Planar Microstrip Patch Antenna Arrays with Semi-elliptical Slotted Patch and ground Structure for 5G Broadband Communication Systems

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Abstract: In fifth-generation (5G) communication systems, the mm-wave (millimeter-wave) frequency band is a key aspect in overcoming the exponential increase in data traffic of the existing cellular networks, which requires compatible and low-profile antenna arrays. In this case, a microstrip patch antenna (MPA) is a viable option. However, MPA has certain limitations, such as the deterioration of the antenna’s bandwidth and radiation efficiency with its substrate thickness. In addition, its gain and directivity are too low to meet the 5G systems requirements in beamforming techniques of massive MIMO systems. Thus, to ameliorate these limitations, in this paper, a microstrip patch antenna arrays (2x2, 4x4, and 8x8) with semi-elliptical shape slotted patch and etched ground structure for 5G broadband applications is proposed. The radiator element of the antenna is designed using Rogers 5880 substrate with a dielectric constant of 2.2 and thickness of 0.3449 mm. It has been designed to operate at 28 GHz in LMDS (local multipoint block)

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PUBLIC INTEREST STATEMENT
Wireless communication has revolutionized our way of communication and life. Increasing the data rate of contemporary communication systems is necessary to satisfy customers’ demands. Among the wireless communication system components, the antenna converts electrical signals into electromagnetic waves and vice versa, interfacing communication devices with the physical (wireless) channel. With the emerging new use cases in fifth-generation (5G) systems and beyond, the requirements of modern antennas for wireless communication systems have changed. The existing antenna systems fall short to meet the system requirement, especially for the emerging technologies devised to operate in the millimetre wave band. Hence, new antenna structures are required to meet the emerging wireless applications’ requirements. In this work, we have designed planar antenna arrays whose elements are elliptically slotted microstrip patch antennas. The antenna is compact, can fit into small devices like cellphones, and has very good characteristics to meet the high data rate requirement of the current and future wireless systems.
distribution service) band. The performance of the proposed structure was analyzed using the CST-MW simulator. The simulation results reveal that the gain, bandwidth, and total efficiency of the studied 2x2, 4x4, and 8x8 MPA arrays are 13.24 dBi, 16.54 dBi; 21.45 dBi; 1.33 GHz, 1.461 GHz, 1.561 GHz; 97.03 %, 81.72 %, 69 %, respectively. Likewise, the return losses of these structures are -43.321 dB, -40.665 dB, and -22.678 dB, respectively. In general, all of the proposed planar semi-elliptical slotted rectangular MPA arrays offer improved performance compared to existing works and meet the requirements of 5G systems’ antennas.

**Subjects:** Electromagnetics & Microwaves; Radio, Satellites, Television & Audio; Telecommunication

**Keywords:** bandwidth; directivity; gain; semi-elliptical; microstrip; planar array

1. **Introduction**

In order to meet the ever-increasing demand of high-speed connections, in addition to the existing mobile networks, the 5G system is expected to include three usage scenarios. These are enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low latency communications (URLLC). The eMBB usage scenario enables very high-speed internet access (up to 1 Gbps). This is expected to increase the quality and efficiency of communication in the community. It will be crucial to enable services based on high-resolution multimedia, augmented reality, virtual reality, and smart city services (O’Connell et al., 2020).

The current standardization of 5G system networks is planned to operate in three frequency bands, i.e. low, medium, and high-frequency bands depending on the characteristics of the bands. In the initial phase of 5G system deployment, the following three bands of frequencies are assumed to be used. These are 700 MHz band (694–790 MHz), 3.6 GHz band (3.4 to 3.8 GHz), and 28 GHz (27.5 to 28.35 GHz). The 28 GHz band is limited in its use in terms of the capacity of spectrum resources and radio signal propagation. It has a wide bandwidth but short-range radio signal coverage due to a high attenuation characteristic of the radio signal propagation at this band. Hence, it can be used for broadband access points and pico-cell (cMTC/URLLC), and facility of internet access via a fixed wireless access service.

To provide a high-speed internet connection to users (up to 1 Gbps), the 5G systems use two technological solutions. These are the usage of high frequencies and beamforming. The Federal Communications Commission (FCC) has made available the 28 GHz band by reallocating the LMDS which lies between 27.5 and 28.35 GHz bands and is about 850 MHz wide (Przesmycki et al., 2021). This is part of the new Upper Microwave Flexible Use License (UMFUS) to support high speed (>1 Gbps) and low latency connections. The LMDS band is further divided into two blocks: block L1 (27.5–27.925 GHz) and block L2 (27.925–28.35 GHz), which has 425 MHz bandwidth.

The LMDS band can be used by several applications that make use of the ability to implement the configurations of fixed PTP (point-to-point) and PTMP (point-to-multi-point), as well as high-speed connectivity. It is suitable to be used for high-speed backhaul, fixed wireless access (FWA), and mobile applications (Tezergil & Onur, 2021). The advancements in wireless technology require antennas with low weight, low profile, low cost, easily mass manufacturable, compatible with planar and non-planar surfaces, and mechanically stable when mounted on rigid surfaces (Sridevi & Mahendran, 2017). From this perspective, a microstrip patch antenna can be considered a viable technological solution. It is ideal for installing on spacecraft, satellites, aircraft, vehicles, and portable communication devices on the outside (Fante & Gemeda, 2021).

Thus, the MPA plays a vital role in the fastest-growing field of wireless communication (Shanthi et al., 2019), (Jones & Gunavathi, 2017). However, compared to classic microwave antennas, MPA has
several limitations, such as the reduction of the thickness of the dielectric substrate to reduce its size and weight decreases the antenna bandwidth and radiation efficiency due to the increasing surface wave, spurious radiation, and the feed-line radiations. This leads to undesired cross-polarized radiation due to feed radiation effects (Johari et al., 2018), (Balanis, 2005). In addition, the MPA suffers from losses such as a dielectric, a conductor, and radiation losses, resulting in a low in bandwidth and gain. These limitations become challenges for the MPA designers to meet the broadband and high gain requirements of 5G mm-wave communication systems (Vamsi et al., 2018), (Kavitha et al., 2020).

Extensive performance analysis of a single element MPA has been demonstrated using a U-slotted patch (Hussain et al., 2020), modifying the feeding techniques (Jeyakumar et al., 2018), (Chaitanya et al., 2019), the defected ground structure, and Y-shaped patch (Awan et al., 2019), X-shape slotted patch (Gupta et al., 2020), the introduction of multiple slots (Ghazaoui et al., 2020), (Karthikeyan et al., 2019), etched patch (Kaeib et al., 2019), various substrate material types (Subramaniam et al., 2020), a substrate integrated waveguide patch, multi-patch designs, multi-layer patch by employing diverse impedance matching techniques (El_Mashade & Hegazy, 2018). But the reported simulation results reveal that the bandwidth is still narrow, the radiation pattern is relatively wide, and gain and directivity are low to be utilized in the 5G communication systems.

To improve the performance of a single MPA, various linear MPA array designs have been described in (Kavitha et al., 2020), (Jeyakumar et al., 2018), (Alwaroth et al., 2020; Maharjan & Choi, 2020; Mungur & Duraikannan, 2018; Shah & Singh, 2020; Gemeda & Fante, 2020). From the reported simulation results, it can be realized that the suggested linear MPA arrays improved the performance of a single element MPA. Despite this, the linear antenna arrays can scan only a one-dimensional plane, i.e., either the elevation plane or azimuth plane. Thus, the main limitations of the linear MSPA array are its inability to scan the beam in more than one direction, and the high magnitude of the sidelobe level of the radiation pattern. Subsequently, to mitigate the performance limitations of the linear array and, in general, to boost a patch antenna performance, a few studies on planar MPA array designs (Keun & Choi, 2018; Mohamed et al., 2020; E Sandi et al., 2020; Gemeda & Fante, 2020) have been carried out.

The existing planar arrays have alleviated the MPA linear arrays inefficiencies in its aspect of scanning capability. However, the attained bandwidth, gain, and directivity of MPA are still low to meet the requirements of 5G wireless communication systems. There is a continued effort by the research community to improve the performance of these antennas in all aspects. To the best of our knowledge,
the existing studies did not explore extensively the performance improvement of planar MPA arrays with large radiator elements by introducing the semi-elliptical shape slotted on both the radiating element and ground plane simultaneously. In this paper, the performance analysis of a planar 2x2, 4x4, and 8x8 rectangular MPA arrays for the 5G broadband access point has been proposed by introducing a semi-elliptical shape slot on a radiator patch and ground plane of the antenna.

The remaining sections of this paper are organized as follows. Section 2 presents design specifications and proposed 2x2, 4x4, and 8x8 semi-elliptical slotted MPA array. The simulation results and discussions are provided in Section 3. Section 4 describes the performance comparisons between previously reported and achieved results of this paper. Finally, the conclusions are discussed in Section 5.

2. Design specifications of the proposed semi-elliptical slotted MPA arrays

In this section, detailed specifications of a planar 2x2, 4x4, and 8x8 semi-elliptical slotted rectangular MPA arrays with two-dimensional beam scanning capabilities are presented. The design of the proposed antenna arrays was started with the selection of Rogers RT5880 substrate material with a 2.2 dielectric constant, the thickness of 0.3449 mm, and a resonant frequency of 28 GHz. Using these initial design parameters, the remaining physical dimensions of the semi-elliptical slotted 2x2, 4x4, and 8x8 MPA arrays were calculated using the mathematical equations given in (Balanis, 2005), (Gemeda et al., 2021).

First, a single element MPA was designed and optimized. Accordingly, the theoretically calculated physical dimensions of the basic single element MPA, which is used as a building block of all planar rectangular MPA arrays, are substrate thickness (ST) of 0.3449 mm, patch width (PW) of 4.23519 mm, patch length (PL) of 3.40451 mm, inset length (IL) of 0.89268 mm, and inset width (IW) of 0.02475 mm. The detailed design analysis of a single element MPA is given in (Goshu et al., 2021). Using a microstrip patch antenna with the above-calculated dimension values, four semi-elliptical slotted single rectangular MPA elements have been used as a building block to design a planar 2x2 rectangular MPA array. These four semi-elliptically slotted rectangular MPA are grouped into a pair of 2x1 linear configurations, which are interconnected together using a 100 Ω microstrip feeder line as shown in Figure 1.

To improve the matching quality between the radiator and the feeder line, a quarter-wave impedance transformer (QWIT) is used as shown in Figure 1. The length of the microstrip transmission line which is denoted by (LLMTL)_{2x2} is 0.41069 mm, the width of the last microstrip transmission line (WLMTL)_{2x2} is 7.24683 mm. The width and length of the quarter-wave impedance transformer are 0.90295 mm and 0.82137 mm, respectively. The remaining theoretically calculated and tuned design parameters of a 2x2 semi-elliptical slotted MPA array shown in Figure 1 are tabulated in Table 1.

The planar 2x2 rectangular MPA would improve the antenna’s performance in terms of the gain and beam-scanning ability in two directions. To further improve the performance of the antenna, a planar 4x4 rectangular MPA array was designed using a sub-array of four 2x2 MPA arrays. These elements are grouped into two pairs of 2x2 planar configurations and placed over each quadrant of the X-Y coordinate axis. Therefore, the design parameters of a single and planar 2x2 rectangular MPA have been used directly for a 4x4 MSPA array design. The calculated and optimized physical dimensions of these arrays are tabulated in Table 2 and the physical structure is shown in Figure 2.

Finally, by increasing the number of radiators in the array, the third planar semi-elliptical slotted MPA array designed in this study was an 8x8 rectangular MPA array. The proposed 8 x 8 MPA array is desired to improve the performance of both the 2x2 and 4x4 MPA arrays. To design an 8x8 MPA array, 64 antenna elements are required. Therefore, the design parameters of the 2x2 and 4x4 MPA arrays above were used as it is, and the remaining parameters are shown in Figure 3 and the respective values are given in Table 1. This shows how the increment in the antenna array size
## Table 1. Theoretically calculated and tuned physical dimensions of 2×2, 4×4, and 8×8 MPA arrays

| Parameters of 2x2 Array | Parameters of 4x4 Array | Parameters of 8 × 8 Array |
|-------------------------|-------------------------|--------------------------|
| Symbols | Initial (mm) | Tuned (mm) | Symbols | Initial (mm) | Tuned (mm) | Symbols | Initial (mm) | Tuned (mm) |
| PW | 4.235 | 4.7 | PW | 4.235 | 4.7 | PW | 4.235 | 4.52 |
| PL | 3.404 | 3.5 | PL | 3.404 | 3.72 | PL | 3.404 | 3.701 |
| IL | 0.893 | 0.95 | IL | 0.893 | 0.67 | IL | 0.893 | 0.95 |
| IW | 0.025 | 0.35 | IW | 0.025 | 0.45 | IW | 0.025 | 0.35 |
| LMTL | 1.806 | 1.7 | LMTL | 1.806 | 1.34 | LMTL | 1.806 | 1.28 |
| WMTL | 0.821 | 0.822 | WMTL | 0.821 | 0.822 | WMTL | 0.821 | 0.822 |
| LPD<sub>2x2</sub> | 0.411 | 0.42 | LFP<sub>4x4</sub> | 0.411 | 0.42 | LPD<sub>8x8</sub> | 0.411 | 0.42 |
| WPD<sub>2x2</sub> | 10.406 | 10.4 | WFP<sub>4x4</sub> | 10.406 | 10.3 | WPD<sub>8x8</sub> | 10.406 | 10.21 |
| GPW<sub>2x2</sub> | 15.890 | 30 | GPW<sub>4x4</sub> | 35.061 | 48 | GPW<sub>8x8</sub> | 73.401 | 116 |
| GPL<sub>2x2</sub> | 17.841 | 28 | GPL<sub>4x4</sub> | 31.737 | 50 | GPL<sub>8x8</sub> | 66.755 | 100 |
| LLMTL<sub>2x2</sub> | 0.411 | 0.42 | LLMTL<sub>4x4</sub> | 0.411 | 0.42 | LLMTL<sub>8x8</sub> | 0.4107 | 0.42 |
| WLMTL<sub>2x2</sub> | 7.247 | 13.8 | WLMTL<sub>4x4</sub> | 17.323 | 23.17 | WLMTL<sub>8x8</sub> | 36.495 | 59.06 |
| IS | 5.35 | 5.3 | IS | 5.35 | 5.32 | IS | 5.35 | 5.34 |
affects the performance of the antenna arrays. The comprehensive analysis of MPA with 4, 16, and 64 array elements (planar) is given in the following sections.

Where LMTL is the length of microstrip transmission line, WMTL is the width of microstrip transmission line, LPD is the length of 1:2 power divider, WPD is the width of 1:2 power divider, LPDA is the length of power divider arm, WPDA is the width of power divider arm, GPW_{2x2} is ground plane width of 2x2 array, GPL_{2x2} is ground plane length of 2x2 array, LFP_{2x2} is the length of the 2x2 feed point, WFP_{2x2} is the width of the 2x2 feed point, IS is inter-element spacing, GPW_{4x4} is ground plane width of 4x4 array, GPL_{4x4} is ground plane length of 4x4 array, LLMTL_{4x4} is the length of last microstrip transmission line, WLMTL_{4x4} is the width of last microstrip transmission line, LFP_{4x4} is the length of the 4x4 feed point, WFP_{4x4} is 4x4 feed point width.

Starting with the calculated dimensions, the parameters of these antenna structures were optimized. The optimization procedure in this work is based on manual tuning of the antenna in both directions of the calculated value (in the lower and higher). In the parameter tuning process, the parameters of the antennas with the best performance were chosen. The parameter optimization can be done either using metaheuristic optimization algorithms, such as genetic algorithms (GA), particles swarm optimization (PSO), etc (Rini et al., 2011) or using manual tuning (Fante & Gemeda, 2021). The manual antenna parameter tuning process is slower than the metaheuristic-based optimization algorithms.

Table 2. Final simulation results of the 2x2, 4x4, and 8x8 MPA arrays

| Array Type | Reflex (GHz) | Gain (dB) | BW (GHz) | S11 (dB) | VSWR | IS (dB) | LFP (mm) | WFP (mm) | GPW (mm) | GPL (mm) | LLMTL (mm) | WLMTL (mm) |
|------------|--------------|-----------|----------|----------|------|--------|----------|----------|--------|--------|-----------|-----------|
| 2x2        |              |           |          |          |      |        |          |          |        |        |           |           |
| 4x4        |              |           |          |          |      |        |          |          |        |        |           |           |
| 8x8        |              |           |          |          |      |        |          |          |        |        |           |           |

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Figure 2. Planar 4x4 semi-elliptical slotted rectangular MPA array.
3. Simulation results and discussions

In this section, simulation-based performance analyses of 2x2, 4x4, and 8x8 planar semi-elliptical slotted MPA arrays are presented. The frequency-domain analysis of CST-MW Studio was utilized to analyze the performance of three antenna arrays in terms of VSWR, return loss, bandwidth, radiation efficiency, gain, and directivity of the radiation pattern. It is worth noting that all
discussions in the following sections use the optimized dimensions of the physical structures listed in Table 1.

3.1. The input matching network, VWSR, and bandwidth
The scattering parameters (S-parameter) of a two-port network model helps to estimate the matching quality and bandwidth of the antenna. From the S-parameter analysis, at center frequency i.e., 28 GHz, the return loss ($S_{11}$) of the proposed 2x2 semi-elliptical slotted MPA array is
about ~43.321 dB as shown in Figure 4 and the magnitude of its VSWR is 1.014 (see, Figure 5). In addition, the −10 dB bandwidth of this antenna is 1.33 GHz. Similarly, the return loss of the studied 4x4 semi-elliptical slotted MPA array at 28 GHz is ~40.665 dB and its VSWR is 1.019 (see, Figure 5), which is very close to the theoretical value. The −10 dB bandwidth of this antenna array is about 1.461 GHz, which is 131 MHz higher than the bandwidth of the 2x2 MPA array.

The designed rectangular 8x8 MPA array has a return loss of ~22.678 dB and a VSWR of 1.159 as shown in Figure 4 and Figure 5 respectively. The −10 dB working bandwidth of this antenna array is 1.561 GHz, which is higher than the bandwidth of the semi-elliptical slotted 2x2 and 4x4 MPA arrays by 231 MHz and 100 MHz, respectively. From the simulation results, as expected, increasing the size of the antenna array increases the bandwidth, the return loss, and VSWR values of the antenna array. The achieved result in terms of bandwidth for the 8x8 antenna array is higher than the performance deterioration in terms of return loss and VSWR because these quantities are within the acceptable limits for many applications. This means that the return loss is less than −10 dB and VSWR is less than 2 within the bandwidth of all the antenna arrays.

3.2. The directivity, gain, and radiation efficiency
From the radiation pattern plot of the proposed antennas, the directivity, gain, and efficiency of three antenna arrays were determined. The directivity, gain, and total radiation efficiency of the 2x2 rectangular MPA array, as depicted in Figure 6, are 12.81 dBi, 13.24 dBi, and −0.1310 dB (97.03 %), respectively.

From Figure 7, the gain, directivity, and overall efficiency of the proposed 4x4 MPA array are 16.54 dBi, 16.38 dBi, and ~0.877 dB (81.72 %), respectively. This implies that increasing the array size from 2x2 to 4x4 improves the directivity and gain of the MPA array by 3.57 dBi and 3.3 dBi, respectively. The directivity and gain of the proposed antenna were increased as the number of array elements were increased to 16 and the ground plane dimensions were properly tuned.

The gain, directivity, and total efficiency of the proposed 8 × 8 semi-elliptical slotted MPA array are 21.45 dBi, 19.60 dBi, and −1.616 dB (69 %), correspondingly as shown in Figure 8. This antenna array improves the directivity and gain of the 2x2 MPA array by 6.79 dBi and 8.21 dBi, respectively. In the same way, the performance improvement observed using the proposed 8x8 MPA array in terms of directivity and gain is 3.22 dBi and 4.91 dBi, respectively, in comparison with the 4x4 MPA arrays. With increasing the proposed MPA array size, the gain and directivity increases, and the radiation efficiency reduce due to the increased mutual coupling between the proposed MPA array elements. This is because the mutual coupling profoundly affects the antenna’s input impedance, reflection coefficients, and gain.

Figure 8. 3D radiation pattern of the proposed planar 8 × 8 MPA array.
In general, the proposed antenna arrays meet the requirements of 5G systems operating in the LMDS band. All three antenna arrays have more than 850 MHz bandwidth. For a stringent matching condition of the proposed antenna arrays (VSWR < 1.25), the proposed antenna arrays achieved wide bandwidth.

3.3. The side lobe level and cross-polarization of the 3D radiation pattern

In transmitting antennas, extreme side lobe radiation results in wastes of energy and minimum information confidentiality. On the other side, in receiving antennas, the side lobes may select the interfering signals, which increases the noise level in the receiver. The magnitude of the side lobe level (SLL) of the planar 2x2, 4x4, and 8x8 semi-elliptical slotted MPA arrays are indicated in
Figure 9. Thus, from the figure, it can be observed that the SLL of the 2x2 MSPA array is −10.6 dB and a 3 dB radiation pattern has a 37.3 degrees span. Whereas the magnitude of SLL of the 4x4 rectangular MPA array is −9.1 dB and the 3 dB radiation pattern has occurred at 25.2 degrees. Nevertheless, the SLL of the proposed 8x8 planar rectangular MPA is −7.9 dB, and the 3 dB radiation pattern of this array has occurred at 12.3 degrees.

Even though accurate design parameters have been considered during design processes, the effect of mutual coupling is increased with array elements. This is because the minimum mutual coupling from each of the quadrant planes is added together to increase the overall sidelobe level of the array. Thus, as the antenna size is increased, side lobes move from the evanescent space to the visible space. Besides, inter-element spacing between array elements has profound effects on the magnitude of the SLL.

The cross-polarization far-field component which is orthogonal to co-polarized component and main lobe direction of the proposed 2x2, 4x4, and 8x8 semi-elliptical slotted MPA arrays are shown in Figure 10a, b, c respectively. As it can be realized from the graph, the gain cross-polarization of the 2x2 MSPA array is −0.7271 dB (see, Figure 10a). Likewise, the 4x4 and 8x8 MPA array cross-polarization magnitude are 6.634 dB and 4.969 dB, respectively (see, Figure 10a and b). As it can be seen from the far-field plot, the cross-polarized component is minimal as compared to that of the desired polarization.

Lastly, final simulation results for the structure of designed planar MPA arrays i.e., the magnitude of the return loss, bandwidth, gain, directivity, VSWR, and total radiation efficiency all of the designed structure is tabulated in Table 2.

As it can be seen from the table, because of the introduced defect structure on both radiating elements and ground plane, the attained performance of the designed antenna arrays is efficiently improved for the dedicated 5G wireless communication systems. For 8x8 planar MPA arrays, it outperforms both 2x2 and 4x4 in terms of bandwidth, gain, and directivity.

Table 3. Comparison of existing works and the proposed 2x2, 4x4, and 8x8 MPA arrays

| Array Type | Ref. | RF (GHz) | S11 (dB) | BW (GHz) | G (dB) | VSWR | η tot (%) |
|------------|------|----------|----------|----------|--------|-------|------------|
| 2x2        | (Johari et al., 2018) | 28 | −19.66 | 0.4 | 8.393 | 1.232 | 82.85 |
|            | (Kavitha et al., 2020) | 28 | −20 | 0.95 | - | - | - |
|            | (Gemeda & Fante, 2020) | 28 | −32.68 | 0.326 | 10.71 | 1.047 | 89.79 |
| This work  |             | 28 | −43.32 | 1.33 | 13.24 | 1.014 | 97.03 |
| 4x4        | (Gemeda & Fante, 2020) | 28 | −33.15 | 0.332 | 15.17 | 1.045 | 85.08 |
|            | (Keum & Choi, 2018) | 28 | −13.48 | 4.91 | 16.48 | - | - |
| This work  |             | 28 | −40.66 | 1.461 | 16.54 | 1.019 | 81.72 |
| 8x8        | (Keum & Choi, 2018) | 28 | −17.79 | 0.368 | 18.33 | 1.298 | 74.23 |
| This work  |             | 28 | −22.67 | 1.561 | 21.45 | 1.159 | 69 |
Even though measurable performance improvement techniques are used, there is degradation in terms of return loss, radiation efficiency, and sidelobe levels as seen with 2x2 and 4x4 arrays. This is because the impact of increasing antenna elements along with the inter-element spaces is great in increasing more mutual coupling added together from each element, which rises input impedance of the patch, as a result, return loss and side lobe level increase and thereafter drops overall efficiency of the antenna as compared antenna array with minimum antenna elements. But as compared to that of existing related works and the requirement for 5G, those results achieved in this work are more prominent and comfortable for the era of 5G communication systems.

4. Performance comparison
At the resonance frequency (28 GHz), the performance comparison between the proposed 2x2, 4x4, 8x8 semi-elliptical slotted rectangular MPA arrays and existing designs in the scientific literature are shown in Table 3. The bandwidth of the proposed planar 2x2 MPA array outperforms the designs reported in (Johari et al., 2018), (Kavitha et al., 2020), and (Tegegn & Anlay, 2020). The bandwidth of the proposed design exceeds these designs by 380 MHz, 930 MHz, and 1.04 GHz, respectively. Similarly, in terms of radiation efficiency, the proposed design surpasses the structures proposed in (Johari et al., 2018) and (Mohamed et al., 2020) by 14.18 % and 7.24 %, respectively. In terms of gain, the proposed design outperforms similar MPA array size designs reported in (Johari et al., 2018) and (Tegegn & Anlay, 2020) by 4.847 dBi and 2.53 dBi, respectively.

Furthermore, the proposed 4x4 rectangular MPA array achieved bandwidth wider than the design reported in (Tegegn & Anlay, 2020) by 1.129 GHz. Its gain exceeds the one reported in (Tegegn & Anlay, 2020) by 1.37 dBi. Similarly, it has greater gain than the MPA arrays reported in (Tegegn & Anlay, 2020) and (Keum & Choi, 2018). Moreover, the proposed 8x8 MPA array improves the bandwidth of the design demonstrated in (Tegegn & Anlay, 2020) by 1.193 GHz and in its radiation pattern's gain by 3.12 dBi. However, its total efficiency is lower than the design reported in (Tegegn & Anlay, 2020). Finally, the 8x8 MPA array design proposed in this work achieved higher return loss, bandwidth, gain, and VSWR compared to the simulation results reported in (Tegegn & Anlay, 2020).

In general, the design proposed in this study offers very competitive and improved performance compared to the existing designs. These improved performances were achieved because of the defect structure introduced on each of the radiating elements as well as on the ground plane. It strongly influences the current distributions of the structure so as to increase the radiation efficiency of the proposed designs. In addition, in the feed networks, between the microstrip transmission line and the feed point, an appropriate impedance matching technique is employed. Also, the arm of the 1:2 power splitter and the edge of the patch have been meticulously designed to bring them up to a suitable level using the impedance matching technique with inset feed, quarter-wave impedance transformer, and tuning the physical dimensions of the structures.

This minimizes power losses due to the impedance mismatch, which in turn increases the radiation efficiency of the antenna and thus its bandwidth. The proposed antenna arrays are designed to operate from the frequency of 27.5 GHz to 28.35 GHz of local multipoint distribution service band, which has an 850 MHz bandwidth requirement (Przesmycky et al., 2021).

5. Conclusion
In this work, the performances of planar 2x2, 4x4, and 8x8 MPA arrays with semi-elliptical slotted rectangular patch and ground plane have been analyzed. The performances of the antennas were evaluated using bandwidth, gain, radiation efficiency, return loss, and VSWR. The results of the bandwidth, return loss, gain, and total efficiency of single element semi-elliptical slotted MPA presented in (Goshu et al., 2021) was 1.132 GHz (4.043 %), −37.784 dB, 7.128 dBi, and −0.05513 dB (98.74 %), respectively. Continuity of that work, in this paper, the bandwidth, gain, and total efficiency of the examined planar 2x2 and 4x4 rectangular MPA arrays are 1.33 GHz (4.75 %),
13.24 dBi, and $-0.1310$ dB (97.03 %) and 1.461 GHz (5.218 %), 16.54 dBi, and $-0.877$ dB (81.72 %), respectively. Finally, the planar 8x8 MPA array attained the gain of 21.45 dBi, the bandwidth of 1.561 GHz (5.75 %), and total efficiency of $-1.616$ dB (69 %).

Compared to existing related works, the obtained simulation results reveal that the proposed rectangular MPA arrays have superior performance (see, Table 3). Because the introduced etched semi-elliptical structure on both the radiating element and ground plane highly influences the current distribution of both structures. In addition, a good impedance matching network has been designed for the feeding network structures. Therefore, the power losses that occur due to the impedance mismatch are dramatically minimized. The key physical dimensions of the antenna have been tuned to find the values with the best performance. Consequently, the performance of the antenna is profoundly improved in terms of bandwidth, gain, and radiation efficiency. All of the designed MPA arrays provide high performance with a very compact size, which is suitable for the 5G communication systems operating in the LMDS band.

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