Abstract: A 72 port (288 antennas) triangular shaped massive multiple-input-multiple-output (mMIMO) antenna system is presented for 5G base stations. Each side of the antenna system consists of 3 layers with a total size of 44.4 × 29.6 × 0.1524 cm$^3$, and contains 24 ports. Each port (subarray) consists of 2 × 2 patches on the top layer, their feeding network with pre-calculated phases is on the bottom layer and the ground plane is in the middle one. Each subarray (one port) is fed in a way to tilt its beam direction with respect to others to achieve uncorrelated individual patterns. The antenna system is the first to support two operating modes: simultaneous individual port operation (i.e.72 port MIMO) and mMIMO array operation (i.e. with beam switching). The design is fabricated and measured to test its performance. The measured bandwidth is 100 MHz that covers the band from 3.45-3.55 GHz. The measured gain of a single port equals to 9.41 dBi. The envelop correlation coefficient does not exceed 0.1198. A beam-steering method to steer the beam of each 24-port side to different locations in the space is presented and applied based on the non-uniform port patterns (unlike most conventional methods using identical array elements). 13 switched beams are obtained with center angle coverage up to 34° in elevation with maximum gain of 19.5 dBi.

1 Introduction

The fifth generation (5G) of wireless standard will significantly improve the performance of wireless systems in terms of data rate and channel capacity. The channel capacity in 5G is expected to be 1000 times its 4G predecessor. This improvement will be achieved by different technologies, such as: ultra-densification, millimeter wave (mmWave) systems, advanced modulation and coding and massive multiple-input-multiple-output (mMIMO) [1].

A MIMO system has multiple antennas at the transmitter and multiple antennas at the receiver to improve the diversity gain and channel capacity [2]. In mMIMO, the number of antennas at the base station side will be very large for higher channel capacities. Also, using mMIMO will increase energy efficiency and reduce the latency [3].

There are few works in literature presenting mMIMO antenna designs. Most of these designs are based on an array mode with beamforming capability as in [4]-[6]. In [4], 64 RF channels were designed using basic 4 × 1 subarrays of patches that is designed at 5.8 GHz. The design was fabricated and measured, and it gave 200 MHz bandwidth and a gain of 18 dBi at boresight for the whole array. Complex phased array beamsteering is applied in the design presented in [5]. This array consisted of 160 dual polarized patches on one planar size. The center frequency was 3.7 GHz with 183 MHz bandwidth. The overall size of the array was 60 × 120 cm$^2$. The design presented in [6] consisted of 4 × 8 subarrays, each with 4 patches. The array covered 450 MHz around 2.6 GHz with maximum coupling between its ports of -19 dB. The gain for each subarray was measured to be 10 dB.

Some other works used dual-polarized antennas as in [7]-[10]. In [7], three layers of 6 sectors are stacked over one another with a rotation. Each sector consisted of 4 subarrays, each with 2 × 2 patches. The bandwidth was 160 MHz around 3.7 GHz, with measured gain of 10.5 dB for the subarray and 16.7 dB for each sector. In [8], a novel patch is proposed that covered 2.535-2.655 GHz. Six sectors were presented with 4 × 4 antenna elements in each sector. The isolation between different ports was 21 dB, and the gain for each subarray (1 × 4 patches) was between 11-12.4 dB. A cross dipole antenna element is used in [9] to get ±45° polarizations. 32 RF channels with 64 antenna elements are used along the whole array to cover a band from 3.6-4.8 GHz with a gain of 26.8 dBi. The design shown in [10] is done for Ka-band from 31.8-33.46 GHz with a coupling less than -15 dB. A dual-polarized patch was the base antenna element with 4 × 8 patches for a sector. mmWave based designs such as [11]-[13] targeted 28-38 GHz 5G bands.

Few works supported a MIMO configuration by using multi-modes at each element without an array mode (beamsteering). In [14], 108 elements were distributed along a 9-faced polyhedron ring that operated at 2.4 GHz. This was achieved using a modified patch to get 3 modes per element; the first (BW of 254 MHz) and second (BW of 238 MHz) modes are with a gain of 6.5 dBi and the third one (BW of 102 MHz) with 1.21 dBi gain. On the other hand, [15] modified a sheet to support 4 modes that covered wide band from 6-8.5 GHz along an 11 × 11 array. The port isolation was better than 20 dB with very low envelop correlation coefficient.

It is clearly seen that most of the previous works were not verified experimentally, used a single element or 1 × 4 subarray configurations for individual ports (except [7] that used uniformly fed 2 × 2, only had one operating mode (individual port MIMO or beam steering), did not cover more than 30° in elevation (except [10]) and all subarrays were with the same radiation pattern shape and direction thus using well known beam steering algorithms for uniform arrays.

In our recent work [16], we only showed the idea of directive ports in a 16-port configuration that had low efficiency, was not verified experimentally or had any beamsteering capability.

In this work, a dual operating mode mMIMO antenna system is presented. The first mode is an individual port MIMO mode with low correlation between different ports for high signal-to-noise-ratio (SNR) environment scenarios (each subarray is operating independently and has a beam directed away from its adjacent ones), the second mode is an array beam switching one for lower SNR scenarios that provides dedicated beams for users. The proposed 72 port (288 patch elements) mMIMO antenna system is suitable for potential 5G base stations. The mMIMO antenna system consists of three
panels/sides (triangular shape), each having 24 ports. Each port has a unique feeding network that provides a tilted beam with respect to its adjacent ports to have low envelope correlation coefficient (ECC) values when operated in individual (MIMO) mode scenarios (i.e., first mode). Each port consists of a subarray of 2×2 patch elements with a feed network providing proper phases for fixed beam tilts. The antenna system operates at 3.5 GHz with 100 MHz measured bandwidth. A beamsteering technique is presented and applied for array mode operation (i.e., second mode) on the non-identical (tilted with respect to one another) port patterns unlike all previous works that assume identical radiation patterns for all its elements. The algorithm is optimized via controlling the complex excitations of each port to provide switched beams for the 24-ports within a panel/side to combine the individual tilted patterns (of each port out of 24) in a unique way. The algorithm provides 19.5 dB gain at broadside, and provides switched beams covering ±34° in elevation (i.e., beam center locations), thus providing almost ±8° extra center beam coverage from both sides compared to most recent works.

The rest of the paper organized as follows. In Section II, the design of the antenna system is discussed in details. Section III discusses the measured and simulated results of the design. Section IV shows the details of the beamsteering algorithm and the results of applying it on the design. Finally, Section V concludes the work.

2 mMIMO Antenna System Design Details

2.1 Single Port Design

A single port consists of a subarray of 2×2 patches that is build on a 3 layer printed circuit board (PCB). The top layer is used for the linearly polarized patch antennas, which are fed using probe feeding via holes that come from the bottom layer. The ground is the middle layer which acts as the reference for both patch antennas and the feeding network. The substrates used are RO4350B with 3.5 dielectric constant, 0.762 mm thickness and 0.003 loss tangent (@ 2.5 GHz). Figure 1(a) shows the stackup of the board design. Fig. 1(b) shows the top layer of the single port subarray. It consists of 2×2 patch antennas designed at 3.5 GHz. They are excited with uniform amplitude and different phase excitations to tilt the beam towards a specific direction. The phase difference between the patches comes from the differences in path length of the microstrip lines that feed them as shown in Fig. 1(c). The dimensions used here were such that a beam tilt of the subarray pattern is achieved towards (θ=27°, φ=244°). The total size of a single port (subarray) is 74×74×1.524 mm³. The other three adjacent ports are made of just a rotation of phase excitations by changing the position of the phase in the feeding network to guarantee a pattern tilt towards an opposite direction to minimize field correlation. The feeding networks for all ports are shown in Fig. 3(c). The four basic configurations for adjacent ports are P1, P2, P5, P6. These 4-configurations with pre-defined tilts are repeated over the 24-port side. Port 1 had phases (0°, 62°, 74°, 133°) to tilt the beam towards (θ=29°, φ=295°), where port 2 had phases of (62°, 0°, 133°, 74°) to tilt the beam towards (θ=27°, φ=244°). Port 3 phases were (62°, 133°, 0°, 74°) giving a maximum gain at (θ=28°, φ=63°), while port 4 had phase excitations of (133°, 62°, 74°, 0°) tilting the beam towards (θ=29°, φ=116°). The maximum gain for all sub-arrays (ports) were around 8.5 dB. Fig. 2(a)-(d) show the simulated 3D radiation pattern for the four basic ports. The tilt of the beam by each port can be easily observed and is important for the MIMO operation showing uncorrelated beams as well as in the beamsteering method applied afterwards.

2.2 72 ports mMIMO antenna system

The triangular 72 port (288 element) mMIMO antenna system is shown in Fig. 3(a). The triangular shape was chosen due to high fabrication costs and limited project budget. Thus a hexagonal (144 ports with 576 antennas) array can be easily made if budget is not limited. Each side of the triangular array consists of six copies of the four basic subarrays. The front view of a single side consists of 6×4 ports shown in Fig. 3(b). The spacing between adjacent ports is 74 mm. The distribution is made in a way to create uncorrelated fields to achieve low ECC values between different ports. The total size of the board for a single side is 44.4×29.6×0.1524 cm³. Fig. 3(c) shows the bottom layer of a single side board. Mini-SMP (PE44489) based connectors are used at the 24 feeding points (ports).

3 Simulation and Measurements results

The designed array was simulated using CST studio suite and then it was fabricated and measured to check its performance. The fabrication was conducted at Printech PCB, UK. Port measurements were done using an Agilent Fieldfox N9928A VNA, while the radiation patterns were measured using a Satimo Starlab Anechoic chamber. A single array side/panel with 24-ports was tested at a time due to the size and weight limitations of the chamber used. The complex radiation pattern of each sub-array was measured individually while
Fig. 2: 3D realized gain pattern of the four basic ports shown in Fig. 3(c) which are tilted to (a) $\theta=29^\circ$, $\phi=295^\circ$, (b) $\theta=27^\circ$, $\phi=244^\circ$, (c) $\theta=28^\circ$, $\phi=63^\circ$, (d) $\theta=29^\circ$, $\phi=116^\circ$.

others were terminated. If the complete assembled system with 3-sides/72-ports is to be tested, a larger chamber can be used. It should be noted here that if over the air (OTA) testing is to be performed, then a different measurement setup should be used and the size of the array should be carefully considered [17], [18]. The fabricated prototype is shown in Fig. 4. Fig. 4(a) shows the bottom view of fabricated side, where Fig. 4(b) shows the top one. In Fig. 4(c), the triangular shaped prototype is shown.

Fig. 4(d) shows the S-parameters measurement setup of the fabricated board. The simulated and measured reflection coefficients at each port are shown in Figs. 5(a), (b) and (c). The isolation between port 6 ($P_6$) and its adjacent ones are shown in Fig. 5(d). The measured band supported by this array is 3.45-3.55 GHz, which gives 100 MHz bandwidth. A difference of 40 MHz in the covered band is observed between the simulated and measured results since a different SMP connector model with a slightly larger ground foot print was used in the simulation. This is believed to be the same reason also for observing some noticeable ripples in some of the ports due to the difficulty of having good GND connections for some of the connectors in addition to the limitations of hand soldering of such small parts. The maximum coupling between the ports is -14.9 dB in the band of interest. The measured total efficiency of a single port reaches 64% (since each port was measured individually).

Fig. 6(a) shows the pattern measurement setup inside the Satimo Chamber. Fig. 6(b) shows the 2D co-polarized simulated and measured radiation patterns of each port as a function of $\phi$ taken at the plane of maximum gain. Remember that the patterns are tilted with respect to one another. It shows a good agreement between simulations and measurements according to the tilt direction of each port.

To guarantee a MIMO mode operation, the radiation pattern for the ports should be orthogonal or semi-orthogonal to each other. The main parameter that measures the correlation between different ports is the ECC [19]. The ECC was evaluated between adjacent sub-arrays using the obtained complex electric field patterns and applying the formula,

$$\rho_e = \frac{\left| \int_{4\pi} |\vec{F}_1(\theta, \phi) \ast \vec{F}_2(\theta, \phi)| d\Omega \right|^2}{\int_{4\pi} |\vec{F}_1(\theta, \phi)|^2 d\Omega \int_{4\pi} |\vec{F}_2(\theta, \phi)|^2 d\Omega}$$  

where $\vec{F}_i(\theta, \phi)$ is the field radiation pattern of the antenna when port $i$ is excited and $\ast$ denotes the Hermitian product. Spatial correlation taking the channel effects on the other hand can be found from the channel matrix taking the antenna effects into account as show in [17], but performing OTA is beyond the scope of this work. The maximum ECC that is calculated using the measured 3D field patterns between the sixth subarray and the adjacent subarrays is equal
Fig. 5: Simulated and measured reflection coefficient at the corner ports (a) \{P1,P2,P5,P6\}. (b) \{P3,P4,P7,P8\}. (c) \{P17,P18,P21,P22\}. (d) Simulated and measured coupling between port 6 and the adjacent ones.

to 0.1198, which means that the ports can achieve good MIMO performance. The measured realized gain by each port is found to be between 6.78-9.41 dBi for different subarrays within the covered band as shown in Fig. 6(c). While the BW, gain and ECC are MIMO based parameters, the beamsteering capability of a mMIMO system requires the assessment of the directed beam HPBW and gain. These will be evaluated and highlighted in the following sections.

4 Beamsteering Method

The designed mMIMO system can be operated in two modes; array mode (switched beamsteering) as well a MIMO mode (simultaneous multi-single ports). The individual port operation mode can be used in good signal-to-noise-ratio (SNR) conditions, while array mode can be used in low SNR conditions or multi-beam configuration to provide higher gain and dedicated user beams. The challenge in the array mode is the fact that different ports have different radiation patterns, unlike all previous works, so, the simple pattern multiplication principle using the array factor cannot be applied here. Instead, the pattern of each port is multiplied by a factor of position and excitation as follows:

$$E_{\text{tot}} = \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn} E_{mn}(\theta, \phi)$$

where $A_{mn}$ is the excitation of the $mn$th port, and $E_{mn}$ is the pattern of that port. (2) gives an approximate result, since it does not include the coupling effect between the ports. Applying (2) on the proposed design can be done by taking into consideration that there

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Fig. 4: (a) Bottom view of the fabricated single side prototype. (b) Top view of the fabricated single side prototype. (c) triangular 72 ports mMIMO system prototype. (d) Measurement setup for port parameters.
are four basic patterns form the basic 4 directions that are repeated along the array (ports P₁, P₂, P₅ and P₆). So, (2) can be written as:

\[
E_{\text{tot}} = \sum_{m=1}^{2} \sum_{n=1}^{3} I_{(2m-1)(2n-1)} \exp \left \{ (4m-7) \frac{\pi}{2} + (4n-9) \frac{\pi}{2} + \beta_{(2m-1)(2n-1)} \right \} E_{1} \\
+ I_{(2m)(2n-1)} \exp \left \{ (4m-5) \frac{\pi}{2} + (4n-9) \frac{\pi}{2} + \beta_{(2m)(2n-1)} \right \} E_{2} \\
+ I_{(2m-1)(2n)} \exp \left \{ (4m-7) \frac{\pi}{2} + (4n-7) \frac{\pi}{2} + \beta_{(2m-1)(2n)} \right \} E_{3} \\
+ I_{(2m)(2n)} \exp \left \{ (4m-5) \frac{\pi}{2} + (4n-7) \frac{\pi}{2} + \beta_{(2m)(2n)} \right \} E_{4} 
\]  

(3)

where \( E₁, E₂, E₃ \) and \( E₄ \) are the four 3D basic patterns of ports \( P₁, P₂, P₅ \) and \( P₆ \), and \( \psi_x \) and \( \psi_y \) are:

\[
\psi_x = k d_x \sin(\theta) \cos(\phi) \\
\psi_y = k d_x \sin(\theta) \sin(\phi) 
\]  

(4)

where \( k \) is the wave number which equals to \( \frac{\pi}{\lambda} \), and \( \lambda \) is the wavelength at the resonance frequency. \( d_x \) and \( d_y \) are the spacings between subarrays along \( x \) and \( y \) directions, respectively. Fig. 7(a) represents the port patterns and their excitations in tabular form, where \( E₁, E₂, E₃ \) and \( E₄ \) represent the patterns of the basic four subarrays \( P₁, P₂, P₅ \) and \( P₆ \). \( I₁, I₂, I₃ \) and \( \beta₁ \) are the amplitude and phase excitations for the \( i \)th port \( P_i \), respectively. The line that contains \( \psi_x \) and \( \psi_y \) is the exponent in (3) without \( \beta \) excitation represents the position of each subarray with respect to the whole array.

Applying the beamsteering method on a single side (24 ports) of the proposed antenna with uniform excitations, i.e. unity amplitude and zero phase for all ports, results in Fig. 7(b) (the measured 3D pattern of each port is used in the algorithm and processed in MATLAB in all the presented contour plots). It shows a maximum at broadside direction (at \( \theta = 0° \)) with sidelobe level (SLL) equal to 9.22 dB. The high SLL comes from the large spacing between the ports, the SLL for each port individually and because of the beam tilts that were imposed on each single port. We applied the most well known SLL reduction techniques, but the SLL did not improve that much since the fixed beams formed at the individual ports were not affected. Since, the main beam has an elliptical coverage area as shown in Fig 7(b), its half power beamwidth (HPBW) at \( \theta =0° \) cut is different comparing it to the HPBW at \( \theta =90° \) cut. The non-uniform Dolf-Chebyshev (D-C) amplitude distribution was used to get a circular pattern (instead of elliptical) at the broadside direction as shown in Fig. 7(c) and (d). The values of the D-C excitations \([0.2, 0.618, 1, 1, 0.618, 0.2]\) are calculated for 6 element linear arrays (with SLL= -40dB condition to minimize their values the most) as outlined in Chapter 6 in [20] to achieve the beam pattern required after several optimization attempts (targeting low SLL) and repeated 4 times along the planar array.

To control the direction of the beam maximum and be able to steer it, amplitude excitation remains as is to keep the circular coverage with the specific SLL (and the constraint of non-identical patterns), and phase excitations should be changed accordingly. The phase control is determined by the well known formulas for planar arrays in [20]:

\[
\beta_x = -k d_x \sin(\theta_d) \cos(\phi_d) \\
\beta_y = -k d_x \sin(\theta_d) \sin(\phi_d) 
\]  

(5)

where \( \theta_d \) and \( \phi_d \) are the desired elevation and azimuth directions of the beam maximum. A switched beam is applied to cover 12 different areas (other than broadside) down to \( \theta = \pm34° \) with 14° HPBW along \( \theta \) direction. Fig. 8 shows some cases for steering the main beam. The HPBW of the beam gets narrower along \( \phi \) direction.
Fig. 7: (a) Symbolic port patterns with the excitation at each one. (b) Normalized 3D contour pattern of the array with uniform excitation. (c) D-C excitation table of the 24 ports. (d) Normalized 3D contour pattern of the array with D-C excitation.

Fig. 8: Three different cases for steering the beam towards (a) $\theta = 12$, $\phi = 268$, (b) $\theta = 14$, $\phi = 2$, (c) $\theta = 20$, $\phi = 226$. (d) Normalized 3D contour patterns of the array with D-C amplitude excitation and different phase excitations, all steered 12 cases combined (without broadside case).
by increasing the elevation tilt angle from 15° at broadside direction to 23° at θ=34° for the maximum case. On the other hand, the realized gain at the main beam decreases by increasing the tilt angle from 19.5 dB at broadside to 12.5 dB at the θ=34° tilt case.

Fig. 8(d) shows all the covered areas by the proposed array. The yellow spots show the covered areas in terms of HPBW. Table 1 show the differences between 10 cases of excitations to cover 12 steered switched beams in terms of Gain, HPBW and SLL. The SLL is decreasing by increasing of tilt angle (θ) from 9.22-5.91 dB. The realized gain also decreased by increasing the tilt angle from 19.5 dB to 12.5 dB.

The beams at the same elevation angle has different characteristics in terms of SLL and gain due to asymmetry of the array since it is a rectangular one not a square array. The triangular fabricated system faces another issue about the coverage of the whole 360° in elevation angle since each side can cover up to θ=42° so, the three sides design can cover 3×2×42° which equals to 252°. This means that there are blind area that cannot be covered when operating in switch beamsteering mode system. We can overcome this problem by utilizing a hexagonal shape base station antenna system.

Table 2 shows a detailed comparison between the proposed work and previous ones in terms of all performance metrics of bands covered, size, etc. It is clear that none of the previous works supported two modes of operation, utilized non-identical sub-array beams, provided a complete multi-sector fabricated array and provided good elevation angle scanning which are all features of the proposed design for 5G enabled base-station m-MIMO antenna systems.

### 5 Conclusion

In this work, a 72 port triangular based Massive MIMO antenna system is presented for future base stations. It is based on linearly polarized patch antennas. Two modes of operation are supported; individual mMIMO and beam switching. Each 2×2 patches (one port/subarray) is excited in a way to tilt their beam. The tilts at every port/subarray are made to achieve low correlation between them. 24 subarrays are placed on a single panel (side), that is one of three within the triangular base station antenna system. The three panels are fabricated and measured. The minimum measured bandwidth is 100 MHz. The maximum measured gain by a single subarray is 9.41 dB, with measured efficiency of 64%. The maximum ECC between the ports was 0.1192.

A switched beam method is introduced to operate the mMIMO system in beam switching array mode. The algorithm is used to cover specific spots in covered space and combines the non-identical individual patterns via specific feed excitations (unlike other methods that assume identical patterns from different ports). 13 beams (including broadside) are shown that cover from broadside down to 34° in elevation (center beam locations). The gain dropped down from 19.5 dB at broadside direction to 12.5 dB at the beam towards the last beam tilt angle. The HPBW along φ direction (azimuth plane) also decreased from 70° at the first beam tilt (towards θ=12°) to 23° at the last beam tilt angle (towards θ=34°). The SLL deviates between 5.91-9.22 dB for the various cases due to the non-identical element patterns.

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7 References