Compact 4G MIMO antenna integrated with a 5G array for current and future mobile handsets

Rifaqat Hussain¹, Ali T. Alreshaid¹, Symon K. Podilchak², Mohammad S. Sharawi¹

¹Electrical Engineering Department, King Fahd University for Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia
²Royal Military College of Canada (RMC) and with the Institute of Sensors, Signals and Systems (ISSS) within the School of Engineering and Physical Sciences (EPS) at Heriot-Watt University, Edinburgh, Scotland EH14 4AS, UK

Abstract: A novel integrated antenna solution for wireless handheld devices is proposed for the existing 4G standards and upcoming 5G systems for broadband, high data rate communications. The complete antenna system is a unique combination of a multiple-input–multiple-output (MIMO) antenna system at microwave frequencies and a millimetre (mm)-wave antenna array. The MIMO antenna system consists of two reactive loaded monopoles while the mm-wave array consists of a planar 2 by four slot antennas. The integrated antenna system covers the frequency bands from 1870 to 2530 MHz for 4G standards along with the upcoming 5G mm-wave band at 28 GHz. In addition, the integrated antenna system is planar and is designed for typical smart phone devices with a standard 60 mm by 100 mm by 0.965 mm back plane. Excellent field correlation values were obtained across the 4G band while realised peak gain values of 4 and 8 dBi were, respectively, measured for the MIMO and mm-wave antenna arrays. The proposed antenna design may also be useful for other compact implementations that support 4G and 5G communications.

1 Introduction

Exponential growth in data rate requirements triggered by new smart wireless devices brings significant changes in setting new wireless standards for communication systems. Long term evolution (LTE), broadband LTE services, and 4G commercial services are adopted in modern wireless standards to meet such high data requirements. After LTE commercialisation, industry and academic researchers started focusing on next generation broadband wireless and mobile communications for future 5G wireless networks. These systems gained popularity recently and wireless devices complying with such 5G standards should be able to operate with intensive data processing capability and high system throughput. This upcoming wireless standard requires large bandwidth (BW) and hence utilises the millimetre (mm)-wave spectrum for multi-Gbps throughput [1]. The prospective 4G/5G integrated communication environment is shown in Fig. 1 for current and future mobile devices.

One of the major technologies that can enhance data throughput in 4G networks is multiple-input–multiple-output (MIMO) systems. This requires the use of multiple antennas and these systems require MIMO characterisation, and as such, multiple antenna evaluations are equally important when compared with more conventional metrics such as input matching, operational frequency, and antenna gain [2, 3].

Several antenna designs complying with 4G standards were presented such as in [4–7] for wireless handheld devices. In [4] a wideband antenna was presented for the 4G LTE system. The frequency bands covered were 1.76 to 2.68 GHz, including PCS, UMTS/LTE, Bluetooth, ISM, and WLAN bands. The single element was circular in shape with a radius of 50 mm. Its large size made it difficult to accommodate more antenna elements in a MIMO configuration within small wireless handheld devices. An LTE mobile handset antenna was presented in [5] with single element dimensions of 15 mm by 40 mm. The two frequency bands covered by this design were 698 to 960 MHz and 1710 to 2690 MHz. In [6], a dual-band monopole antenna for WiFi and 4G LTE applications was presented. The dimensions of the given antenna were 41.6 mm by 28.38 mm by 1.52 mm. The two frequency bands covered were 2.3 to 3.0 GHz and 4.7 to 5.9 GHz. In [7], two different single element slot meander patches were presented complying with 4G LTE standards. The frequency bands covered were 1.68 to 3.88 GHz for the first antenna, while the second multi-band antenna covered three frequency bands 0.5 to 0.75 GHz, 1.1 to 2.7 GHz, and 3.3 to 3.9 GHz. The total dimensions of the antenna system was 100 mm by 35 mm by 1.635 mm. Moreover, the LTE 4G antennas presented in [4–7] were either complicated in structure or with large dimensions and thus integration into a compact MIMO configuration for small handheld devices and mobile terminals could be challenging. MIMO antenna elements for 4G standards were further presented in several references such as [5–13]. In [8], a two element PIFA antenna was presented for WLAN and LTE bands. The frequency bands covered were 2.1 to 2.9 GHz with single element dimensions of 10 mm 40 mm by 20 mm. A non-planar MIMO antenna was also presented in [9]. The design was a combination of a monocone and a microstrip antenna. The design was fabricated on a circular board with a radius equal to 126 mm and height 39.15 mm. The presented design offered connectivity between 750 and 2730 MHz covering several well-known frequency bands. A MIMO dielectric resonator antenna for LTE applications was also presented in [10]. Two orthogonal modes of the antenna were excited by using a coplanar waveguide and a coaxial probe feed mechanism. The two frequency bands achieved were 2.09 to 3.38 GHz and 2.40 to 3.09 GHz, respectively. The dimensions of board used were 70 mm by 70 mm by 11.60 mm. In [11–13], frequency reconfigurable antennas were also presented covering several well-known LTE bands. The given antenna designs were compact and suitable for MIMO operation in wireless handheld devices complying with 4G standards. The dimensions of the boards used were typically 65 mm by 120 mm.

To continue these efforts researchers started developing different antenna designs to be used in handheld devices after announcing the 28 GHz band was a candidate for the upcoming 5G standard for cellular networks [14, 15]. A complex mesh-grid antenna array with 16 radiating elements was proposed in [16]. The achieved BW by the system was almost 3 GHz with a gain of 10.9 dBi. Although the size of such a structure was small (placed at the edge of a phone), the mesh structure is considered a complex
multi-layered via based design, and this work did not show the feeding network for such a mesh array along with its accompanying losses or a prototype to compare against. In [17], a BW of 2.85 GHz was achieved using a patch antenna, which was mounted on a low temperature co-fired ceramic structure. In addition, good behaviour was noted in [18], where a tapered slot antenna array was fed by a surface integrated waveguide. The BW in that work was as high as 10 GHz with a gain of 14.5 dBi.

In this paper we propose a novel integrated antenna system that will be a viable solution for both 4G and the upcoming 5G standards. The antenna structure is a unique combination of a microwave MIMO antenna system along with a mm-wave slot antenna array for high gain when considering short range data links. The integrated structure could be utilised in 4G wireless networks covering several well-known frequency bands from 1870 to 2530 MHz along with the mm-wave frequency band at 28 GHz.

To the authors’ knowledge none of the reported designs found in the literature are able to provide such a novel integrated antenna system.

The design procedure for the single MIMO antenna element started with a simple microstrip monopole antenna operating at a higher frequency band than desired. The initial optimised design is shown in Fig. 3a-i which was resonating at 2.925 GHz. Microstrip line stubs (as shown in red colour in Fig. 3a-ii) were added to the optimised antenna structure (as shown in pink colour in Fig. 3a-ii), for miniaturisation and reactive loading to reduce the resonance frequency to the desired 4G band (see Fig. 3a-ii). HFSS™ was further used for the optimisation process. Parametric sweeps were also performed on various antenna parameters including the size of the gap between the two long radiating lengths. All three branches of the antenna were selected to increase the effective BW. Optimised dimensions of the final MIMO system are shown in Fig. 4a. The reflection coefficient curves for the antennas given in Figs. 3a-i and a-ii are shown in Fig. 3b as case A and case B, respectively.

The proposed antenna design was further studied by reducing the ground plane as shown in Figs. 3a-iii and a-iv, respectively. The reflection coefficient curve of the given modified monopole design

The rest of the paper is organised as follows. Sections 2 describes the antenna system design for both the MIMO antenna and the mm-wave antenna array. The simulation and measurement results are given in Section 3 while some conclusions are provided in Section 4.

2 Antenna system design

The proposed integrated microwave MIMO antenna system along with the mm-wave antenna array and its feed network are shown in Fig. 2a. The complete antenna system is a multi-layer design placed on a 60 mm by 100 mm by 0.965 mm backplane. Four layers are used in our planar design, and thus by proper placement of the recessed ground plane and orientation of the mm-wave antenna array, good MIMO operation is possible for the two 4G antennas. In particular, the ground plane layer acts as a clever co-planar reflector for the two MIMO antennas enabling beam tilting, and is sandwiched between the two dielectric layers (top that is holding the MIMO antennas and bottom holding the mm-wave feed network). This ground plane is also adhered to the top layer by a bonding material with a thickness of 0.05 mm and a relative dielectric constant ($\varepsilon_r$) of 2.94. Further design details of the two antenna systems are given in the following sections. The fabricated model of the proposed design is reported in Fig. 2b. Fig. 2b-i shows the top view of the two-element MIMO antenna system. Fig. 2b-ii shows the bottom layer of the fabricated antenna system containing the feed network for the slot antenna array.

2.1 Operation of the MIMO antennas

The design procedure for the single MIMO antenna element started with a simple microstrip monopole antenna operating at a higher frequency band than desired. The initial optimised design is shown in Fig. 3a-i which was resonating at 2.925 GHz. Microstrip line stubs (as shown in red colour in Fig. 3a-ii) were added to the optimised antenna structure (as shown in pink colour in Fig. 3a-ii), for miniaturisation and reactive loading to reduce the resonance frequency to the desired 4G band (see Fig. 3a-ii). HFSS™ was further used for the optimisation process. Parametric sweeps were also performed on various antenna parameters including the size of the gap between the two long radiating lengths. All three branches of the antenna were selected to increase the effective BW. Optimised dimensions of the final MIMO system are shown in Fig. 4a. The reflection coefficient curves for the antennas given in Figs. 3a-i and a-ii are shown in Fig. 3b as case A and case B, respectively.

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Fig. 1 Microwave and mm-wave wireless communication scenario for current and future mobile devices
is also shown in Fig. 3b as case C. The given antenna demonstrated a minimum in its reflection coefficient at 2.66 GHz and generated an omni-directional radiation pattern similar to a monopole as can be observed in Fig. 3c. Thus the proposed MIMO antennas are essentially a planar and compact monopole-like ones, with additional ground plane reflector sections complimented by the mm-wave antenna array, to enhance MIMO performance (the reflector is shown in the final configuration, see Fig. 4b).

2.2 Integrated 4G MIMO antenna

The proposed MIMO antenna system consists of a modified monopole design as shown in Fig. 4. The two elements were separated by a distance of 42 mm to be placed at the two top corners of the mobile device with single element dimensions of 7.9 mm by 25.4 mm. The MIMO elements were mounted on the top layer of the board as shown in Fig. 4a while the ground plane of the designed system is shown in Fig. 4b. The MIMO antennas were simulated and fabricated on a Rogers RO3003 board with $\varepsilon_r = 3 \tan\delta = 0.0013$, and a thickness of 0.76 mm.

2.3 mm-wave 5G antenna array

Due to the high path loss at the 28 GHz mm-wave band, antenna arrays can be used to provide improved gain. Aiming at handheld devices, which mainly limit the size of the design due to the available real estate, a $2 \times 4$ antenna array was adopted in this work. Due to the structural advantages of the slot antenna, it is chosen to be the radiating element of the mm-wave antenna array. A half wavelength slot antenna is fed by a microstrip line of width 0.18 mm, which corresponds to 50-Ω via slot coupling. The feeding point was calculated and found to be 0.05 λ from one of the slot short edges. The material used for the substrate is also RO3003 with a thickness of 0.13 mm.

The design procedure of mm-wave antenna array was started with a corporate feed combiner/splitter design. The $2 \times 4$ antenna array is fed by four parallel microstrip lines separated by 7.5 mm, where each line is feeding two elements in series. The line widths of feed network were selected as 0.35 and 0.18 mm corresponding to 70.7 and 50 Ω, respectively. The lengths of the feeding arms from the splitter to the array as well as the small extension beyond the second slot were optimised for proper impedance matching. The delivered power at the each output port of the feed network without the array were approximately −6 dB as expected with same phase as shown in Figs. 6a and b. The second stage of mm-wave array was the design of slot antenna elements with a
microstrip line feed coupling. The slot antenna was designed at 28 GHz corresponding to a wavelength of 7 mm on the RO3003 substrate used with 0.13 mm thickness. The antenna was optimised with almost half-wavelength resonance with final dimension of 3.75 mm by 0.75 mm. The feeding location was placed closer to the edge to provide matching to 50 \( \Omega \).

The orientation of the 4G, two-element MIMO antenna system with respect to the mm-wave slot antenna array is shown in

![Simulated and measured reflection coefficient and isolation curves of the two-element MIMO antenna system](image)

Fig. 5 Simulated and measured reflection coefficient and isolation curves of the two-element MIMO antenna system

a) Reflection coefficients for the MIMO antenna system at its two ports
b) Isolation curves between the two MIMO antennas

dimension of 3.75 mm by 0.75 mm. The feeding location was placed closer to the edge to provide matching to 50 \( \Omega \).

The orientation of the 4G, two-element MIMO antenna system with respect to the mm-wave slot antenna array is shown in

![Simulated and measured curves of the mm-wave array](image)

Fig. 6 Simulated and measured curves of the mm-wave array

a) Amplitude of transmission coefficients of the feednetwork
b) Phases of transmission coefficients of the feednetwork
c) Reflection coefficient versus frequency for the 5G mm-wave antenna array
A mini-smp connector (PE44489) was connected to the single feed of the mm-wave array. The 0.13 mm-RO3003 substrate has the system ground plane on one end and the mm-wave array feed network on the other. Its ground side is glued to the top thick substrate holding the MIMO antenna system via a 0.05 mm prepreg, covering the slot antenna array as shown in Fig. 4. Fig. 4 shows the combination of two layers containing the slot antenna array and its feed network for better visualisation. Although the mm-wave array is being fed with a corporate feed for broadside radiation, a switched beam feature can be added by utilising a Butler matrix feed network. Such a network will occupy more space though for the added beam switching capability.

3 Simulation and measurement results

The complete integrated antenna system was modelled and simulated using HFSS<sup>TM</sup>. The optimised design was fabricated using state-of-the-art fabrication processes at Printech Labs, UK. The scattering parameters of the fabricated design were measured using an Agilent PNA-N5227A at King Fahd University for Petroleum and Minerals (KFUPM), Saudi Arabia. The gain patterns and efficiencies were measured at the Royal Military College (RMC), Canada and Microwave Vision Group, Italy, using a far field mm-wave setup and a SATIMO Starlab anechoic chamber, respectively. All measured and simulated results of the integrated MIMO antennas and mm-wave slot antenna arrays are summarised in the following subsections.

3.1 4G MIMO antenna scattering parameters

The simulated and measured reflection coefficients of the two-element MIMO antenna system are shown in Fig. 5 while the isolation curves are shown in Fig. 5. Reflection coefficient measurements were made on two port for MIMO antennas while the third port was terminated with 50 Ω load. The wide-band MIMO antenna is resonating at a centre frequency of 2160 MHz...
with a $-6$ dB impedance BW of 660 MHz. It can be observed that the MIMO antenna system covers frequency bands ranging from 1870 to 2530 MHz. The measured isolation was more than 15 dB between the MIMO antennas and more than 25 dB between the MIMO antennas and the mm-wave array across the entire band of 4G/5G operation. Moreover, the measurements and simulations are in agreement. A slight difference in the simulated and measured results were observed because of the substrate properties, connector modelling and fabrication tolerances that are unavoidable. However, such differences are minor and do not affect the behaviour of the MIMO antenna system [8, 10].

Antenna radiation efficiency and resonances are affected in the presence of a user hand and head especially in small antennas used in mobile handsets [3]. In [19], the head and hand influence were investigated in mobile handset antennas and suggested solutions to characterise it were provided. In practical designs, the placement of the radome will minimise such detuning.

### 3.2 mm-wave antenna array scattering parameters

An important part of the mm-wave antenna array was the feeding network. The feeding network was optimised to deliver maximum power at the output with minimum losses. Ideally, each output port should receive $-6$ dB power as each of the two power dividers halves the delivered power. The feeding network was simulated without the array in HFSS™ to characterise its response. The amplitude and phase of the transmitted signals are shown in Figs. 6a and b, respectively. It shows the power received from input port-1 and their phases at each of the output port-k ($k = 2$ to 5) in the frequency range from 27 to 28.5 GHz. The output power at each of the four output ports was $-6.369$, $-6.279$, $-6.008$ and $-6.261$ dB with same phase at 28 GHz.

Fig. 6c shows the simulated and measured reflection coefficients of the mm-wave array. The frequency bands covered ($-10$ dB reference level) were 26.8 to 28.4 GHz in simulation and 26.0 to 28.4 GHz in measurements. The simulation results were obtained without taking the effect of the mini-smp connector, soldering or fabrication tolerances. This can explain the slight difference between the measured and simulated curves. The measured $S_{11}$ at 28 GHz covered the whole band of the simulated results showing good agreement. Such behaviour is very common at very high frequency bands and has appeared in such mm-wave based antennas such as that in [20–22].

### 3.3 4G MIMO antenna current distribution

The MIMO antenna elements were further analysed by studying the excited surface current densities using HFSS™. The goal of these simulations was to identify the resonant antenna parts and illustrate the amount of coupling between these elements. The analysis is shown at 2250 and 2450 MHz in Fig. 7. It shows the current density on the top surface antenna elements as well as the ground plane layer. Figs. 7a and b show the current density when the rectangular path of current was activated at 2250 MHz while Figs. 7c and d show the shorter straight line current path activated at 2450 MHz. As observed in these figures, a high current density
was generated along the top side of the antenna elements while there was also some currents on the ground plane near each antenna element with reduced amplitude. This suggests that the ground plane is contributing to the radiation. Moreover, it is also noted that there is slight coupling between the two antenna elements.

### 3.4 mm-wave antenna array current distribution

The current distribution for the mm-wave array is shown in Fig. 8a. The important thing to note is that the current between the two slots is in phase and thus the patterns will add up in the far field, in addition, the magnitude difference between them was not exceeding 0.5 dB (the calculation was based on a microstrip line model ignoring the slot loading for a 1 λ inter-element spacing).

### 3.5 4G MIMO antenna gain patterns

The gain pattern measurement for the MIMO antenna system were carried out at the Microwave Vision Lab, Italy, using a SATIMO Starlab anechoic chamber. The measurement setup is shown in Fig. 8b.

The three-dimensional (3D) radiation patterns of the proposed MIMO antenna system were computed using HFSS™. The gain pattern for a single element was obtained when that element was excited while terminating the second element with a 50-Ω load. The simulated 3D gain patterns were studied at three different frequencies which were 2.0, 2.25 and 2.35 GHz; corresponding peak gain values were 4.13, 4.32 and 4.39 dBi, respectively. The gain patterns for the two-element MIMO antenna are shown in Figs. 9a and b. The maxima of each element is tilted with respect to the other suggesting low field correlation which is desirable for MIMO operation.

The 2D simulated and measured gain patterns for the MIMO antenna system are presented in Figs. 9c and d at 2250 MHz. Figs. 9e and d show the simulated and measured gain patterns for both antenna elements for their co-pol xz-plane and yz-plane, respectively. The pattern beam tilts are clear in Fig. 9d. For example, beam maximum are observed at ±90° for Antenna-1 and Antenna-2, respectively. In all measurements, one port was under investigation while the other was terminated with 50 Ω load.

### 3.6 mm-wave antenna array gain patterns

The simulated realised gain of the mm-wave antenna array reached 9 dB at 28 GHz. The mm-wave array gain patterns were measured at The RMC of Canada. The measurement setup is shown in Fig. 8c and patterns are reported in Figs. 10a and b. Measured peak gain values were 8.2 dBi and results are in agreement with the simulations.

The difference between the measured and simulated curves in Figs. 10a and b is due to the measurement setup and its limitation. The pattern beam tilts are clear in Fig. 9d. For example, beam maximum are observed at ±90° for Antenna-1 and Antenna-2, respectively. In all measurements, one port was under investigation while the other was terminated with 50 Ω load.
metallic cover or another PCB with a GND plane for the LCD or something will block and reflect back most of this back radiation.

3.7 MIMO antenna characterisation

MIMO antenna characterisation is an essential part to qualify its operation. In this section, the proposed MIMO antenna system is characterised for its maximum gain, efficiency, correlation coefficient and the total active reflection coefficient (TARC).

For the given MIMO antenna system, the maximum gain and efficiency were also measured. The measurements were performed over a frequency band between 1.6 and 3 GHz as shown in Fig. 10c. The antenna performed very well in the desired frequency bands between 1.8 and 2.5 GHz. The efficiency of the antenna is more than 75% while the maximum gain is more than 3 dBi between 2.2 and 2.4 GHz.

The correlation coefficient (\( \rho \)) is an important parameter for MIMO antenna characterisation. It is a measure of isolation among various MIMO channels. The calculation of \( \rho \), based on the radiation patterns, shows the effect of various antenna elements operating simultaneously. For good MIMO operation, \( \rho \) should be less than 0.3. This value is the square root of the envelop correlation coefficient (\( \rho_e \)) which can be calculated in a uniform multipath environment using [3]

\[
\rho_e = \frac{\left| \int_{4\pi} F_i(\theta, \phi) \times F_i(\theta, \phi) d\Omega \right|^2}{\int_{4\pi} |F_i(\theta, \phi)|^2 d\Omega \int_{4\pi} |F_i(\theta, \phi)|^2 d\Omega} \tag{1}
\]

where \( F_i(\theta, \phi) \) is the field radiation pattern of the antenna when port \( i \) is excited and * denotes the Hermitian product. For the given MIMO antenna system, \( \rho_e \) was calculated at three distinct frequencies, 2.0, 2.25 and 2.35 GHz, and the corresponding values were 0.1343, 0.1815, and 0.0058, respectively. It is clear that the given MIMO antenna system satisfies the requirement for good MIMO operation.

TARC is another metric for MIMO antenna systems and is defined as the ratio of the square root of the total reflected power divided by the square root of the total incident power in a multiport antenna system [3] and is given by

\[
\Gamma' = \frac{\sqrt{\sum_{i=1}^{N} |b_i|^2}}{\sqrt{\sum_{i=1}^{N} |a_i|^2}} \tag{2}
\]

where \( a_i \) and \( b_i \) are the incident signals and reflected signals, respectively.
TARC curves for the proposed MIMO antenna system are reported in Fig. 10d. The analysis was carried out by keeping the excitation of one port at $10^{-9}$ while the phase of the second port was changed using different phase excitations. The TARC curves in Fig. 10d are shown for excitation phases of $0^\circ$, $30^\circ$, $60^\circ$ and $90^\circ$. TARC curves also identify the effective operating BW of the MIMO antenna system. It is clear that the operating BW of the MIMO antenna system will not be affected by a phase change in the excitation of the other port.

4 Conclusions

A novel integrated antenna system was presented complying with existing 4G wireless standards and upcoming 5G communication systems for broadband operation. The integrated solution consists of a microwave MIMO antenna embedded with a mm-wave slot antenna array with its feed network on the same multi-layer board. The compact microwave MIMO antenna covered a wide frequency band between 1870 and 2530 MHz while the mm-wave antenna array was designed to operate at 28 GHz with a minimum BW of 1.7 GHz. The antenna system was also characterised for MIMO parameters and offers suitable values in the desired band of operation. The maximum measured gain and the efficiency for the MIMO antenna system were 3.86 dBi and 83%, respectively.

The proposed system is well integrated and suited for existing 4G and upcoming 5G technology in wireless handheld devices and mobile terminals. The simple structure for the planar antenna elements also allow for practical integration with other electronic circuitry.

5 Acknowledgments

This work was supported by project number RG1423 through the Deanship of Scientific Research (DSR) at KFUPM, Dhahran, Saudi Arabia.

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