Millimetre-Wave MIMO Array of a Compact Grid Antenna for 5G Wireless Networks and Beyond

Syeda Fizzah Jilani[1,2], Qammer H. Abassi[3], and Akram Alomainy[2]
[1]Frontier Institute for Research in Sensor Technologies (FIRST), University of Maine, Orono 04469 ,USA
[2]School of Electronic Engineering and Computer Science, Queen Mary University of London, London, E1 4NS, UK
[3]James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK
{s.f.jilani, a.alomainy}@qmul.ac.uk

***Abstract*—This paper presents a 4-element multiple-input-multiple-output (MIMO) configuration of planar and compact two-dimensional (2D) grid antennas. The proposed grid is a 2D array of thirteen circular patches each with a radius of 0.175λo, having a single feed point. Measured results of the single-element microstrip-fed grid-array antenna show a 6 GHz bandwidth in the range of 27–33 GHz. The realized gain is above 9 dBi in almost the whole range with a peak gain of 11.57 dBi at 29 GHz. The numerically calculated antenna efficiency is above 80%. The transmission characteristics of the 4-element MIMO array are below -27 dB that indicates low mutual coupling and high isolation. These high-performance aspects of the proposed millimetre-wave (mm-wave) MIMO antenna array validate its potential for the 5th generation (5G) cellular devices especially in indoor base-stations.**

Keywords—5G, antennas, array, millimeter-wave, MIMO.

I. Introduction

The recent advancement in wireless networks towards 5G and beyond necessitate the utilisation of unused resources of bandwidth at mm-wave spectrum. Higher bandwidth ensures a high-speed communication while sparing enough room for the future upgrades [1, 2]. Current 5G wireless networks have initiated utilisation of the 28 GHz band to mitigate bandwidth scarcity issues [3, 4]. This spectrum transition towards mm-waves is anticipated to deliver numerous advantages such as; shorter wavelengths for smaller antenna form factor, channel-width enhancement, wideband spread-spectrum ability, as well as an accessibility to certain high-attenuation bands for a secure and short-distance point-to-point link [5, 6]. The 5G architecture is highly reliant on versatile antenna designs to deal with the critical challenges of the mm-waves spectrum. One major challenge is to overcome the high free-space path loss, which severely attenuates the signal strength through the blockages or long transmission distances [7]. In order to resolve this issue, an ultra-dense and short-range cell area is recommended where the advanced indoor base-stations with high-performance antennas will be used. Compact MIMO antenna arrays offer a smart choice to fulfil the high-gain demands required for mm-wave path loss compensation and enhanced bandwidth for high data rates. Additionally, a MIMO array comprising of multiple wideband antennas is suggested as essential for future communication networks, to ensure higher capacity, capability to mitigate multipath fading effects, improvement of the transmission quality, better coverage, and many other attractive features [8].

Antennas being the centralised unit of any wireless system have recently gathered huge attention and several novel design techniques have been established to accomplish exceptional performance. Conventional geometries of patch antennas though offer planar integration and ease of fabrication and installation, still suffer from limited gain and bandwidth. Bandwidth can be increased with structural alterations, such as addition of slots, fractals and monopole geometries, which are often associated with lower gain and efficiency [9]. On the other hand, antenna gain can be improved with a larger radiating area by using parasitic patches or arrays, which typically compromise on compactness due to a significant extend in the size and holds limited bandwidth [10]. The antenna elements of arrays are spaced apart to avoid mutual coupling and formation of grating lobes and are designed with a well-matched feeding network thus causing an additional increase in the overall area of a prototype.

Recent developments on antennas for 5G and beyond have addressed these challenges, efforts have been set forth to deal with these shortcomings and emphasized on simultaneously achieving high gain and wide bandwidth [11–13]. Several linear and 2D grid antenna arrays have been proposed for 5G applications with high gain and wider bandwidth while preserving the compactness [13–16]. This paper presents a versatile MIMO antenna array to combine the advantages of high gain, wide bandwidth, high diversity and compact structure. A planar and compact 2D grid of circular radiating patches is designed as a single antenna at 5G band of 28-GHz and utilised in a 4-element MIMO assembly.

II. MIMO Antenna Design and Analysis

A. Single Antenna Element

The grid geometry of the antenna is designed with thirteen circular patches each with a radius of $0.175\lambda_o$ (where wavelength, λ_o = speed of light (c)/resonant frequency (f_o), estimated at resonant/centre frequency (f_o) = 30 GHz). Rogers RT/Duroid 5880 ($\varepsilon_r = 2.2$, and $\tan\delta = 0.0009$) of 21.5 ($2.15\lambda_o$) × 23 ($2.3\lambda_o$) × 0.8 ($0.08\lambda_o$) mm^3 dimensions is used as a substrate material. The design contains a continuous bottom copper ground. The top surface of the substrate includes the designed grid along with a well-matched network of feedlines that connects the radiating patches, symmetrically organised in a planar 2D grid structure [16]. Microstrip feed line with a stub of optimised dimensions is designed for the impedance matching between the single feed point and the grid.

The simulation modelling of the proposed antenna as well as the computational analysis of the electromagnetic (EM) performance are performed in the CST STUDIO SUITE software. The 50-Ω matched K-connector is also designed as a part of the simulated antenna model to visualise the close approximation of the real-time measurement process. Fig. 1 shows the designed antenna grid array with the optimised dimensions obtained after careful a parametric analysis. The fabrication of the designed antenna array is carried out by using the in-house LPKF milling machine. Rogers RT/Duroid substrate with a copper cladding thickness of 17.5 μm on both sides of the substrate is used. The prototyping is done on one side of the substrate while the bottom metal cladding remained intact as a continuous ground plane.

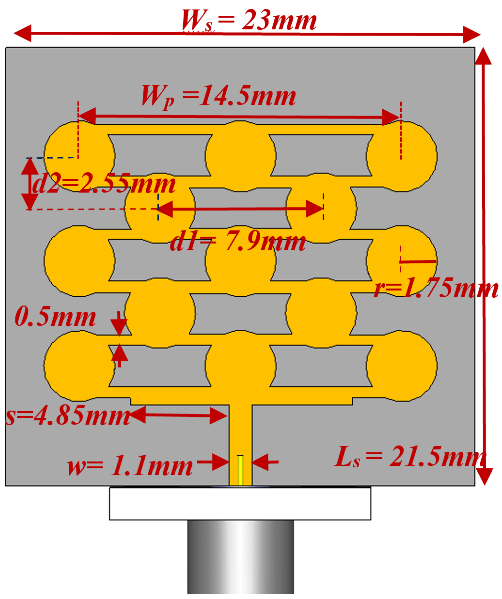


Fig. 1. Proposed compact grid antenna element (single radiator) with parametrically optimised dimensions.

B. 4-Element MIMO Array

The next step is to incorporate the antenna design into a four-element MIMO configuration for cellular base-station units, as well as in printed circuit board (PCB) layouts for wireless devices. The placement of all the four antennas has been carried out on a single substrate of 42 × 42 × 0.8 mm^3. The conventional array design requires that minimum spacing between the patches should be λ/2 or more (i.e. to minimise coupling effects). Here, as each grid antenna itself is an array of multiple circular patches, thus the minimum spacing criteria was justified with a 7.9 mm distance between the centres (*d1*) (as λ_o = 10mm at f_o = 30 GHz). In order to lower the mutual coupling between the individual grid antennas and increase the individual independence, an orthogonal arrangement is suggested where each antenna is placed orthogonally to the adjacent antenna. Four K-connectors for individual antennas are also included in the simulated MIMO design for accurate modelling. Fig. 2 shows the simulated model of the proposed 4-element MIMO antenna array.

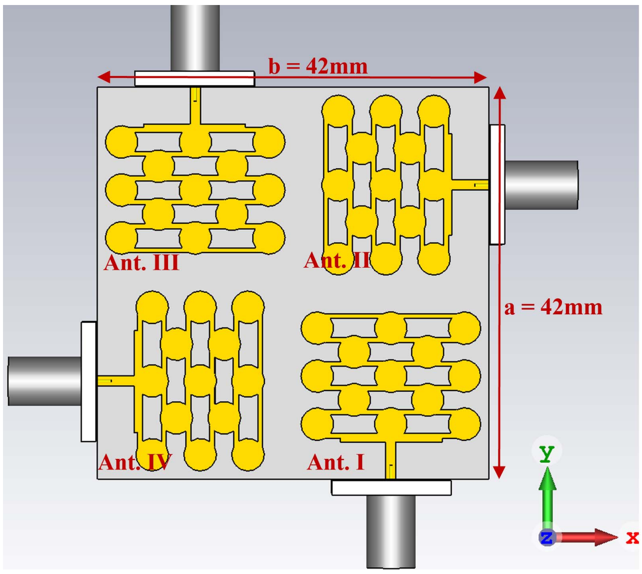


Fig. 2. Proposed compact grid 4-element MIMO antenna array with parametrically optimised dimensions.

III. Results and Discussion

The performance of the compact grid MIMO antenna array is fully analysed in the computational parametric analysis in CST software. The S-parameters, radiation patterns, surface current density and realised gain have been examined in order to evaluate the proposed antenna performance.

A. Single Antenna Element

The fabricated single element grid antenna prototype is shown in the inset figure of Fig. 3. Experimental tests of the fabricated prototype by using the Vector Network Analyser (VNA) and a near-field scanning setup validate the simulation outcomes. Fig. 3 shows the reflection coefficient (S_{11}) plots with simulated bandwidth of 27.5–33.3 GHz with -10 dB reference, while the measured results cover a range of 27–33 GHz. This refers to a good agreement between the two plots, though slight shift towards lower frequency is observed in the measured profile may be due to the fabrication intolerances or because of some insignificant measurement discrepancies from connector/cables losses.

The simulated and measured normalised radiation patterns of the proposed grid antenna at E and H-plane cuts are shown in Fig. 4. The E-plane plots show that the antenna radiation splits into two beams towards broadside and the side lobes are below -10 dB as in H-plane plots. Table I shows the realised gain of the proposed antenna at distinct frequencies of the operating range. The simulation results (referred as sim. in Table I) showed that a realised gain of above 9 dBi is observed in 27.5–33 GHz range, with a peak gain of 11.31 dBi at 29 GHz. Measurements (i.e. Mea. in Table I) of the fabricated antenna show close results with a peak gain of 11.57 dBi, though profile observes same shift towards lower frequency as in the S_{11} plot. The total antenna efficiency obtained from the CST computation is 80% or above in the entire bandwidth.

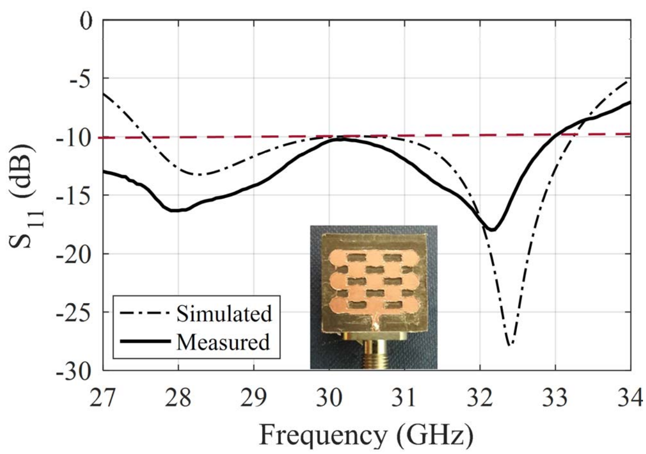


Fig. 3. Simulated and measured S_{11} profile of the proposed compact grid antenna with an inset figure of the fabricated prototype.

TABLE I. Realized Peak Gain of the Proposed Antenna

Gain (dBi)	Frequency (GHz)						
	27	*28*	*29*	*30*	*31*	*32*	*33*
Sim. Gain	7.8	11.18	11.31	10.86	10.91	11.03	10.9
Mea. Gain	8.9	11.02	11.57	11.55	11.12	9.45	6.16

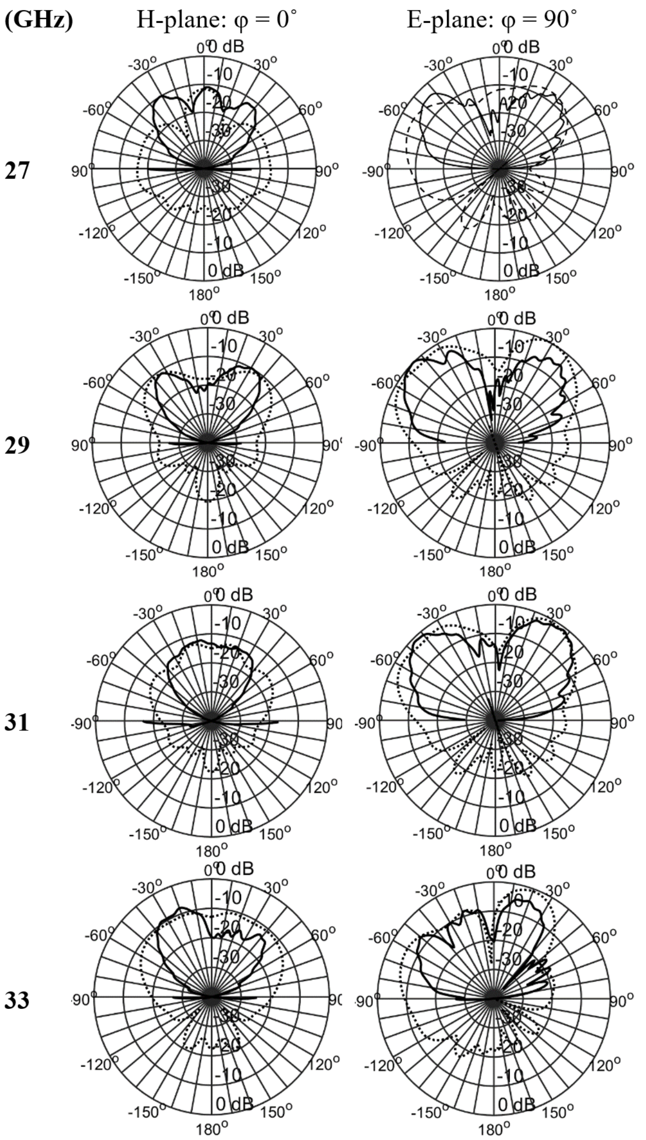
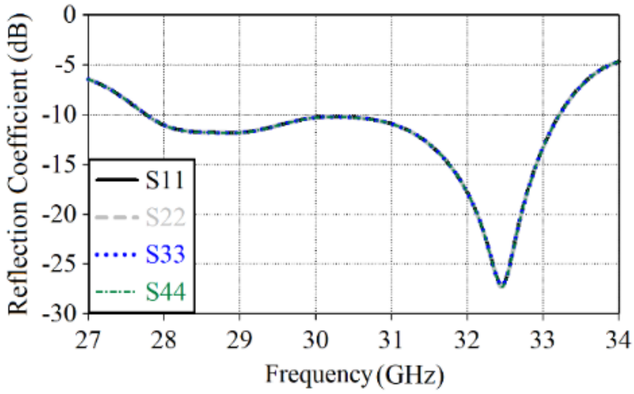


Fig. 4. Simulated and measured radiation pattern of the proposed compact grid antenna.

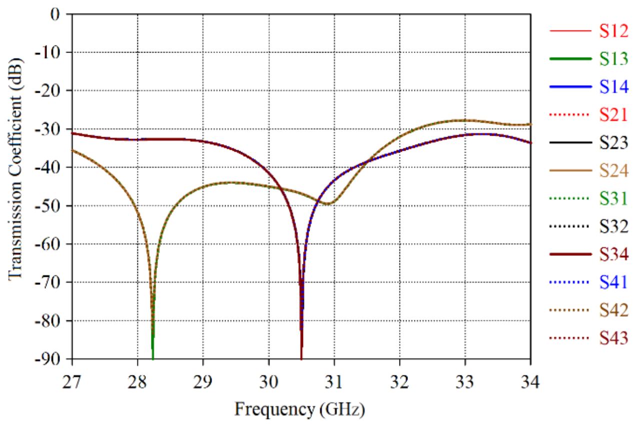
B. 4-Element MIMO Array

The simulated S-parameters plots of the designed MIMO antenna array are shown in Fig. 5 where all the four elements of the 2D MIMO array display same reflection coefficient response (in shown in Fig. 5(a)). It is essential to account for the mutual coupling between the individual antennas of the MIMO array to avoid interference from the neighbouring antennas. The simulated transmission characteristics of the MIMO antenna array in Fig. 5(b) shows low magnitudes below -27 dB in the complete operating bandwidth that implies to lower mutual coupling and high isolation between the adjacent antenna elements.

To obtain an insight of the effects associated with the excitation of one antenna on the neighbouring antennas the surface current density of the proposed MIMO antenna has been computed in the CST simulation. The surface current distribution plots examine how independent antennas are in their individual performance and extent of parasitic coupling with adjacent radiators. Fig. 6 shows the current density plot when only one antenna of the MIMO array is excited at a time. The plot shows lower parasitic coupling of the single antenna with the adjacent elements.

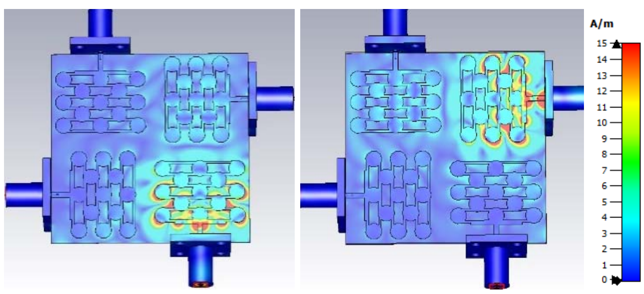


(a)

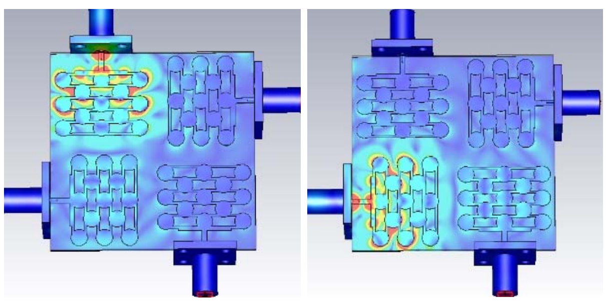


(b)

Fig. 5. Simulated S-parameters of the compact grid 4-element MIMO antenna array: (a) Reflection coefficient plots, (b) Transmission coefficient plots for the four antennas.



(a) (b)



(c) (d)

Fig. 6. Simulated surface current density profiles of the proposed compact grid 4-element MIMO antenna array: (a) Antenna I, (b) Antenna II, (c) Antenna III, (d) Antenna IV.

IV. CONCLUSION

This paper has presented a 4-element MIMO configuration of a compact microstrip-fed 2D grid array antennas as a potential solution for future wireless networks high gain and bandwidth demands are extremely critical. The designed geometry of a single grid antenna has thirteen circular patches each of the radius $0.175\lambda_o$, arranged in a 2D planar assembly of a grid. The MIMO configuration is comprised of a compact orthogonal integration of four grid-array elements into an area of 42×42 mm^2.The measured results of the fabricated single-element grid antenna show a bandwidth of 6 GHz in the range of 27–33 GHz. The measured gain profile shows above 9 dBi over almost the entire range with the peak gain of 11.75 dBi at 29 GHz. Numerically estimated efficiency of the antenna is above 80%. The 4-element MIMO shows lower mutual coupling with the transmission coefficients below -27 dB in the overall bandwidth. These high-performance attributes suggest the suitability of the designed MIMO antenna for the advanced 5G networks and beyond.

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