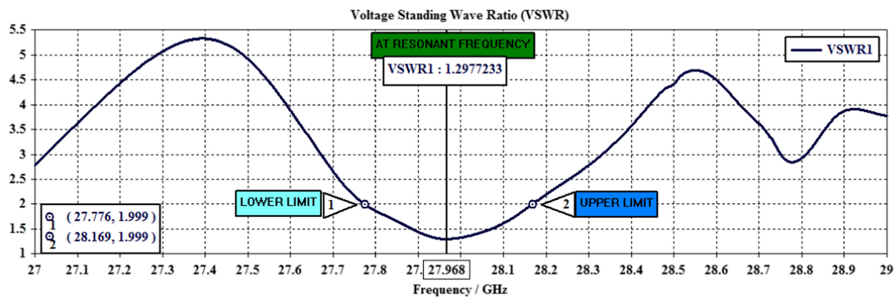

Fig. 19. VSWR versus frequency plot for 8×8 inset-feed rectangular MSPA array.

Generally, from simulation results of all the studied antenna arrays summarized in Table 4, the performance of the linear antenna arrays improved as

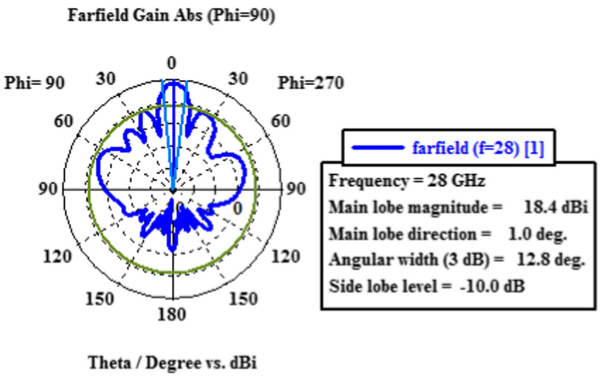

Fig. 20. 2D radiation pattern of 8×8 inset-feed rectangular MSPA array.

the number of radiating elements increases from one to four. However, we have observed that the trend does not continue further. For instance, the performance of a linear antenna array of 8×1 is significantly lower than that of 4×1 in terms of return loss, mutual coupling, and VSWR, and they are out of the acceptable range. In addition to this, a linear increment of the antenna array size reduces the compactness of the structure which is not desired in many applications. The 4×4 antenna array structure achieves the lowest values of the return loss and VSWR due to the introduction of a quarter-wave impedance transformer in the matching network design. The planar structures (4×4 and 8×8) have lower radiation efficiency as compared to the linear antenna array structures (1×1, 2×1, and 4×1). This is due to the increased loss and mutual coupling between the elements in the planar antenna array structures. However, their directivity and gain are significantly above that of the linear structures as can be depicted from Table 4. Overall, our extensive study of different antenna array structures using simulation shows that there is no single best design in terms of all the performance parameters of the antenna. Hence, there is a design trade-off that should be considered depending on the requirements of a particular application.

Table 4. Simulation results of all studied inset-feed rectangular MSPA array.

Type	F_0 (GHz)	S_{11} (dB)	DIR (dBi)	GAIN (dBi)	VSWR	η_{rad} (%)	η_{tot} (%)	SLL (dB)	BW (MHz)
1×1	28	−20.24	7.404	7.18	1.216	94.95	94.2	−12.1	572
2×1	28	−19.88	9.451	9.299	1.344	96.56	92.53	−16.8	575
4×1	28	−27.42	11.2	11.06	1.106	97.41	96.56	11.8	1394
4×4	28	−33.15	15.8	15.17	1.045	86.54	85.08	−11.1	332
8×8	28	−17.75	19.31	18.33	1.298	79.73	74.28	−10	368

Where, η_{rad} denotes radiation efficiency, η_{tot} denotes total radiation efficiency, S_{11}, SLL denotes side lobe level ,and BW denotes bandwidth.

4 Conclusions

In this paper, the performance of single element, 2×1, 4×1, 4×4, and 8×8 inset-feed rectangular MSPA arrays have been meticulously optimized for 5G mobile applications. At the resonant frequency, the simulation result shows that, the return loss and bandwidth of the proposed single, 2×1, and 4×1 inset-feed rectangular MSPA arrays are −20.234 dB, −19.89 dB, −27.42 dB, and 572 MHz, 575 MHz, 1394 MHz; also, their directivity are 7.41 dBi, 9.451 dBi, 11.2 dBi respectively. The radiation efficiency of all one-dimensional antenna arrays is above 95%. Similarly, the return loss of the designed 4×4 and 8×8 MSPA arrays are −33.15 dB, −17.75 dB and the bandwidth are 332 MHz and 368 MHz. Moreover, the directivity and radiation efficiency are 15.8 dBi, 19.31 dBi and 86.54%, 79.7% respectively.

From the simulated result analysis of the linear MSPA array structures, it has been observed that increasing the array element from one to four, the antenna shows the improvement in directivity, gain, radiation efficiency, and bandwidth. However, the magnitude of the side lobe has increased which is unwanted. Similarly, in planar MSPA array structures, as the array element is increased from sixty to sixty-four the improvement is obtained in terms of directivity, gain, and bandwidth. But, in terms of the magnitude of return loss, VSWR, and radiation efficiency, MSPA array with sixty elements outperforms the one with sixty-four radiating elements. Generally, as compared to existing antenna array designs reported in the scientific literature, the proposed antenna arrays show significantly improved performance. Therefore, all optimized MSPA array structures proposed in this paper have suitable performance characteristics for the emerging 5G mobile applications.

Annex

Optimized Design Parameters of Proposed MSPA

Table 5. Optimized design parameters of single inset-feed MSPA.

Optimized design parameters	Symbols	Values
Width of the patch	PW	3.3 mm
Length of the patch	PL	2.47 mm
Width of the ground plane	GW	8.5 mm
Length of the ground plane	GL	8.5 mm
Length of inset-feed	YO	0.9054 mm
Length of inset-gap	Gp	0.23915 mm
Substrate thickness	SH	0.244 mm
Length of microstrip feeder line	LMFL	2.55 mm
Width of microstrip feeder line	WMFL	0.4783 mm

Table 6. Optimized design parameters of 2×1 inset-feed MSPA array.

Design parameters	Symbols	Values
Width of the patch	PW	3.2602 mm
Length of the patch	PL	2.478 mm
Width of the ground plane	GW	16 mm
Length of the ground plane	GL	9 mm
Substrate thickness	SH	0.244 mm
Gap of inset-feed	Gp	0.23917 mm
Length of inset feed	YO	0.745 mm
Distance between the patch	D	5.4 mm
Length of microstrip feeder line	LMFL	2.0219 mm
Width of microstrip feeder line	WMFL	0.4784 mm
Length of 1:2 microstrip power divider	LFMPD	0.23915 mm
Width of 1:2 microstrip power divider	WFMPD	11 mm

Table 7. Optimized design parameters of 4×1 inset-feed MSPA array.

Design parameters	Symbols	Values
Width of the patch	PW	3.2602 mm
Length of the patch	PL	2.478 mm
Width of the ground plane	GW	33.1 mm
Length of the ground plane	GL	9.92 mm
Length of inset-feed	YO	0.744 mm
Gap of inset-feed	Gp	0.2392 mm
Substrate thickness	SH	0.244 mm
Length of microstrip patch feeder	LMFL	2.0209 mm
Width of microstrip patch feeder	WMFL	0.4783 mm
Length of 1:2 microstrip power divider	LFMPD	0.23915 mm
Width of 1:2 microstrip power divider	WFMPD	11 mm
Length of 1:4 microstrip power divider	LSMPD	0.23915 mm
Width of 1:4 microstrip power divider	WSMPD	22 mm

Table 8. Optimized design parameters of 4×4 inset-feed MSPA array.

Design parameters	Symbols	Values
Width of the patch	PW	3.261 mm
Length of the patch	PL	2.47819 mm
Width of the ground plane	GW	31 mm
Length of the ground plane	GL	33.1 mm
Length of inset-feed	YO	0.9054 mm
Gap of inset-feed	GP	0.23916 mm
Length of microstrip feeder line	LMFL	2.55 mm
Width of microstrip feeder line	WMFL	0.4783 mm
Length of 1:2 microstrip power divider	LFMPD	0.23915 mm
Width of 1:2 microstrip power divider	WFMPD	10.8 mm
Length of last microstrip feeder line	LLMFL	0.23915 mm
Width of last microstrip feeder line	WLMFL	15.38 mm
First quarter transform width	FQTW	0.3 mm
First-quarter transform Length	FQTL	0.47831 mm
Second quarter transform length	SQTL	0.338 mm
Third-quarter transform width	TQTW	0.23915 mm

Table 9. Optimized design parameters of 8×8 inset-feed MSPA array.

Design parameters	Symbols	Values
Width of the patch	PW	3.2602 mm
Length of the patch	PL	2.4781 mm
Width of the ground plane	GW	66 mm
Length of the ground plane	GL	60.5 mm
Gap of inset-feed	GP	0.23916 mm
Length of inset-feed	YO	0.95 mm
Distance between the patch	D	5.4025 mm
Length of microstrip feeder line	LMFL	2.227 mm
Width of microstrip patch feeder	WMFL	0.4783 mm
Length of 1:2 microstrip power divider	LFPD	0.23915 mm
Width of 1:2 microstrip power divider	WFPD	10.8 mm
Length of last microstrip feeder line	LLMFL	0.23915 mm
Width of last microstrip feeder line	WLMFL	32.9726 mm
First quarter transform width	FQTW	0.3 mm
First-quarter transform Length	FQTL	0.47831 mm
Second quarter transform width	SQTW	0.4783 mm
Second quarter transform length	SQTL	0.338 mm
Third-quarter transform width	TQTW	0.23915 mm
Third-quarter transform length	TQTW	1.2769 mm

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