Analysis and Design of an Efficient and Novel MIMO Antenna for 5G Smart Phones Using FDTD and FEM

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Abstract ─ A novel and compact antenna element is analyzed and designed to achieve an efficient 4x4 MIMO antenna for a mobile phone at 3.5 GHz band for 5G communication. FTDT and FEM techniques are used to analyze and compare modeling accuracy of the proposed MIMO antenna. It has achieved a minimum isolation of 19.7dB between two antennas with radiation efficiency of 86%. The improved isolation and efficiency for the proposed MIMO antenna has been achieved without any decoupling structure between antennas, instead larger separation between elements due to compact size of the proposed element facilitated to achieve good performance. Pattern diversity is also achieved by arranging adjacent asymmetric antennas in reverse direction with each other. The envelope correlation coefficient (ECC) is less than 0.002 and Channel Capacity loss (CCL) is also less than 0.4 bps/Hz in the whole frequency band (3.36-3.66 GHz), which is suitable for 5G MIMO systems.

Index Terms ─ Channel Capacity Loss (CCL), Envelope Correlation Coefficient (ECC), Finite Difference Time Domain (FDTD), Finite Element Method (FEM), Multi-Input Multi-Output (MIMO).

I. INTRODUCTION

The aspiration of high speed data transmission rate for smart phones is increasing exponentially. 5G wireless communication system is a consequent telecommunication standard that may achieve data rates up to tens of gigabits/second [1-2]. Such high data rates may be achieved by using multi-input multi-output (MIMO) system with multiple isolated antennas in a mobile phone [3-10]. These multiple antennas may transmit and receive data simultaneously on a single radio frequency channel. MIMO uses multiple path propagation at the same time that ensures the reliability and higher data transmission rate without using extra bandwidth.

Quality of signal transmission can be enhanced if higher isolation is achieved between MIMO antennas of a portable communication device. The mutual coupling among antenna elements causes poor isolation and reduced efficiency [3]. Design of highly efficient MIMO antenna with better isolation and improved bandwidth within a mobile phone is a challenging issue due to common ground of MIMO antenna system.

Several techniques have been reported recently to reduce mutual coupling between antenna elements of a MIMO system. Some popular techniques are: orthogonal arrangement [4-6], neutralization line [7], diagonal arrangement [8, 9], protruded ground plane [10], common grounding branch [11, 12], balanced open slot [13], metamaterial structure [14] and defected ground [15, 16, 17]. However, all these techniques may reduce the coupling between MIMO antenna elements at the cost of reduced efficiency.

Analysis and design of an efficient and compact multi-input and multi-output (MIMO) antenna element is presented for 5G smart phones. FDTD and FEM techniques are used to analyze and compare modeling accuracy of the 4x4 MIMO antenna. Better isolation and bandwidth enhancement is achieved by the novel MIMO antenna system. A minimum isolation of 19.7dB has been achieved between antenna elements without using

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any decoupling structure.

II. MIMO ANTENNA GEOMETRY

Geometry of the proposed novel antenna elements array is shown in the Fig. 1. All dimensions of parameters are in millimeters. Similar to the modern smart phones, the horizontal system substrate has dimensions of 75×150×0.8 mm^3 and it is connected with two vertical substrates on longer sides of the system substrate. The dimension of each vertical substrate is 0.8×150×6 mm^3. All the four antennas are printed on both sides of vertical substrate as shown in Fig. 1. The material for both system and vertical substrate is FR-4 with ε_r = 4.4 and loss tangent = 0.02 and the material for ground and printed patch elements is copper annealed with thickness of 0.035 mm.

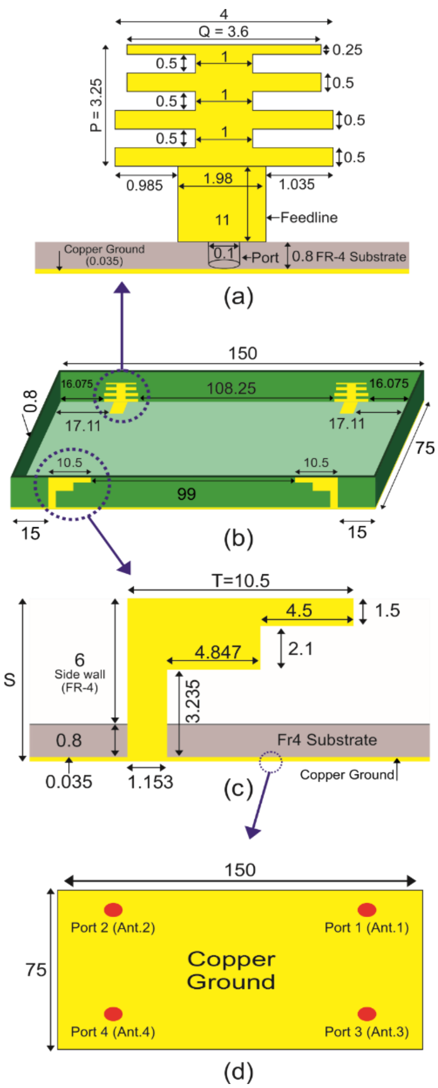

Fig. 1. Proposed structure of MIMO antenna: (a) Yagi-Uda shaped element, (b) complete structure of MIMO antenna, (c) staircase element, and (d) copper ground.

Each antenna consists of a Yagi-Uda shaped element (connected with microstrip feed) on front side of the vertical substrate and a staircase element (connected with ground) on backside of Yagi-Uda shaped element. Each of the microstrip feed line is excited with a 50 Ω coaxial probe. Yagi-Uda shaped element is used to reduce antenna size due to multiple current paths available in Yagi-Uda shaped element. It helps to increase electrical length while keeping the antenna size compact. Asymmetric staircase element is used to concentrate current density on one side of the patch antenna that helps to increase effective spacing and hence isolation between two adjacent antennas arranged in reverse direction. Such reverse arrangement of adjacent asymmetric elements also helped to achieve pattern diversity. The reason for higher isolation and pattern diversity is explained in next section.

III. ANALYSIS OF MIMO ANTENNA

A. Computational analysis using FDTD and FEM

Computational analysis of 4x4 MIMO antenna is performed using two different computational analysis techniques in CST Microwave Studio, first technique is FDTD (Finite Difference Time Domain) of time domain solver while the other technique is FEM (Finite Element Method) of frequency domain solver. FDTD is used with Perfect Boundary Approximations (PBA) on a hexahedral grid while FEM is used on a tetrahedral grid with open boundary conditions.

S-parameters for FDTD computational analysis are shown in Fig. 2. It can be seen that all the reflection coefficients (S_{11}, S_{22}, S_{33}, S_{44}) are less than -10 dB (2:1 VSWR), which ensures acceptable impedance matching from 3.33 to 3.66 GHz, while transmission coefficients depicts the minimum isolation of 19.7 dB at 3.5GHz. Due to evenness and simplicity, the analysis has been made by considering only following transmission coefficients: $S_{21} = S_{12,}$, $S_{31} = S_{13}$ and $S_{41} = S_{14}$. It can be seen that all the transmission coefficients are less than the required standard of at least -15 dB without any decoupling network. The isolation is achieved due to larger effective spacing between compact elements. It is the reason, due to which maximum isolation of greater than 29 dB is achieved between antenna 1&4, as they are diagonally placed. So, the proposed MIMO antenna is best suited for smartphones used for 5G applications.

To verify modeling accuracy of the proposed MIMO antenna, it is also analyzed using FEM technique. S-parameters for FEM technique are shown in Fig. 3. It can be seen that the impedance bandwidth and isolation between MIMO antennas are almost similar to those achieved through FDTD technique. A very little deviation in impedance matching and a frequency shift is ignorable due to a minor convergence error in any of the computational techniques. Therefor the proposed MIMO antenna model may be used to achieve required isolation and impedance bandwidth performance.

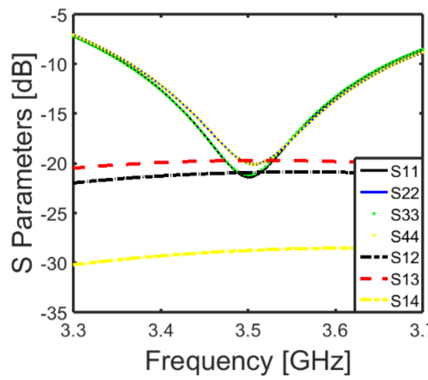

Fig. 2. S-parameters for the 4x4 MIMO antenna using FDTD.

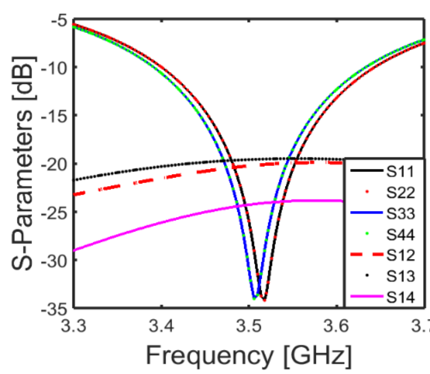

Fig. 3. S-parameters for the 4x4 MIMO antenna using FEM.

B. Parametric analysis

In parametric analysis, some computational aspects of the proposed design are presented. It may help to perceive in-depth understanding about modeling issues of the critical parameters, which are used to optimize the proposed MIMO antenna patch elements.

The parametric analysis for P and Q dimensions of Yagi-Uda shaped element for return loss are shown in Figs. 4 and 5, respectively. It can be seen that the resonance curve shifts from right to left with increase in P, while impedance matching at 3.5 GHz is better for optimized value of P=3.25 mm. In a similar way the resonance curve shifts from right to left with increase in Q, however, return loss also increases with increase in Q. The optimized value of Q=3 mm is selected to have moderate return loss at 3.5 GHz.

Similar parametric curves for T and S dimensions of staircase element are shown in Figs. 6 and 7, respectively. It can be seen that resonance curve shifts again from right to left while return loss decreases with increase in value of T. The return loss is minimum at optimum value of T=10.5 mm. It can also be seen that the S dimension has very important role in impedance matching and the return loss decreases with increase in S at 3.5 GHz.

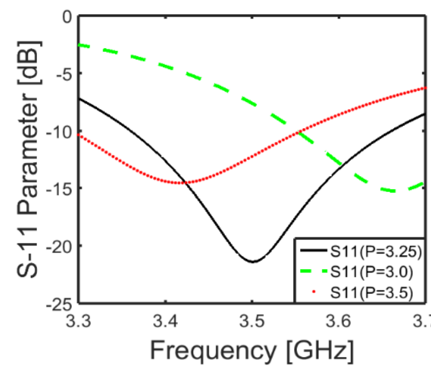

Fig. 4. Parametric analysis of dimension P for return loss.

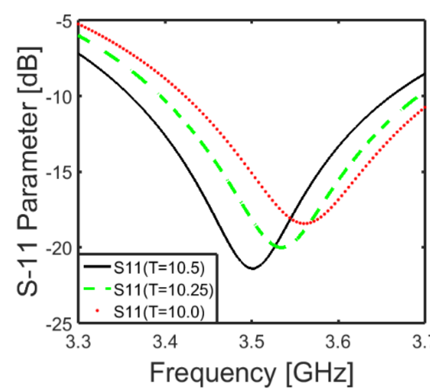

Fig. 6. Parametric analysis of dimension T for return loss.

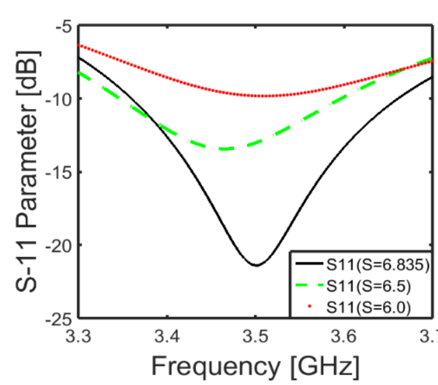

Fig. 7. Parametric analysis of dimension S for return loss.

C. Surface current analysis

Surface current distributions at 3.5GHz on all the four antennas when Antenna-1 is excited and remaining ports are matched with 50Ω load are shown in Fig. 8 (a). The isolation between MIMO antennas is evident from the maximum current distribution on Antenna-1 while minimum current distribution on remaining three antennas. For Antenna 1 in Fig. 8 (b), it can be seen that the density of current distribution is higher on left side of the Yagi-Uda and staircase elements. As arrangement of Antenna-2 on the same edge is kept in reverse direction to that of Antenna-1, so if it is excited then surface current density for Antenna-2 elements will be higher on right side of the Yagi-Uda and staircase elements of Antenna-2. This will increase the effective spacing and hence isolation between the antenna elements on the same edge. Similar arrangement for Antenna-3 and Antenna-4 on the other edge causes similar higher isolation between the two antennas. There is already enough separation of 75mm (greater than λo/2) between the two edges, so all the four antennas have enough isolation (greater than 19.7 dB). So, the larger effective spacing among antennas is the key reason for higher isolation between MIMO antennas.

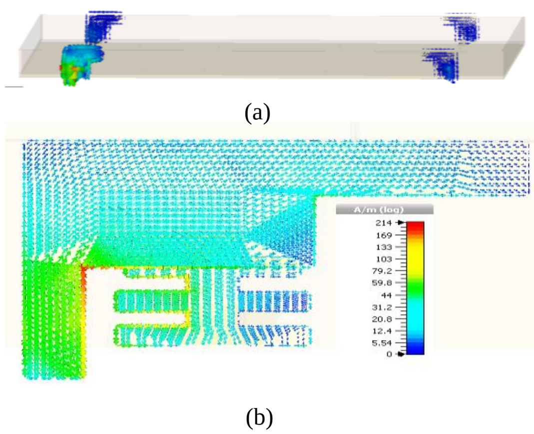

Fig. 8. Surface current distribution analysis: (a) current on all antennas, and (b) current on Antenna 1.

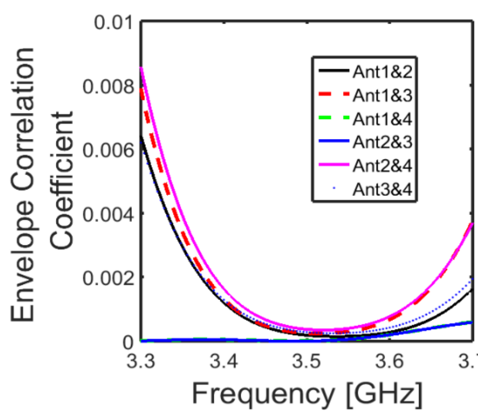

Fig. 9. Envelope Correlation Coefficient (ECC) between antennas of the 4x4 MIMO antenna system.

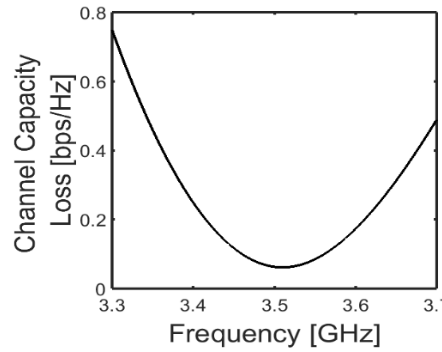

Fig. 10. Channel Capacity Loss (CCL) of the 4x4 MIMO antenna system.

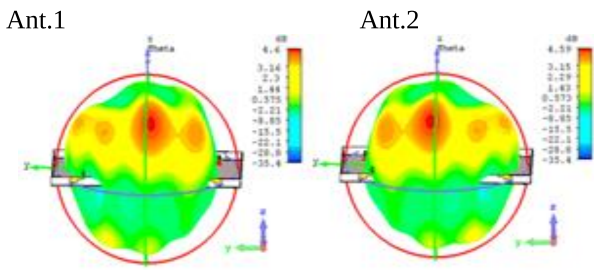

Fig. 11. 3D radiation patterns: (a) Antenna-1 and (b) Antenna-2.

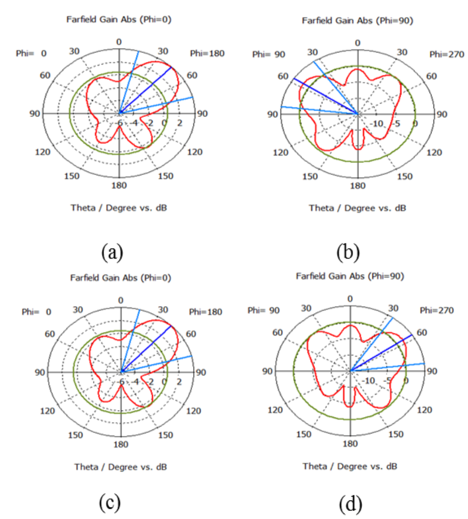

Fig. 12. 2D radiation patterns: (a) Antenna-1, xz-plane; (b) Antenna-1, yz-plane; (c) Antenna-2, xz-plane; (d) Antenna-2, yz-plane.

D. Diversity analysis for gain and radiation pattern

Channel Capacity Loss (CCL) and Envelope Correlation Coefficient (ECC) are used to evaluate gain diversity performance of the proposed MIMO antenna. ECC is plotted in Fig. 9, it can be seen that ECC is less than 0.002 in the desired frequency band of 3.33-3.66 GHz. ECC between antenna 1&4 and antenna 2&3 is almost zero as they are diagonally placed.

Channel capacity loss (CCL) of the MIMO antenna is calculated by using following equations:

$$C_{loss} = -Log_2 \det(\varphi^R), \quad (1)$$

$$\varphi^R = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix}, \quad (2)$$

$$\rho_{ii} = 1 - \left(|S_{ii}|^2 + |S_{ij}|^2\right), \quad (3)$$

$$\rho_{ij} = -\left|S_{ii}^* S_{ij} + S_{ji}^* S_{ij}\right|. \quad (4)$$

The value of CCL is also below 0.4 bps/Hz in the desired frequency band as shown in Fig. 10. As the values of ECC and CCL are below than the required standard limits for a 4x4 MIMO antenna system, so the proposed MIMO antenna has decent gain diversity performance.

Radiation patterns for adjacent antennas, Antenna-1 and Antenna-2, are shown in Figs. 11 and 12. All the antennas have achieved similar gain performance and peak gain for each antenna is 4.6 dBi as shown in Fig. 13, for Antenna-1, while the radiation efficiency of each antenna varies from 81 to 86% in the desired frequency band. However, it can be seen that the radiation beam of Antenna-2 is directed towards opposite direction to that of Antenna-1 due to reverse arrangement of both asymmetric antennas with respect to each other. Such radiation patterns verify that the pattern diversity is also achieved.

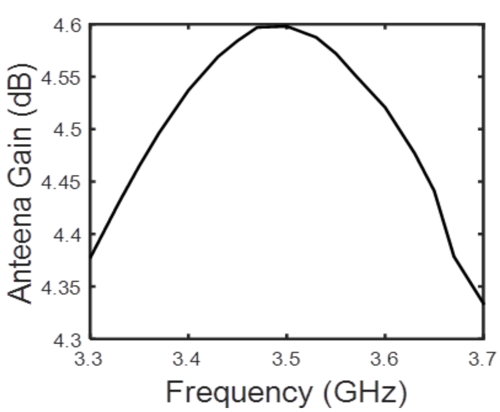

Fig. 13. Gain performance for Antenna-1 of the MIMO antenna system.

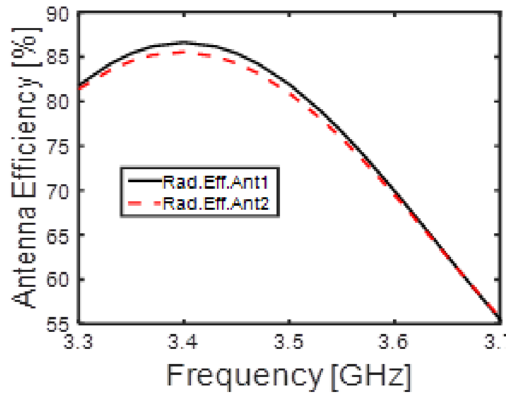

Fig. 14. Radiation Efficiency for Antenna-1&2 of the MIMO antenna system.

IV. COMPARISON WITH PREVIOUS WORKS

The performance of the proposed MIMO antenna is compared with previous recent works in Table 1 to highlight significance of the proposed antenna. It can be seen that the proposed MIMO antenna has achieved comparable performance with improved isolation greater than 19.7 dB, radiation efficiency up to 86%, total efficiency up to 77% and -10dB impedance bandwidth of 300 MHz without any decoupling structure between compact size (71.1mm^2) antennas. Therefore, the proposed MIMO antenna system is a suitable potential player for future 5G MIMO smart phone applications.

V. CONCLUSION

This work has been proposed a 4×4 efficient MIMO antenna system at 3.5 GHz frequency band (3.36–3.66 for 5G smart phone applications. The proposed model is analyzed using FDTD and FEM to verify its modeling accuracy. The adjacent antennas are arranged in reverse direction to achieve higher isolation with suitable gain and pattern diversity. Higher isolation (> 19 dB) has been achieved without any decoupling structure between antennas. The proposed MIMO antenna has also achieved radiation efficiency up to 86% and low value of ECC (< 0.02). The Channel capacity loss (CCL) of the proposed 4×4 MIMO antenna system has also been calculated and it is less than 0.4 bits/Hz in the desired frequency band. Therefore, the proposed MIMO antenna system is a suitable potential candidate unit for massive MIMO system in future.

Table 1: Comparison with previous recent works

Ref.	BW (GHz)	Isolation (dB)	ECC	TE (%)	Antenna Element Size (mm^2)	Isolation Technique	Antenna Array
[5]	3.4-3.6 (-6dB)	> 20	< 0.06	< 74	12×7	Orthogonal arrangement	4×4
[6]	3.4-3.6 (-6dB)	> 12	< 0.15	< 40	26×3	Neutralization line	4×4
[9]	3.4-3.6 (-10dB)	> 17	< 0.1	< 73	9.4×7	Common grounding branch	4×4
[10]	3.4-3.6 (-10dB)	> 10	< 0.2	< 70	17×5	Protruded ground plane	8×8
[11]	3.4-3.6 (-10dB) 4.8–5.0 (-10dB)	> 17	< 0.03	< 67	10×7	Common grounding branch	4×4
[12]	3.4-3.6 (-6dB) 4.8–5.0 (-6dB)	> 12	< 0.02	< 80	3.9×17.7	Linear + diagonal arrangement	4×4
This work	3.36-3.66 (-10dB)	> 20	< 0.002	< 77	10.5×6.835	Reverse + diagonal arrangement	4×4

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