4G/5G Multiple Antennas for Future Multi-Mode Smartphone Applications

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ABSTRACT A hybrid antenna is proposed for future 4G/5G multiple input multiple output (MIMO) applications. The proposed antenna is composed of two antenna modules, namely, 4G antenna module and 5G antenna module. The 4G antenna module is a two-antenna array capable of covering the GSM850/900/1800/1900, UMTS2100, and LTE2300/2500 operating bands, while the 5G antenna module is an eight-antenna array operating in the 3.5-GHz band capable of covering the *C*-band (3400–3600 MHz), which could meet the demand of future 5G application. Compared with ideal uncorrelated antennas in an 8×8 MIMO system, the 5G antenna module has shown good ergodic channel capacity of $\sim$40 b/s/Hz, which is only 6 b/s/Hz lower than ideal case. This multi-mode hybrid antenna is fabricated, and typically, experimental results such as S-parameter, antenna efficiency, radiation pattern, and envelope correlation coefficient are presented.

INDEX TERMS MIMO, multi-antenna, multi-mode, channel capacity, 5G application.

I. INTRODUCTION

With the rapid development of radio access technologies, wireless communication network environment has become a mixture of different kinds of heterogeneous networks. As a result, the development and exploitation of multi-mode mobile terminals has aroused worldwide interest in the wireless communication field [1]. Thus, multi-mode and multi-band smart phone antenna is a prerequisite requirement for present and future terminal devices, especially those with MIMO (multiple–input–multiple–output) system included. Due to the limited volume size of mobile terminal devices (such as mobile handset), strong mutual coupling among antenna elements is inevitable, which results in affecting the antenna efficiency and also influences the correlation. Therefore, it is vital to apply decoupling technique between antenna elements for MIMO system.

A number of techniques have been reported to mitigate strong mutual coupling between two antenna array elements for MIMO system [2]–[8]. Amid these techniques, besides loading a slit into the ground [2], other conventional methods such as protruding a single or dual ground branch have also been proposed to acquire low mutual coupling [3]–[5]. Recently, novel neutralization technique has also been reported, in which a neutralization line (NL) is linked between the feeding strips or the shorting strips of antenna elements [6]–[8]. By doing so, reverse coupling can be excited to reduce the mutual coupling between antenna elements that are within very close proximity. Thus, in this paper, a previously reported antenna design [9] for 4G applications (4G antenna module) is initially reinvestigated and slightly modified. Here, a combination of protruded ground and NL techniques are applied into this antenna, so that enhanced isolation can be achieved for this 4G antenna module.

Because of the demand for faster data transmission well beyond the 4G standard, some countries and regions have already defined their very own fifth generation (5G) wireless standards that will be 100 times faster than the fastest 4G LTE standard currently available [10]. In November 2015, one of the key outcomes of WRC-15 (World Radio Communication Conference 2015) is the allocation of 3.5-GHz C band (3400–3600 MHz) as future broadband mobile services [11]. Therefore, besides considering the possibility of

implementing beamforming techniques which are envisaged as enablers for 5G mobile systems, mobile terminal device with massive MIMO antenna array operating in this C band is presently also a good candidate for future 5G operation.

To the best of author's knowledge, most internal mobile phone with dual element MIMO antenna array designs usually cover the LTE/WWAN operation [9], [12], which only takes into the consideration of 4G frequency bands. On the other hand, the work reported in [13] has proposed a hybrid dual-antenna formed by an inverted-F antenna and an open-slot antenna that only focus on 3.6-GHz band (3.4–3.8 GHz) operation [13]. To satisfy future 5G applications, MIMO antennas for 5G applications have been discussed in [14] and [15]. For smartphone applications, the recent works reported in [16]–[18] have proposed 8-element 10-element and 16-element antenna arrays, respectively, for massive MIMO operation in the 3400–3600 MHz frequency band, however, they have failed to satisfy either multi-mode or multi-antenna design need for 4G frequency bands. Notably, other investigations have also been performed for 4G systems in the 3.4–3.6 GHz frequency band, although they are initially studied for WiMAX system [19], [20].

In this paper, a hybrid antenna composed of two modules (4G antenna module and 5G antenna module) is proposed, the novelty of this paper is the use of 8×8 MIMO array instead of a single antenna. The 4G antenna module is a two-antenna array (2×2 MIMO configuration) that can cover the GSM850/900/1800/1900, UMTS2100, and LTE2300/2500 operating bands. As for the 5G antenna module, it consists of eight identical antenna elements (8×8 MIMO configuration) operating in the 3.5-GHz band (3.4–3.6 GHz) for future 5G communication. Typical results such as S-parameters and radiation performances of this proposed antenna are presented in this study, and as predicted, the 5G antenna module can significantly improve the ergodic channel capacity as compared with a SISO (single input single output) type.

II. PROPOSED ANTENNA DESIGN

Fig. 1(a) shows the complete geometry of proposed multi-antenna module. As illustrated in Fig. 1(a), a 0.8-mm thick FR4 substrate that has a relative permittivity of 4.4 and a loss tangent of 0.024 is used as the system circuit board. The whole system circuit board has a dimension of 140 mm × 70 mm, in which a 130 mm × 70 mm ground plane is printed onto it to serve as the system ground plane. Here, a 9.5 mm × 12 mm protruded ground plane is connected to the system ground for decoupling and impedance matching [9]. The two 4G antennas (Ant1 and Ant2) are placed at the bottom edge of the system ground plane, separated by a protruded ground, while the eight 5G antennas are printed along two long side edges.

A. 4G ANTENNA MODULE

The 4G antenna module design proposed here is an extended version of the antenna array reported in [9] that can cover WWAN/LTE operation bands. It is composed of
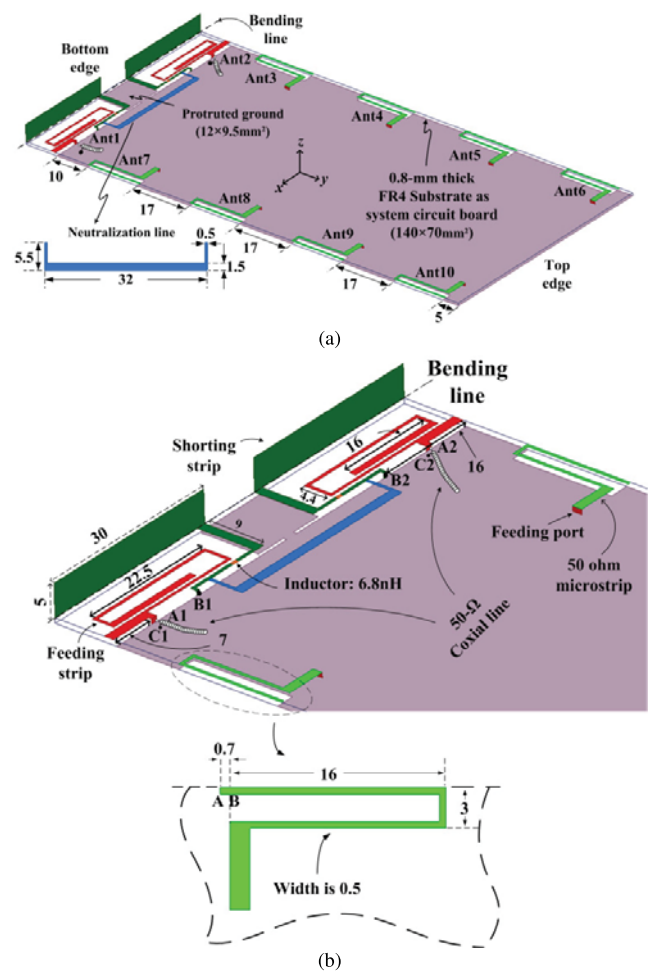

FIGURE 1. (a) Configuration of proposed antenna, (b) Structure of 4G and 5G antenna modules.

two 4G antennas, and its detailed structure and optimized dimensions are given in Fig. 1(b). Each 4G antenna is comprised of a feeding strip fed by a 50 Ω mini coaxial feeding line (with point A1 and A2 serving as the feeding point) and a bended shorting strip embedded with a 6.8 nH chip inductor (with point B1 and B2 serving as shorting point). As discussed earlier, the protruded ground plane is to provide decoupling effects in the upper bands and improving the impedance matching in the lower bands, however, it will also lead to deterioration of isolation in the lower bands. Thus, a neutralization line (NL) is loaded between the two 4G antenna elements, so that the decoupling effects in the lower bands can be improved. Notably, the results of this 4G antenna module are similar to the one reported in [9]. The feeding strip and shorting strip can excite a fundamental resonant mode at 950 MHz and 850 MHz, respectively, forming a combined dual resonance that can cover the lower bands for GSM850/900 operations. In addition, the shorting strip can also generate a higher-order resonance at 1800 MHz, which combined with the resonance at about 2600 MHz (introduced by the protruded ground) can cover the GSM1800/1900/UMTS operations.
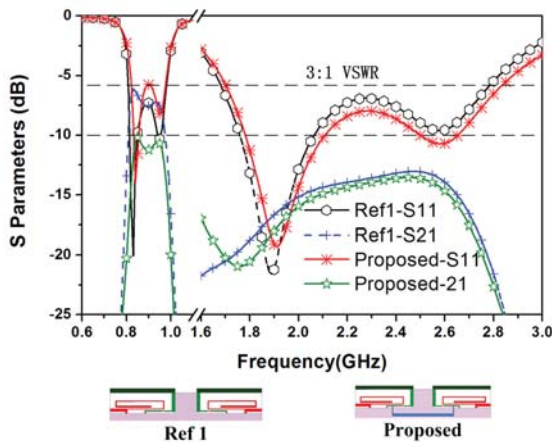
FIGURE 2. Simulated S-parameters of Ref1 and proposed 4G antenna module.

As previously mentioned, the NL loaded between the two 4G antenna elements is for increasing the isolation in the lower bands. To analyze the function of this NL, Fig. 2 shows the simulated S-parameters of the proposed 4G antenna array, and a reference antenna 1 (Ref1) that is the proposed one without the NL. By loading the NL into Ref1, the proposed one has shown an enhancement in isolation (S21) of at least 3 dB in the lower bands, especially at 900 MHz, in which the S21 is improved from −7.5 dB to −11.25 dB. Therefore, the proposed 4G antenna module can successfully cover the GSM850/900/1800/1900/ UMTS/LTE2300/2500 bands with desirable isolation.
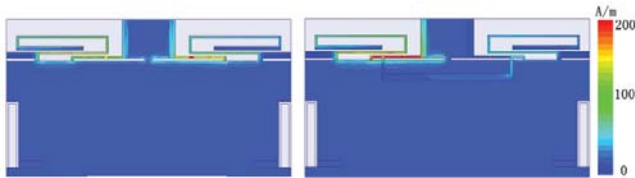

FIGURE 3. Simulated surface current distributions of Ref1 (left) and proposed 4G antenna module (right) at 950MHz.

To further validate the results of Fig. 2, Fig. 3 shows the current distributions of Ref1 and proposed 4G antenna array at 950 MHz. In both cases, their respective Ant1 is excited and Ant2 is terminated to 50Ω load. Compared with Ref1, the surface current distribution along Ant2 of proposed one is visibly reduced (lower mutual coupling). This is because the NL has modified the current distributions on the system ground plane of Ant2, with intense current on the NL that leads to corresponding strong phase-reversal coupling, which could offset the original mutual coupling [21].

B. 5G ANTENNA MODULE

Figure 1 shows the configuration of the proposed 5G antenna module, and its detail dimensions are also presented. The proposed 5G antenna module is formed by eight identical antennas (Ant3 to Ant10) printed along the two long side

edges of the system circuit board. Eight rectangular clearance regions of 16 mm × 3 mm are also reserved for accommodating the proposed 5G antennas. The adjacent two antennas located on the same side edge has a spacing of 17 mm, and all the 5G antennas are arranged to have their open-end pointing toward the same direction (positive *y*-axis). Here, Ant3 and Ant7 are 10 mm away from the 4G antenna module, while Ant6 and Ant10 are 5mm away from the top ground edge. Each antenna element of the proposed 5G array is a bending monopole strip printed along the perimeter (about 35 mm in total length and 0.5 mm in width) of the clearance region located below it. All 5G antennas are excited through a 50Ω SMA connector. As depicted in Fig. 1(b), a protruded tuning stub (AB) of only 0.7 mm is extended from the open end of the 5G monopole strip. Besides the ability to enhance the capacitive coupling between the tuning stub and the ground plane, simply extending the length of this tuning stub can shift the excited monopole resonant mode to the lower frequency band. Here, the dimension of this 5G monopole is specifically designed for covering the 3.5 GHz band (3400–3600 MHz) [11].
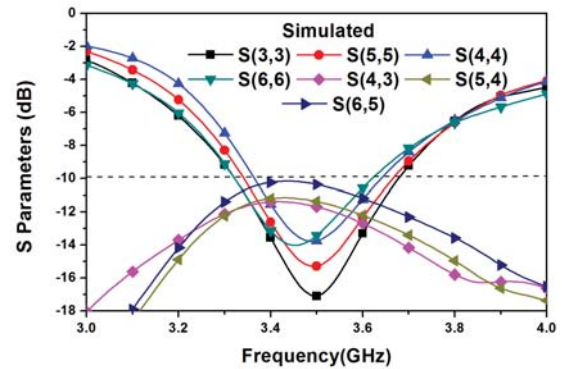

FIGURE 4. Simulated S-parameters of 5G antennas.

Figure 4 shows the simulated reflection coefficients of Ant3–Ant6, and their corresponding isolations (S43, S54 and S65). All 5G antenna elements located on the right side edge have shown good impedance matching of less than 10 dB between 3400–3600 MHz. Due to enough distance among each elements, good isolation of less than 10 dB are also exhibited between any two antennas. For brevity, those on the left side edge (Ant7–Ant10) will not be presented. It is noteworthy that Ant6 has a shorter distance of 5 mm to the top ground edge, as compared with that of Ant3, Ant4, Ant5 that have longer distances to the top ground edge. From Ant3 to Ant6, the distance from the open-end of these monopoles to the top ground edge decrease gradually, which leads to a gradual degradation in the impedance matching from Ant3 to Ant6. It is also observed that the degradation of the impedance matching makes the antenna efficiency decrease gradually (Ant3–Ant6) in the 3.5 GHz band, which can be seen in Fig. 5. Here, the antenna efficiency for Ant1 is approximately 65%–70%, while that of Ant4, Ant5, Ant6 are approximately 56%–63%. As a result, the efficiencies of
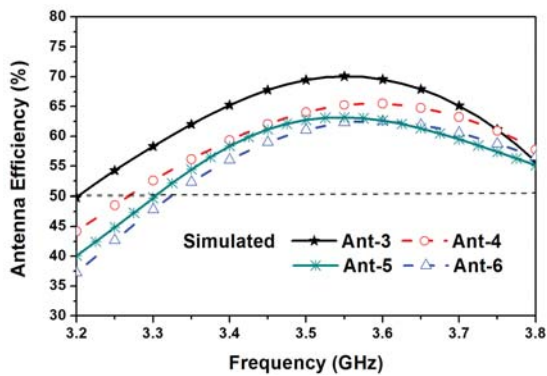
FIGURE 5. Simulated efficiencies of 5G antennas along the right side edge.
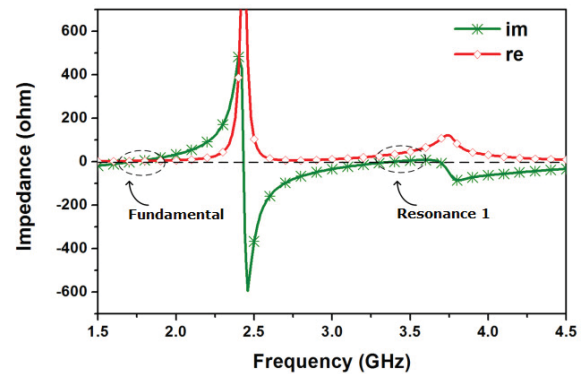

FIGURE 7. Simulated input impedances of 5G antenna element.

these 5G antennas can still meet the requirement for smartphone applications.

To fully comprehend the excitation of the 5G monopole resonant mode, the simulated surface current distributions at 3.5 GHz of Ant3 (representing the rest) is shown in Fig. 6. In this figure, a current null is observed along monopole strip with total length of 35 mm (approximately $0.41\lambda_0$), which indicates that the 3.5 GHz mode is a higher-order resonance. To explain this phenomenon, Fig. 7 shows the fundamental resonance (with reactance value is zero) of the 5G monopole is actually at approximately 1.75 GHz. However, this fundamental resonance has exhibited very poor impedance matching due to very small resistance value. Thus, it has very little influence on the 4G antenna module operating bands.
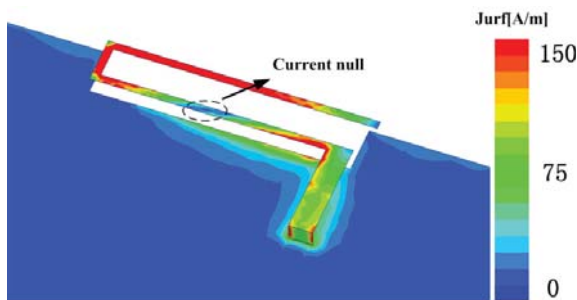

FIGURE 6. Simulated surface current distribution at 3.5 GHz for Ant3.

III. RESULT AND DISCUSSION

A. S-PARAMETERS AND ANTENNA EFFICIENCY

The proposed multi-antenna array prototype was fabricated and tested, and its front and back photographs are shown in Fig. 8. The simulated results were performed by using Ansoft HFSS ver. 14, and an Agilent N5247A vector network analyzer was used for the measured S-parameters results. Due to identical dimensions and symmetrical placement of the ten array elements, only S-parameters of Ant1 and Ant2 (4G antenna module), and Ant3–Ant6 (5G antenna module) are presented.

The measured and simulated return losses of the prototype 4G and 5G antenna modules are presented in Fig. 9(a) and (b), respectively. In this figure, good agreement
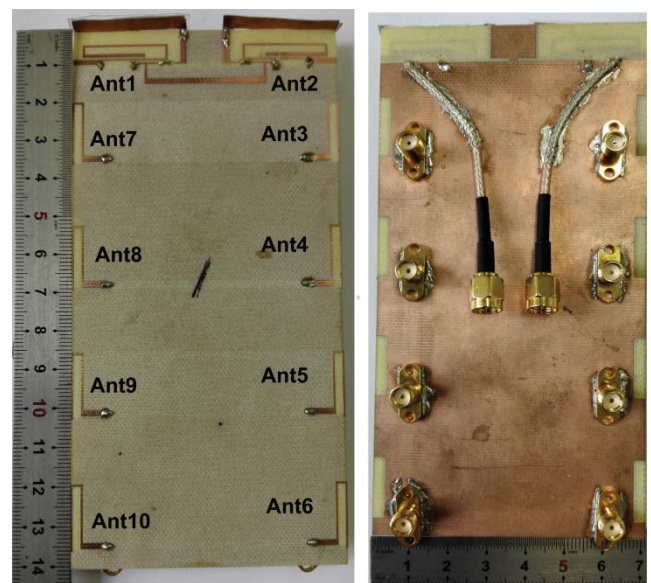

FIGURE 8. Photograph of the fabricated multi-antenna array prototype.

between the simulation and measurement are obtained. Slight differences or variations between the two results may be due to imperfect SMA connector assembly, fabrication tolerance and inevitable small misalignment between the 5G monopole strip and its bottom clearance zone.

As shown in Fig. 9(a), the 4G antennas have exhibited desirable measured 6-dB impedance bandwidths (3:1 VSWR) of 16% (823–968 MHz) and 46% (1697–2706 MHz), and measured isolation better than 10-dB in both desired frequency bands. As for the 5G antennas (Ant3–Ant6) shown in Fig. 9(b), Ant6 has shown a minimum measured 6-dB impedance bandwidth (3:1 VSWR) of approximately 12% (3300–3720 MHz), while Ant3–Ant5 have shown even better impedance bandwidths that can also cover the 3.5 GHz operating band. Because the isolations of nonadjacent 5G elements are much larger than 18 dB, for brevity, Fig. 9(b) only just shows the isolation between adjacent antenna elements (Ant3–Ant6), and the measured results (S43, S54, and S65) across the 3.5 GHz band were better than 10-dB.
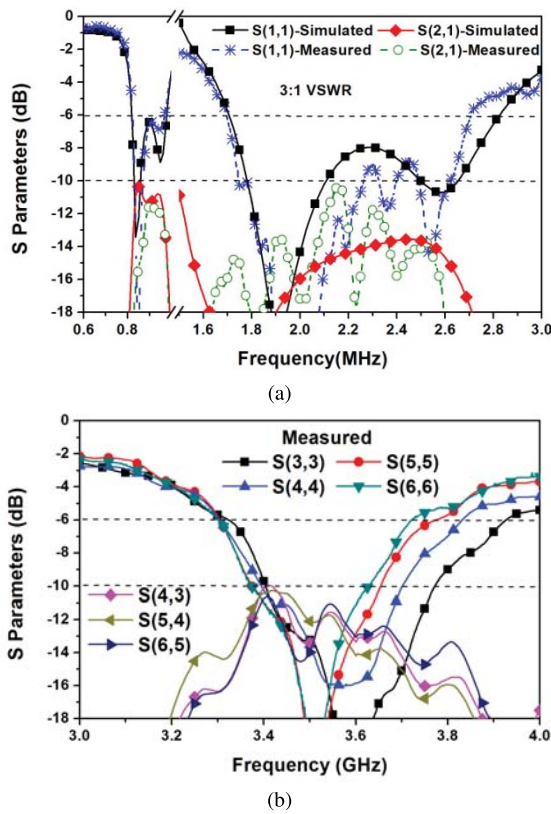
(a)

(b)

FIGURE 9. S-parameters of (a) 4G antenna module, (b) 5G antenna module.
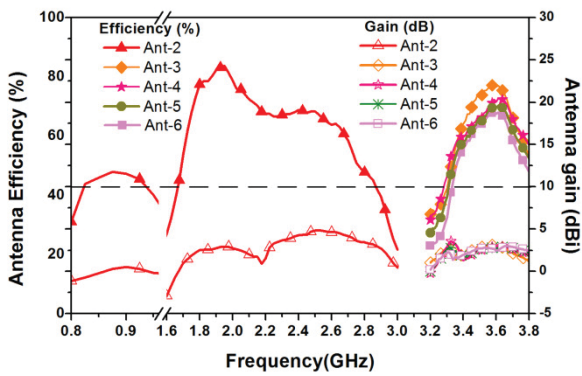

FIGURE 10. Measured antenna gains and radiation efficiencies across the operating bands of proposed multi-antenna module.

The antenna efficiencies (includes mismatching losses) and antenna gains of proposed multi-antenna module were measured with one antenna excited while the other antennas terminated to 50Ω matched load in the SATIMO microwave anechoic chamber, and the results are shown in Fig. 10. In this figure, the measured 4G antenna (Ant2) efficiencies over the lower and upper bands were more than 40% and 60%, respectively, while their corresponding antenna gain variation were $-0.5-0.43$ dBi and $0.99-3.7$ dBi. Within the desired 3.5 GHz bands (3400–3600 MHz), the measured 5G antennas (Ant3–Ant6) efficiencies were about 62%–78%, while its corresponding antenna gains were approximately 1.9–3.2 dBi.
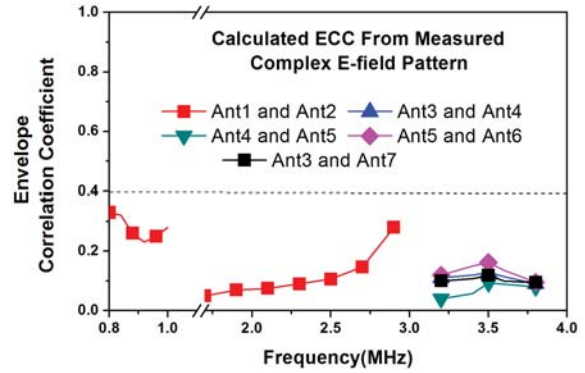

FIGURE 11. Calculated ECC from the measured complex electric field patterns.

B. CALCULATED ECC

For diversity and MIMO application, the correlation between signals received at the same side of a wireless link by the involved antenna is an important figure of merit for the whole system. The envelop correlation coefficient (ECC) is usually used to evaluate the diversity capability of multi-antenna system, in which low ECC value means higher isolation and large diversity gain. In general, the ECC value should be less than 0.5, so that good characteristic of diversity for mobile terminal applications can be achieved [22]. Because the detail formulae of ECC has already been discussed in [22]
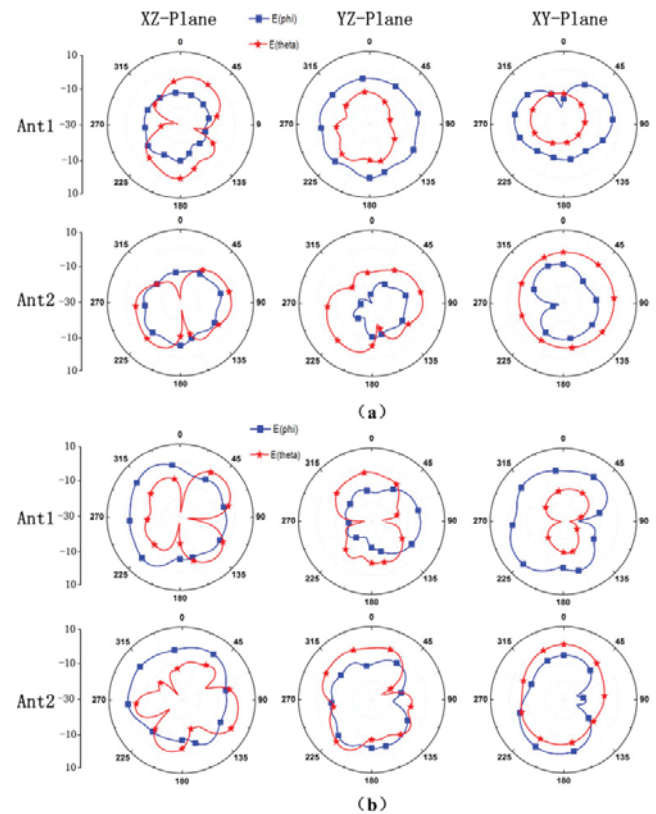

(a)

(b)

FIGURE 12. Measured radiation patterns of 4G antennas at (a) 900 MHz, (b) 2000 MHz.

for diversity antenna, for brevity, it will not be shown in here. Fig. 11 shows the ECC characteristic computed from the measured complex E-field patterns. The ECC values for 4G and 5G antennas are less than 0.4 and 0.2, respectively, over their corresponding desired bands of interest.

Fig. 12 shows the measured two-dimensional radiation patterns of 4G antennas at 900 and 2000 MHz for Ant1 and Ant2. For the 4G antennas, as explained in [21], because of their symmetrical placement, Ant1 and Ant2 have demonstrated distinct complementary characteristics at the same frequency. These behaviors are advantageous for achieving smaller ECCs, which also explain the lower ECCs obtained over the operating bands. Fig. 13 shows the measured two-dimensional radiation patterns of Ant3–Ant6 at 3500 MHz. As expected, each 5G antenna element has exhibited similar radiation patterns in the three principal planes, in which near bi-directional patterns were observed in the XZ-plane, while both YZ- and XY-planes have demonstrated broadside patterns in the +Y (90°) direction.

C. CHANNEL CAPACITIES OF 5G AND 4G ANTENNAS

Similar to a SISO (single input single output) system, the channel capacity of a MIMO system is a function of the system bandwidth and the statistic of its equivalent SNR (signal to noise ratio), that is usually adopted to evaluate the system performance [23]–[25]. When the transmitter does not know the channel conditions, the power is equally divided
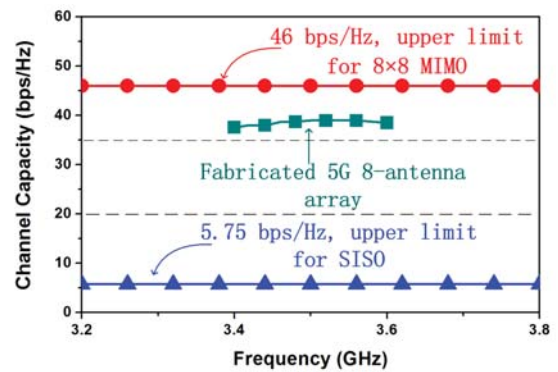

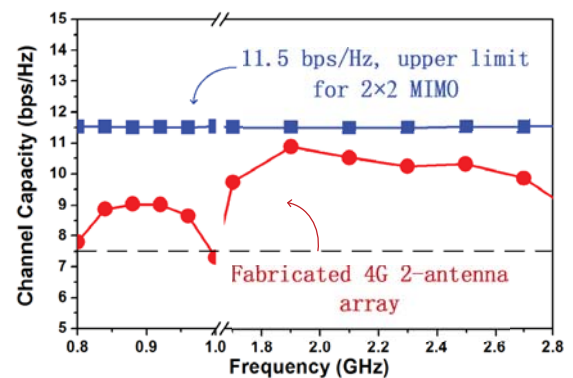**FIGURE 14.** Calculated ergodic channel capacities of 5G antenna array prototype in an 8 × 8 MIMO system.

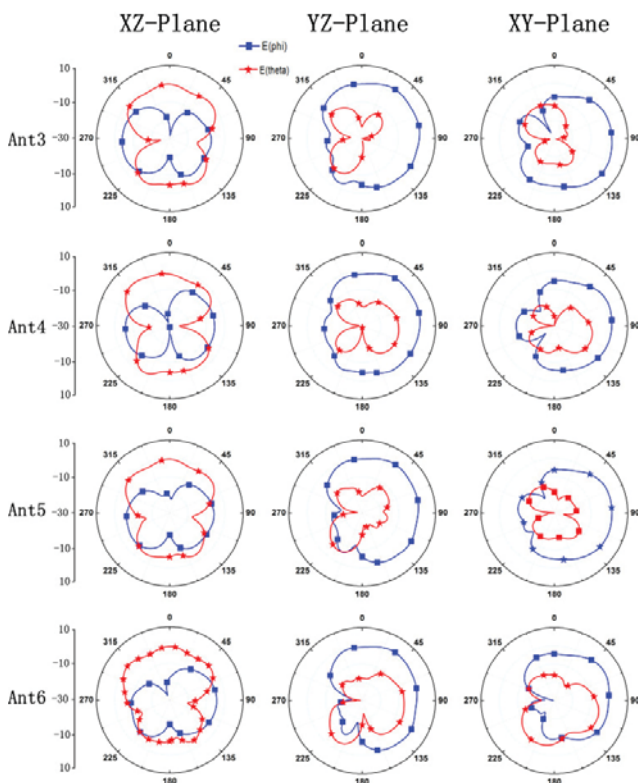**FIGURE 15.** Calculated ergodic channel capacities of 4G antenna array prototype in an 2 × 2 MIMO system.

to each transmit antenna element, and its ergodic channel capacity is defined as

$$C = E\left\{ \log_2\left[\det\left(I + \frac{SNR}{n_T} HH^H \right) \right] \right\},$$

whereby E denotes expectation with respect to different channel realizations, I is an identity matrix, SNR denotes the mean SNR at the mobile terminal, n_T is the number of transmitting antennas, H is the channel matrix, and H^H denotes the Hermitian transpose of matrix [16]. In this case, the uncorrelated transmitting antennas, and the i.i.d. (independently identically distributed) channels with Rayleigh fading environment of SNR = 20 dB are considered. For 5G antenna module operated at 3400–3600 MHz band, theoretically, it could greatly improve the channel capacity compared with the case that only one antenna at the mobile-terminal side. The results of calculated ergodic MIMO capacity for 5G antenna module is presented in Fig. 14. The proposed 5G antenna aray is compared with the case of eight ideal transmitting and receiving antennas, (ideal 8 × 8 MIMO system), and the case of one ideal transmitting and receiving antenna (ideal SISO system). It is shown that the proposed 5G antenna array in an 8 × 8 MIMO system has achieved capacity much larger than that of a SISO system, but lower than the ideal 8×8 MIMO system case by only about 6 bps/Hz in a uniform environment.

FIGURE 13. Measured radiation patterns of 5G antennas at 3.5 GHz.

To ensure that the proposed 4G antenna array prototype is workable in a 2×2 MIMO system, its corresponding ergodic MIMO capacity is also calculated and presented in Fig. 15. Here, the proposed 4G antenna array is also compared with the case of two ideal transmitting and receiving antennas, (ideal 2×2 MIMO system). It is shown that the proposed 4G antenna array in an 2×2 MIMO system has achieved capacity of above 7.5 bps/Hz with a 20-dB SNR, but lower than the ideal 2×2 MIMO system case (11.5 bps/Hz) in a uniform environment.

IV. CONCLUSION

This work has successfully reported a multi-antenna module that composed of a 4G and 5G antenna modules, which can be applied for 4G/5G applications. The 4G antenna module can cover two wide operating bands of 824–960 MHz and 1710–2690 MHz, and the 5G antenna module with eight monopole antennas can cover the 3400–3600 MHz band. The ergodic channel capacities of 5G antenna array in a 8×8 MIMO system have been calculated to reach about 40 bps/Hz with a 20-dB SNR, which is approximately 7 times larger than that of an ideal SISO system. Typical results such as S-parameters, radiation efficiency, antenna gain, radiation pattern, and ECCs were measured, and they can meet the requirements of MIMO systems. Therefore, the proposed multi-antenna module is promising for future multi-mode smartphone applications. Lastly, as far as the authors concern, a combined 4G and 5G antenna modules has never been reported in the open-literature or anywhere else.

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