A Reliable Antenna Array for the 28GHz mmWave Band in a 5G Massive MIMO Communication.

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***Abstract*—The high communication performance specifications of the 5G wireless cellular communication standards require electronic components that can reliably support such standards. One such component is the antenna. The antenna is one of the most useful components in wireless communication, and hence, its performance heavily influences the performance of a wireless communication system. In this study, we propose a planar 10x10 microstrip patch antenna (MPA) array for a 5G massive multiple inputs multiple outputs (mMIMO) wireless communication. The antenna was designed and simulated using Pathwave Advanced Design System (ADS), and it achieves a gain of 21.97dBi, radiation efficiency of 0.93, and bandwidth of 0.45GHz on the 28GHz millimeter wave (mmWave) band.**

***Index Terms*—patch antennas, telecommunication, wireless communication, 5G, massive MIMO, mmWave communication.**

I. INTRODUCTION

Wireless cellular communication standards [1] have evolved over the years and many technologies have been developed to support the different wireless cellular communication standards. Starting with 1G, then 2G, 3G, 4G, and now 5G standards, there has been much improvement in communication reliability from one standard to another [2]. This reliability in terms of performance includes measures such as data transfer rate, latency, traffic capacity, and spectral efficiency [3].

As defined by the 3GPP consortium [4], [5], the 5G wireless cellular communication standards can achieve up to 10Gbps data transfer rate (10 to 100x speed improvement over 4G and 4.5G networks), 1-millisecond latency, 1000x bandwidth per unit area (compared with 4G LTE), up to 100x number of connected devices per unit area (compared with 4G LTE) i.e., 1 million devices for 1 km^2, 99.999% availability, 100% coverage, and 90% reduction in network energy usage.

This makes the 5G standard attractive for any applications where high reliability is required such as in IoT networks, vehicular networks, and medical networks. One method to achieve this high performance is to use high-frequency microwaves. Based on this method, 3GPP has classified the mmWave (above 24GHz) region into different groups [6] such as the n257 (or 28GHz) band which ranges from 26.5-29.5GHz, the n258 (or 26GHz) band which ranges from 24.25–27.5 GH, and the n261 (or 28GHz) band which ranges from 27.5–28.35 GHz. We shall focus on the n258 band because it is currently the most deployed 5G mmWave spectrum.

Technically, wireless cellular communication [1] is a type of radio communication technology where a large geographical region is divided into smaller sections called cells, each with a low-power wireless transmitter, for optimizing the use of a limited number of frequencies. This is different from other radio communication technologies such as WiFi, Bluetooth, and ZigBee, which are mostly used for short-distance device-device communication and which can access the internet (a larger region) using any broadband technology [7] such as cellular, fiber optic, or satellite communication technologies.

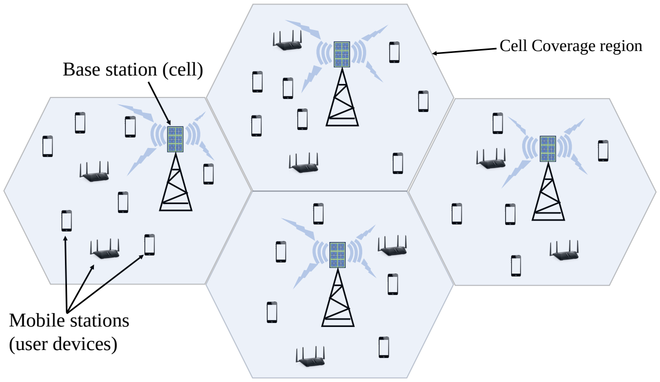


Fig. 1. A wireless cellular network architecture with base and mobile stations.

In this study, we focus on radio communication based on the 5G wireless cellular communication technology, whose architecture is shown in Figure 1. All radio communication technologies make use of transmission and reception (Tx/Rx) antennas together with a chain of different signal processing operations such as amplification, filtering, modulation, sampling, quantizing, coding, and multiplexing. Thus, the antenna is a key component in all radio communication technologies.

In wireless cellular technology, two sets of antennas are used, the base station antennas and the mobile station antennas, with each having a set of Tx/Rx elements for transmitting and receiving radio signals. The base station antenna is mostly geographically fixed and radiates radio waves constantly over a certain geographical region, to cover all mobile stations that move to that region.

One challenge in wireless cellular communication is to enable multiple communication links between the mobile stations and the base station to create a MIMO communication setting. This is very important because, with multiple communication channels at any given instance, the data transfer rate between the base station and the mobile station will increase. Due to this advantage, many technologies have been developed to support MIMO communication in wireless cellular communication [8], and 5G technology focuses heavily on MIMO optimization techniques such as beamforming.

Moreover, depending on the number of connected mobile stations to a base station, MIMO communication can be categorized into Single User MIMO (SU-MIMO) and Multiple User MIMO (MU-MIMO) [8]. However, with the increase in the number of mobile devices and content creation in recent years, the communication traffic has surged and there is much concern to support high traffic, especially in a MU-MIMO. This has given rise to a new MIMO paradigm, called Massive MIMO (mMIMO) [9]. A simplified architecture of a mMIMO wireless cellular communication is presented in Figure 2.

Generally, all MIMO technologies for radio communication (i.e., physical layer MIMO communication) are based on the antenna component. The number of antennas a radio station or device have for transmitting and receiving radio signal defines its MIMO status. For example, a 2×2 MIMO radio station has two antennas for signal transmission and two antennas for signal reception. With mMIMO technology, the higher the number of Tx/Rx antennas on a cellular device, the higher the amount of traffic it can support, making mMIMO an attractive technology for 5G communication.

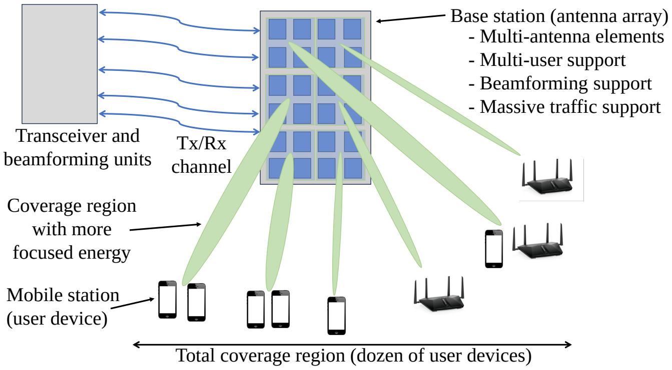


Fig. 2. A mMIMO antenna array base station with related mobile stations.

However, designing and deploying a set of connected antennas (i.e., array antenna) to support mMIMO service in 5G communication technology is not an easy task because of the material and financial costs that may be required. For example, the number of antennas required may occupy a space that may be larger than the allocated space on the radio frequency (RF) device, especially in compact RF devices. Actually, mMIMO technology for wireless cellular communication is currently implemented mostly on the base station antennas, one reason being the large antenna size such stations can support.

In the next section, different related studies on the design of antennas and antenna arrays in 5G MIMO/mMIMO wireless cellular communication are discussed.

II. RELATED WORKS

Many studies have been done on the design of antennas for 5G MIMO wireless communication but fewer studies focus on 5G mMIMO wireless communication due to its cost.

Wani et al. [12] proposed a 4-port MIMO 28GHz antenna for 5G applications. By using an array of metamaterial unit cells, each antenna element has an end-fire gain of about 10 dBi. The return loss and isolation for all ports of the antenna in the frequency range 26 GHz to 31 GHz is below $S_{nn} < -10$dB and $S_{nm} > 21$dB, respectively.

Rana et al. [13] proposed a microstrip patch antenna operating at 28GHz for 5G wireless communication systems. From their study, they obtained a return loss, gain, radiation efficiency, and side-lobe level of -38.348 dB, 8.198dB, 77%, and-18.3 dB respectively. The gain of their antenna is low for a 5G MIMO/mMIMO system. One reason for this is the use of a single-element antenna in their study which may not generate enough radiation energy required to support the specification of a 5G MIMO/mMIMO wireless communication system.

Sunthari et al. [14] proposed a 4-element linear antenna array for 5G MIMO mobile (i.e., cellular) communication. The antenna is designed based on the resonant cavity model and the dominant mode of (0,1,1). The antenna operates in the 28 GHz, 37GHz, 41 GHz, and 74 GHz bands with an initial gain of -22dB,-37dB,-10 dB, and -19dB, respectively. They improved the gains during their study.

Abdulkareem et al. [15] proposed a new MIMO patch antenna for 5G applications. The proposed antenna has a bandwidth of 4.337 GHz (24.22 – 28.557) GHZ and a gain of 3.68dBi which are average values for a practical single-element antenna in 5G applications but very low for simulated performance. Furthermore, for mMIMO applications, such gain may be low to support the 5G requirements.

Gemeda et al., [16] proposed 28GHz Microstrip Patch Antenna for 5G communication systems. The antenna produces a beam gain of 7.587 dBi, directivity of 7.509 dBi, radiation efficiency of 98.214 %, and bandwidth of 1.046 GHz which are compatible with a single element antenna in a 5G application. However, such an antenna may not be able to support the high requirements in a 5G MIMO/mMIMO application.

Jose et al. [17] proposed a linearly polarized 4-port MIMO antenna array working at 28GHz band mmWave. Its return loss is less than -10dB in the frequency range of 26.69- 30.29GHz and provides a wide bandwidth of 3.53 GHz. it has a gain of 19.6dBi, with a mutual coupling value less than -25dB for each element, and better ECC due to proper element spacing.

In this study, we proposed a planar 10x10 microstrip patch antenna design with high operational performance to support 5G mMIMO communication services. The patch antenna was selected because of its low cost and ease of compartmentalization, which can lead to its production in large quantities and use in smaller stations including even mobile stations. The design analysis and simulation results of the proposed antenna array were presented and compared with other models.

The rest of the paper is divided as follows: Section III focuses on the design analysis of the antenna and its geometrical structure. Section IV is the simulation results and discussion. The study is concluded in Section V.

III. ANTENNA DESIGN

A radio antenna is a transducer of electromagnetic (EM) energy (in radio waves) and electrical energy. It is used to convert radio waves from the environment to electric signals, and vice-versa. The design of a radio antenna is based on its geometric, material, and other functional properties such as its operating frequency and impedances. These design properties influence the performance properties of the antenna such as its gain, directivity, radiation efficiency, and bandwidth.

Different types of radio antennas exist such as dipole antennas, horn antennas, parabolic antennas, yagi-uda antenna, and microstrip patch antennas. We focus on the microstrip patch antenna in this study. The specification of the antenna is based on the requirement of the 28GHz band 5G mMIMO communication [18], [19]. The requirement specifications in Table I were used as a baseline to guide the design process.

TABLE I
REQUIREMENT SPECIFICATIONS OF A 28GHZ 5G MMIMO MPA

Requirement Specifications	
Design requirement specifications	
Operating frequency (GHz)	28
Patch material type	Copper
Patch material thickness (mm)	0.018
Substrate type	Rogers R03003 [20]
Relative permittivity of substrate	3
Thickness of substrate (mm)	0.13
Loss tangent of substrate	0.0011
Size of antenna array (LxW) (mm^2)	100x100 = 10000
Feeding (input) impedance (Ω)	50
Performance requirement specifications	
Directivity of a single element MPA (dBi)	10 - 15
Directivity of 10×10 MPA array (dBi)	30 - 35
Radiation efficiency of single element MPA	0.65 - 0.95
Radiation efficiency of 10×10 MPA array	0.65 - 0.95
Gain of a single element MPA (dBi)	6 - 9
Gain of 10×10 MPA array (dBi)	26 - 29

L and W are the length and width of the antenna array, respectively.

In Table I, the performance requirement specifications values are the achievable high simulated performance ranges for a single element MPA and a 10×10 MPA array of identical elements. Generally, the achievable range of a high simulated gain of a single element MPA is between 6-9dBi, the directivity is between 10-15dBi, and the radiation efficiency is between 0.65-0.95. These values may be lower in practice, since practically, a high achievable radiation efficiency of an antenna is between 0.5-0.6.

Using Eq (11) and assuming zero loss, we obtained the theoretical high simulated performance values of a 10×10 MPA array with 100 identical elements based on the achievable high simulated performance values of a single element MPA. These theoretical performance values are considered as the baseline performance values of the 10×10 MPA array in this study. Unfortunately, the higher the number of elements, the higher the associated loss, and so the actual simulated and practical performance values from an antenna array are expected to be far less than their theoretical (ideal) baseline values.

The design process of the antenna consists of defining the width, length, and impedances of the patch, transmission line, and feed line of each single antenna element in the array. Using the design requirement specifications in Table I, we design a planar 10×10 MPA array with identical array elements, and the design properties of our proposed MPA array and its elements are based on those defined in [21]–[25], which we summarize below.

Width of the patch:

$$W_p = \frac{v}{2f_o}\sqrt{\frac{2}{\epsilon_r + 1}} \tag{1}$$

where v is the speed of light (3×10^8)m/s, f_o is the operating frequency, and ϵ_r is the relative permitivity of substrate.

Length of the patch:

$$L_p = \frac{v}{2\epsilon_{\text{eff}}} - 2\Delta L \tag{2}$$

where ΔL is the length extension of the patch, and ϵ_{eff} is the effective relative permitivity of substrate.

Impedance of the patch:

$$Z_p = \frac{90\epsilon_r^2}{\epsilon_r - 1}\left(\frac{L_p}{W_p}\right)^2 \tag{3}$$

Matching impedance of the transmission line:

$$Z_T = \sqrt{Z_o Z_p} \tag{4}$$

where Z_o is the feeding impedance (50Ω).

Width of the transmission line: This is obtained from a closed-form equation of the matching impedance, given as,

$$Z_T = \frac{60}{\sqrt{\epsilon_r}}\ln\left(\frac{8h_s}{W_p} + \frac{W_p}{4h_s}p\right) \text{ and } \frac{W_T}{hs} \leq 1 \tag{5}$$

where W_p is the width of the transmission line, and h_s is the thickness of the substrate.

Length of the transmission line:

$$L_T = \frac{1}{4f_o\sqrt{\epsilon_{r_T}}} \tag{6}$$

where ϵ_{r_T} is the relative permittivity of the transmission line.

Width of the feedline:

$$W_F = \frac{8h_s e^A}{\epsilon_r^{2A} - 2} \tag{7}$$

$$\text{where } A = \frac{Z_o}{60}\sqrt{\frac{\epsilon_r + 2}{2}} + \frac{\epsilon_r + 1}{\epsilon_r + 1} \text{ and } \frac{W_F}{hs} \leq 2$$

Length of the feedline:

$$L_F = \frac{1}{4f_o\sqrt{\epsilon_{r_F}}} \tag{8}$$

where ϵ_{r_F} is the relative permittivity of the feed line.

Using these MPA element design properties, the design properties such as the array factor of the planar 10×10 MPA array can be evaluated using the following equation.

Array factor:

$$AF = \sum_{i=1}^{N} a_i e^{(k_i d_i \cos\theta_i + \phi_i)} \quad (9)$$

where N is the number of antenna element, a is the excitation amplitude, d is the inter-element distance, θ is the excitation angle, ϕ is the excitation phase, and k is the propagation constant. We considered $d = \lambda/2$ and $\phi = 90°$.

Furthermore, using these design properties, the theoretical (or expected) values of the element and array performance properties such as the gain can be estimated as shown below.

Single element Gain:

$$G_e = \eta D \quad (10)$$

where η is the radiation efficiency, D is the directivity.

Array Gain (aggregated, directional, and phased):

$$G_A = 10\log(N) + G_e - O_L - S_L - I_L \quad (11)$$

where N is the number of antenna element, G_e is the element gain, O_L ohmic los, S_L is the scan loss, and I_L is the impedance mismatch loss.

Using these formulas, we obtained the proposed design and performance specifications of our proposed antenna array. The proposed specification is summarized in Table II.

TABLE II
PROPOSED SPECIFICATIONS OF A 28GHZ 5G MMIMO MPA

Proposed Specifications	
Proposed design specifications	
Operating wavelength (mm)	10.71
Width of element Patch (mm)	3.79
Length of element Patch (mm)	3.05
Inter-element distance, ($\lambda/2$) (mm)	5.355
Inter-element thickness (mm)	0.15
Impedance of element Patch (Ω)	241.09
Matching impedance of each transmission lines	109.8
Width of 10×10 transmission lines (mm)	0.15
Length of 10×10 transmission lines (mm)	1.02
Width of 10×10 array feed	0.7
Length of 10×10 array feed	0.9
Feeding technique	Edge feed
Number of array element	10×10 = 100
Size of 10×10 array, L×W (mm × mm=mm^2)	83.5×90.9 = 7590.15
Array geometry	planar
Poposed performance (simulation results))	
Directivity of a single element (dBi)	6.81
Directivity of 10×10 array (dBi)	23.64
Radiation efficiency of a single element	0.71
Radiation efficiency of 10×10 array	0.93
Gain of a single element (dBi)	5.3
Gain of 10×10 array (dBi)	21.97
Impedance Bandwidth of a single element (GHz)	0.5 (27.80-28.30)
Impedance Bandwidth of 10×10 array (GHz)	0.45 (27.85 - 28.30)

L and W are the length and width of the antenna array, respectively.

The physical geometry of a single antenna element in the MPA array is presented in Figure 3 and that of the proposed MPA array is presented in Figure 4. The MPA array has 10 power feeds (P1 to P10), making it a 10-dimensional antenna array suitable for MIMO optimization operations such as beam steering which is required in a mMIMO technology.

The downside of a multidimensional antenna array is that it requires more feed power to generate and stir the beams. However, this depends on the radio frequency (RF) standard under which the antenna will be used. For example, the Japanese RF standard [26] requires a limited amount of feed power to any antenna irrespective of the number of antenna elements it contains. It is left to the designer to distribute this power over the different antenna power feeds. Other RF standards such as those from the International Telecommunication Unit (ITU) [27] and European Union (EU) [28] do not have such restrictions on feed power but instead focus more on the radiated power, such as the Effective Radiated Power (ERP) and the Effective Isotropic Radiated Power (EIRP).

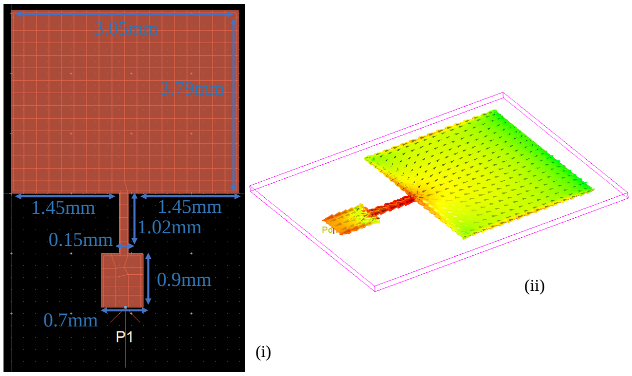


Fig. 3. A single element antenna for 5G mMIMO communication, i) geometric view, ii) radiating view.

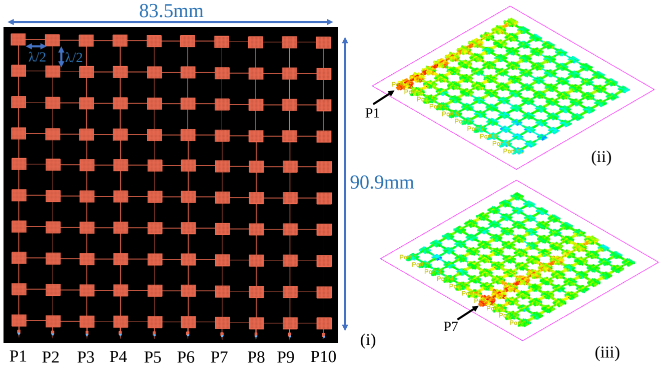


Fig. 4. A planar 10×10 array antenna for 5G mMIMO communication, i) geometric view, ii) P1 radiating view, iii) P7 radiating view.

Using the proposed design specifications in Table II, we carried out simulations of the antenna to evaluate its simulated performance. The results are presented in the next section.

IV. SIMULATION RESULTS AND DISCUSSION

We design and simulate the MPA element and array in Pathwave Advanced Design System (ADS) [29], suitable for a realistic design of RF components. The simulated performance results for a single antenna element are presented in Figure 5, Figure 6, Figure 7, and Figure 8. Those for a single feed power source (precisely P1) of the MPA array are presented in Figure 9, Figure 10, Figure 11, and Figure 12.

These performance results include the gain, directivity, radiation efficiency, radiation intensity, radiated power, and return losses (S_{nn}).

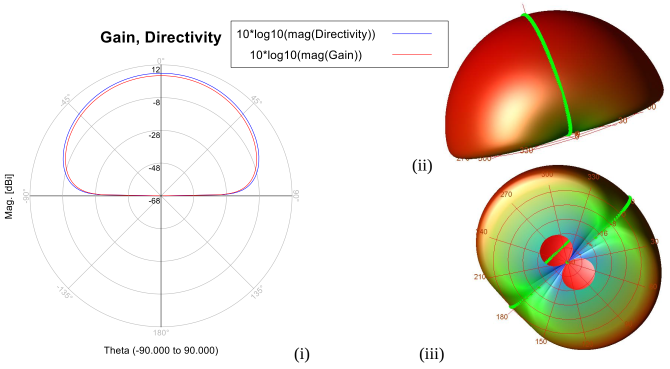


Fig. 5. i) Gain and directivity polar plots of the single element MPA, ii) azimuth and elevation radiating view of the single element MPA.

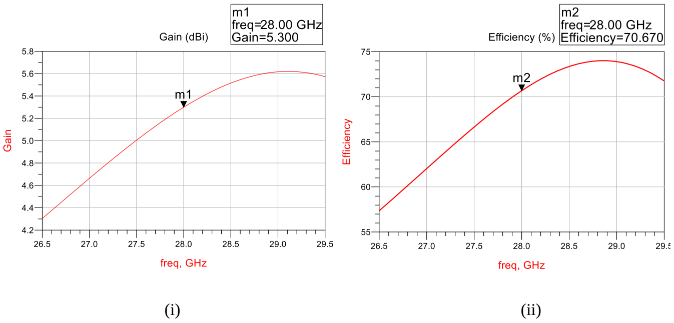


Fig. 6. i) Gain and radiating efficiency over frequency of the single element MPA, i) gain, ii) radiating efficiency over frequency.

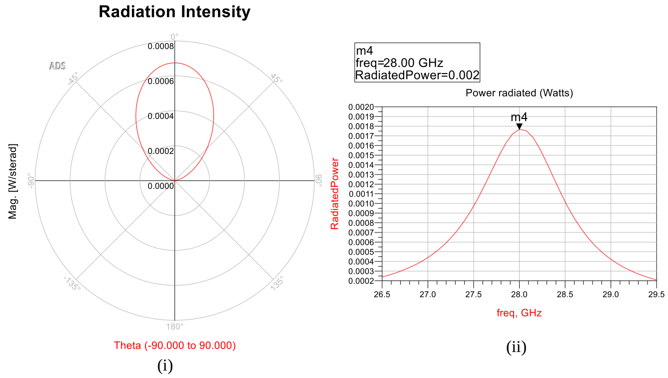


Fig. 7. i) Radiating intensity polar plot of the single element MPA, ii) power radiation over frequency of the single element MPA.

From the simulations, the P1 linear MPA array has a higher directivity, gain, and radiation intensity but lower radiation efficiency and a higher return loss (S_{11}) loss as compared to the single-element MPA. This is normal because the more antenna we add to an antenna array also adds more loss in the array. This loss affects the radiation efficiency of the array and the overall gain of the array as shown in Eq (11).

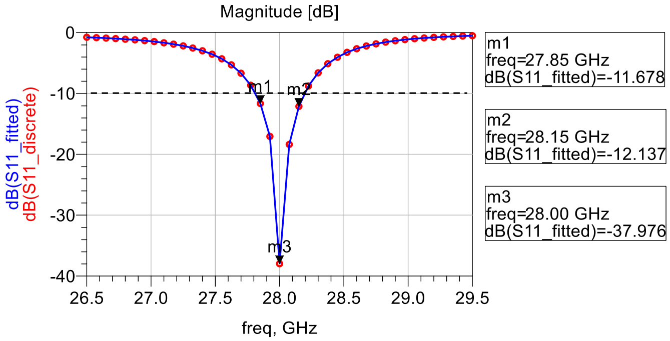


Fig. 8. Return loss (S_{11}) of the single element MPA.

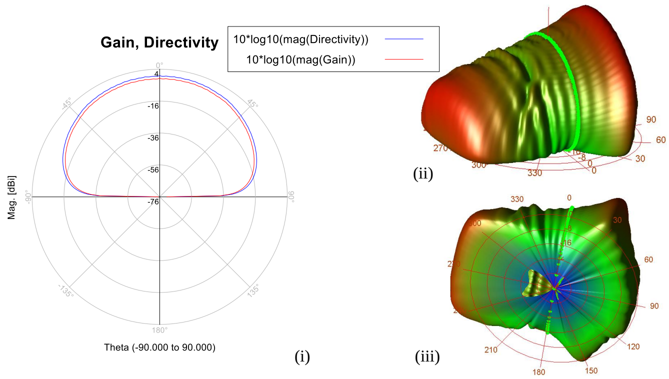


Fig. 9. i) Gain and directivity polar plots of the P1 linear array in the 10×10 MPA array, ii) azimuth and elevation radiating view of the P1 linear array.

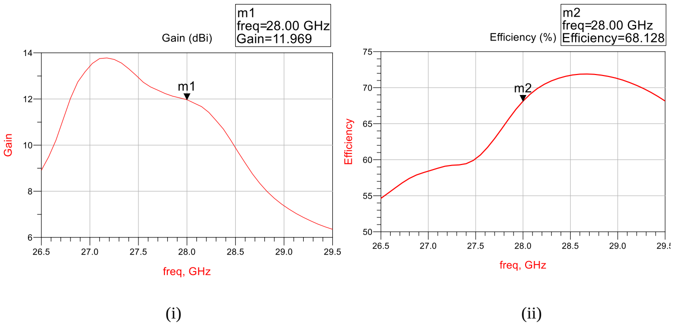


Fig. 10. i) Gain and radiating efficiency over frequency of the P1 linear array in the 10× MPA array, i) gain, ii) radiating efficiency over frequency.

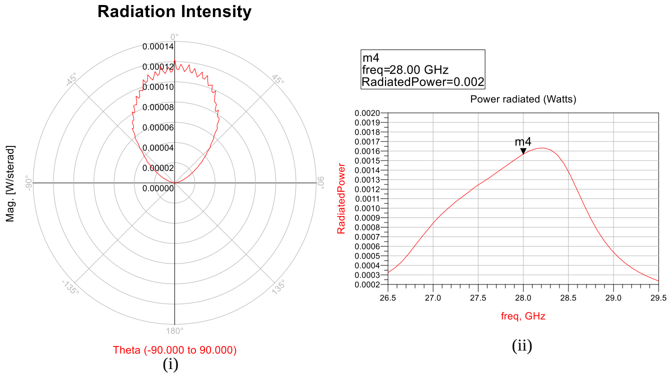
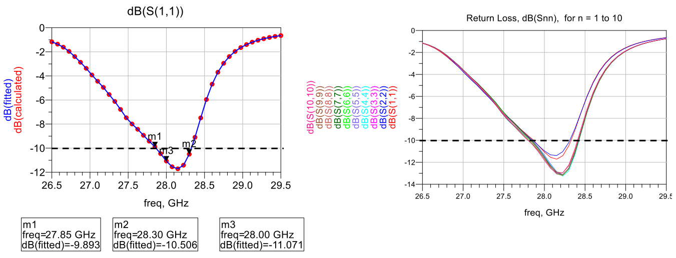


Fig. 11. i) Radiating intensity polar plot of the P1 linear array in the 10×10 MPA array, ii) power radiation over frequency of the P1 linear MPA array.



(i) (ii)

Fig. 12. i) Return loss (S_{11}) of the P1 linear MPA array, ii) Return losses (S_{nn}) of all the 10 power inputs to the 10×10 MPA array.

TABLE III
PERFORMANCE COMPARISON OF DIFFERENT 5G MMIMO MPA

Comparative measures	Baseline	[12]	[15]	[17]	our model
Comparative design specs.					
Number of antenna elements	100	4	4	4	100
Number of power feed ports	/	4	4	4	10
Antenna array size (100mm^2)	100	14.88	25	10.64	75.9
Comparative perf. results					
Directivity (dBi)	30-35	/	4.83	20.42	23.64
Radiation efficiency	0.65-95	/	0.76	0.96	0.93
Gain (dBi)	26-29	10	3.68	19.6	21.97
Supported Bandwidth (GHz)	/	/	4.553	3.53	0.45

Specs. indicate specification and perf. indicates performance.

However, the aggregated performance of the 10×10 MPA array from the simulated results of the P1 linear MPA array can be obtained using Eq (11), assuming all feed signals are in phase and zero loss. These results were then compared with the baseline and evaluation models, and presented in Table III.

V. CONCLUSION

In this paper, an MPA array and its elements for a 28GHz mmWave 5G mMIMO communication were designed. The antennas were simulated and the results were compared with that of a baseline model and other models in related literature.

The simulation results show that the proposed array antenna has a gain of 21.97dBi, a radiation efficiency of 0.93, a return loss value <-10dB, and a bandwidth of 0.45GHz suitable for the 28GHz mmWave band in a 5G mMIMO cellular communication. However, we look forward to further optimizing the performance of the antenna in terms of feed power usage, and to developing different approaches to optimize the use of the antenna in mMIMO applications.

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