Sub-6 GHz Dual-Band 8×8 MIMO Antenna for 5G Smartphones

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Abstract—In this letter, a dual-band 8×8 MIMO antenna that operates in the sub-6 GHz spectrum for future 5G multiple-input multiple-output (MIMO) smartphone applications is presented. The design consists of a fully grounded plane with closely spaced orthogonal pairs of antennas placed symmetrically along the long edges and on the corners of the smartphone. The orthogonal pairs are connected by a 7.8 mm short neutral line for mutual coupling reduction at both bands. Each antenna element consists of a folded monopole with dimensions 17.85×5 mm² and can operate in 3100–3850 MHz for the low band and 4800–6000 MHz for the high band ($|S_{11}| < -10$ dB). The fabricated antenna prototype is tested and offers good performance in terms of Envelope Correlation Coefficient (ECC), Mean Effective Gain (MEG), total efficiency and channel capacity. Finally, the user effects on the antenna and the Specific Absorption Rate (SAR) are also presented.

Index Terms—Dual-band, mutual coupling, multiple input multiple output (MIMO), smartphone antenna, SAR.

I. INTRODUCTION

As the radio access technology is continuously evolving, there is a need for improvements in system capacity and signal quality. The fifth generation (5G) of mobile communications has drawn great interest in recent years. Massive MIMO systems with several antennas can achieve higher data rates and will therefore be one of the core technologies in 5G communications [1]. When several antennas are loaded within limited available space in a smartphone, antenna elements may be tightly coupled to each other leading to low isolation, reduced antenna efficiency and high peak SAR values. Therefore, loading a smartphone with multiple antennas may prove to be a challenging task. Several techniques exist that can improve the isolation between antenna elements when they are closely spaced together. A neutralization line is a decoupling element that connects antenna elements close to each other to reverse the effect of mutual coupling and has been demonstrated successfully in [2]–[4]. Furthermore, in [5] spatial, polarization and pattern diversity schemes examined for different antenna configurations within a smartphone may further improve the isolation level. Mutual coupling reduction techniques along with diversity techniques are required for antennas in mobile phones when they are spaced closely together to reduce any degradation in performance and low isolation due to common ground effects [6], [7].

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It is preferable that MIMO antennas facilitate multi-band operation over a wide bandwidth for various broadband services. Several MIMO antenna designs have been reported with multi-band operation [8]–[14]. One approach is by introducing a gap-coupled feeding structure between dual-antenna arrays [8], [9] where each antenna array operates at a different frequency. Nonetheless, while these designs are compact in size, they operate with a quite narrow impedance bandwidth that is not sufficient to cover the desired bands of operation. This problem may be solved using antennas with re-configurable feedings [10]–[12]. However; The diodes integrated into the design will decrease the MIMO performance. Furthermore, by integrating lumped components in the design a wider bandwidth can be achieved [13], [14]. Although; Lumped components will introduce extra losses which will lead to reduced efficiency. It is quite a challenge to achieve multi-band operation over a wide bandwidth with a compact MIMO antenna design. Thus, introducing a compact dual-resonating single-element MIMO antenna that covers a wide bandwidth is a good candidate for 5G MIMO operation in the sub-6 GHz spectrum.

The 3GPP New Radio (NR) specification will support the 3300–3800 MHz band from the beginning of 5G deployment as it has been identified as the band with the greatest potential of global harmonization [15]. Moreover, the 4800–5000 MHz band is further supported by countries such as China and Russia, while the 5150–5925 MHz band is also being considered for MIMO antenna design within the sub 6-GHz region [16]. In this letter, a dual-band 8×8 MIMO antenna has been designed and optimized to operate in 3100–3850 MHz for the low band (LB) and 4800–6000 MHz for the high band (HB) for 5G sub-6 GHz smartphone applications. The 8×8 MIMO consists of orthogonal pairs of antennas that can be placed on the corners of the smartphone while each antenna has a simple structure and can be fabricated easily. The orthogonal antennas which are located very close to each other are connected by a short strip for decoupling at both frequency bands. Furthermore, by making use of the frames and placing the MIMO pairs on the corners, mutual coupling between the pairs is reduced since they are far apart from each other as opposed to when they are placed in a row along the edge of the ground plane.

II. PROPOSED 8×8 MIMO ANTENNA

The detailed dimensions of the proposed MIMO antenna are shown in Fig. 1. The size of the system ground plane is 70 mm $\times$ 150 mm, typical for the dimensions of a 5.3 inch

Fig. 1: Geometry and dimensions of the proposed 8x8 MIMO and detailed dimensions of a single antenna element with neutral line (Arm L4).

TABLE I
OPTIMAL DIMENSIONS OF THE PROPOSED MONOPOLE ANTENNA WITH NEUTRAL LINE

Parameter:	L1	L2	L3	L4	t1	t2	t3	t4
Value (mm):	10.95	11.11	10.45	3.9	1.5	1	0.5	1

handset. The substrate used for the antenna is FR-4 with dielectric constant of 4.3, loss tangent of 0.025. An FR-4 loop frame with thickness of 0.8 mm and height of 6 mm is found on the edges of the ground plane and the antenna elements are located on the outside surface of the loop frame. The folded monopole antennas placed orthogonal to each other have dimensions of $17.85 \times 5 \text{ mm}^2$. The antenna elements are fed by a 50Ω micro-strip feed-line that is directly connected to a 50Ω SMA connector via the edge of the system ground and therefore no ground clearance is required. As shown in Fig. 1, the design is symmetrical with four pairs of antennas placed on the corners of the mobile phone with a short neutral line connecting them. Optimal dimensions for each single antenna element are summarized in Table I.

III. RESULTS AND DISCUSSION

A. Antenna performance

In this section, the performance metrics of the proposed 8x8 MIMO are analyzed and the measured results are compared to the simulated ones. The MIMO antenna has been prototyped and tested in an anechoic chamber. Fig. 2 shows the fabricated FR-4 substrate pieces where the antennas are located are attached together with connectors that act as ports to form an 8x8 MIMO. Fig 2(a) shows the back view of the 8x8 MIMO and Fig 2(b) shows the side view where the orthogonal antenna pairs can be clearly observed. The material placed in the middle between the substrate is Rohacell ($\epsilon_r=1$) to fix the antennas in the proposed MIMO configuration.

As the structure is symmetrical and complementary in terms of placement of the orthogonal pairs, only ant1, ant2 is discussed in this section and the results for the S-parameters in relation to ant3-ant8 are omitted. Fig. 3(a) shows the simulated and measured $|S_{ii}|$ for ant1, ant2. A dual resonant response is achieved at 3.5 GHz and 4.9 GHz with a 10 dB return-loss bandwidth. By optimizing the pairs in relation to the size of

Fig. 2: Photos of 8x8 MIMO. (a) Back view. (b) Side view.

Fig. 3: Simulated versus measured results for the orthogonal mode pair, Ant1-Ant2. (a) $|S_{ii}|$. (b) $|S_{ij}|$.

the ground plane, a good impedance match is obtained across a wide bandwidth. Even though some slight discrepancies can be observed to due minor fabrication error, the measured results are in agreement with the simulated ones covering well the bands of interest. In Fig. 3(b) the measured $|S_{ij}|$ is compared to the simulated one. By connecting the orthogonal antennas with a neutral line, the mutual coupling is reduced indicating high isolation levels between ant1-ant2 with $|S_{12}| < -17 \text{ dB}$ and their adjacent elements ant3 and ant8 with $|S_{23}| < -20 \text{ dB}$ and $|S_{18}| < -18 \text{ dB}$ measured across both the LB and HB.

The resonance mechanism comes from the fact that the monopole arms are folded to achieve quarter-wavelength and half-wavelength modes of operation. The current distribution for ant1 and ant2 when port 1 is excited and port 2 is terminated to 50Ω at both bands can be observed in Figs. 4(a) and 4(b) respectively. Arms L1 and L3 are used to excite the antennas at 3.5 GHz where the current distribution observed is approximately equal to quarter-wavelength. Similarly, the antennas are excited at 4.9 GHz by arms L1, L2 and L3 where the current distribution observed is approximately equal to half-wavelength due to the higher resonant frequency. As the antennas are connected by a neutral line, when port 1 is excited a very small amount of current flows through ant2 indicating that the isolation between ant1-ant2 is high.

B. MIMO Performance

In this section, the MIMO performance metrics of the proposed design are presented in terms of ECC, total efficiency, MEG and channel capacity. ECC is a measure of how tightly coupled the antenna elements are to each other and it is calculated using the far-field radiation patterns in equation (1). Fig. 5(a) shows the measured ECC between the orthogonal

Fig. 4: Current distribution for ant1, ant2 when port 1 is excited. (a) Current distribution at 3.5 GHz, (b) Current distribution at 4.9 GHz.

Fig. 5: (a) Calculated ECC values from measured results, (b) Calculated total efficiency for ant1, ant2.

pair ant1, ant2 and their adjacent elements ant8 and ant3. The measured ECCs across both bands are <0.06 which are well below the acceptable value of 0.3.

$$\rho_e = \frac{|\int_{4\pi} F_1^{\rightarrow*}(\theta, \phi) \cdot F_2^{\rightarrow*}(\theta, \phi) d\Omega|^2}{\int_{4\pi} |F_1^{\rightarrow*}(\theta, \phi)|^2 d\Omega \times \int_{4\pi} |F_2^{\rightarrow*}(\theta, \phi)|^2 d\Omega} \quad (1)$$

Total efficiency is calculated using the S-parameters in equations (2) and (3). As shown in Fig. 5(b) the antenna efficiency has been calculated for ant1, ant2. The measured efficiency at the LB and HB considering any mismatch and coupling losses is 65%-75% and 60%-71% respectively. Overall, the efficiency

TABLE II
CALCULATED MEGs FROM MEASURED 3D COMPLEX E-FIELD PATTERNS

Freq (GHz)	MEG-1 (dBi)	MEG-2 (dBi)
3.1	-4.92	-4.61
3.5	-4.72	-4.78
3.85	-5.24	-5.62
4.8	-5.67	-5.51
5.4	-4.83	-4.18
6	-5.02	-4.75

Fig. 6: Calculated channel capacity of 8x8 MIMO from measured results.

achieved for ant1, ant2 is desirable for obtaining small losses in capacity.

$$\eta_{1,total} = \eta_{1,rad}(1 - |S_{11}|^2 - |S_{21}|^2) \quad (2)$$

$$\eta_{2,total} = \eta_{2,rad}(1 - |S_{22}|^2 - |S_{12}|^2) \quad (3)$$

MEG is the ratio of power received by an antenna in a fading environment and what power could be received by an isotropic antenna. MEG is calculated using equation (4) where it is assumed that the channel is uniform Rayleigh with equal vertical and horizontal polarization power densities. MEG then is equal to half of the radiation efficiency (η_{rad}). Equation (5) denotes that the MEG variations must be below 3 dB meaning that the MIMO elements have comparable MEGs. The calculated MEGs for the orthogonal pair of antennas excited independently are presented in Table II. According to the table, the MEGs vary from -4.18 to -5.67 dBi across both operating bands and therefore equation (5) is satisfied.

$$MEG_i = 0.5\eta_{i,rad} = 0.5 \left[1 - \sum_{j=1}^M |S_{ij}|^2 \right] \quad (4)$$

$$K = |MEG_1 - MEG_2| < 3dB \quad (5)$$

In addition, the channel capacity is measured and compared to that of ideal uncorrelated antennas. The channel capacity is measured under the conditions of ideal uncorrelated antennas and averaged over 10000 realizations by assuming an independent and identically distributed Rayleigh fading channel of 20 dB SNR for the 8x8 MIMO. It is calculated using equation (6) where E is the expectation, I is an identity matrix, SNR is the average signal-to-noise ratio at the mobile terminal, η_T is the number of transmitting antennas and H is the channel matrix where H^H is the Hermitian transpose of the matrix. As shown by Fig. 6 the channel capacities of the 8x8 MIMO are about 39-39.5 b/s/Hz and 38.5-39.5 b/s/Hz for the LB and

Fig. 7: Simulated S-parameter results with (dashed line) and without (solid line) the Voxel model for ant1, ant2. (a) $|S_{ii}|$. (b) $|S_{ij}|$.

Fig. 8: Simulated radiation pattern with the Voxel model for ant1; (a) radiation pattern at 3.55 GHz, (b) radiation pattern at 5 GHz.

HB respectively, which are acceptable compared to the upper bound (46/b/s/Hz) for an 8×8 MIMO.

$$C = E \log_2 \left[\det \left(I + \frac{SNR}{\eta_T} H H^H \right) \right] \quad (6)$$

C. User's Effects and SAR Analysis

The influence of the human body on the antenna is further considered. To model human tissues, it is possible to define a multilayer phantom or to use the built-in voxel models [17] in CST MWS. As the second approach will lead to a more realistic result, the Gustav voxel model has been chosen to study the effect of human proximity on the antenna performance. The effects of the model on the S-parameters of ant1-ant2 are shown in Figs. 7(a) and 7(b). A small deviation in the operating frequency can be observed to 3.55 GHz for the LB and 5 GHz for the HB. Despite the changes observed in the S-parameters, the antenna covers well both bands with isolation better than 12.5 dB. Figs. 8(a) and 8(b) illustrate the radiation pattern for ant1. For the LB, ant1 has a directivity of 5.62 dBi and total efficiency of -5.84 dB while for the HB ant1 has a directivity of 6.23 dBi and total efficiency of -6.88 dB. From Fig. 8 it can be observed that radiation is mostly directed away from the human head where a null is observed due to the fully grounded plane.

Moreover, SAR is the absorption of power from a mobile terminal to the human body due to radiation. It is challenging to obtain low peak radiation levels as the number of antennas within the handset increases. SAR recommended levels lie between 0.1 and 0.5 W/Kg. The maximum permissible level is 1.6 W/Kg averaged over the volume containing 1 g of tissue [18] and 2.0 W/Kg averaged over the volume containing 10

TABLE III
SAR VALUES AVERAGED OVER 1 GRAM AND 10 GRAMS OF TISSUE

Port	Head SAR (W/kg)				Head + Hand SAR (W/Kg)			
	1 g average		10 g average		1 g average		10 g average	
	LB	HB	LB	HB	LB	HB	LB	HB
1	0.641	0.25	0.235	0.071	1.3	0.454	0.378	0.13
2	0.244	0.296	0.092	0.082	0.724	0.489	0.376	0.12
7	0.521	0.556	0.243	0.196	0.528	0.586	0.315	0.25
8	0.852	0.69	0.465	0.255	0.941	0.861	0.559	0.36

Fig. 9: Simulated SAR pattern for ant1 when averaged over 1g of tissue; (a) SAR at 3.55 GHz, (b) SAR at 5 GHz.

g of tissue [19]. The SAR levels have been simulated for the upper portion of the handset (ant1, ant2, ant7, ant8) where the antennas are closer to the human head. The simulation is performed with the presence of the human head only as well as with the human head and hand together, averaged over 1 g and 10 g of tissue based on the IEC/IEEE 62704-1 averaging method [20]. The transmit power set to flow through the structure is 0.5 W while the mobile handset is placed at a separating distance of 2 mm from both head and hand. The results are presented in Table III where the values obtained are acceptable according to the limits and can be attributed to the design structure and arrangement as well as the high isolation between the antennas. Figs. 9(a) and 9(b) show the SAR pattern of ant1 at 3.55 and 5 GHz, respectively. From the results presented in Fig. 9 and Table III it can be deduced that the radiation is mostly directed towards the hand.

IV. CONCLUSION

In this letter, a dual-band 8×8 MIMO antenna with compact size and simple structure is designed to operate in the 3100-3850 MHz and 4800-6000 MHz bands. Isolation between the orthogonal antennas is improved due to the addition of a short neutral line. A good ECC of less than 0.06 is obtained between the measured antennas, MEG variations are < 3 dB and total antenna efficiency ranges between 65%-75% for the LB and 60%-71% for the HB. The calculated channel capacities of the MIMO antenna are 39-40 b/s/Hz, 38-39 b/s/Hz for the LB and HB respectively, indicating that the antenna has a good MIMO performance. Additionally, the user's effects on the antenna are also studied and a SAR analysis is conducted where low peak SAR values are obtained.

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