Self-Decoupling Antennas

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***Abstract*—A novel self-decoupling tri-port antenna is introduced, with its three ports exciting a radiator on the smartphone frame's inner surface. Using mode cancellation and active reflection coefficient theory, the antenna's self-decoupling is analyzed. The results show the ports are well isolated without needing a decoupling structure. Simulations indicate that the antenna maintains high isolation and low envelope correlation coefficients across a specific frequency band. A MIMO system with four of these antennas was built and tested, confirming high isolation and low correlation. The total efficiency and channel capacity remain within defined ranges at a given signal-to-noise ratio.**

***Index Terms*—MIMO, Self-Decoupling, tri-port antenna, smartphone antenna.**

I. Introduction

Wireless communication technology has advanced considerably. The efficiency and reliability of communication systems have been improved without an increase in the transmitting power and additional spectrum resources using multiple-input-multiple-output technology. For 5G mobile terminals, the miniaturization of MIMO antennas and performance improvement are critical research topics.

The channel capacity within the existing bandwidth can be improved by increasing the number of elements in the MIMO array. MIMO arrays with various numbers of elements have been reported, achieving different levels of channel capacity performance.

To compress the size of the MIMO array for use in size-limited mobile terminals, two solutions are currently used: integrating multiple antennas into a compact structure, and sharing a radiator among antennas. Techniques such as equivalent transmission line theory, neutralization line principles, and mode cancellation have been employed to achieve high isolation and self-decoupling in these compact MIMO antenna designs.

In this communication, a self-decoupling tri-port antenna is proposed. The three ports simultaneously excite a radiator, and the self-decoupling characteristic is analyzed using mode cancellation and active reflection coefficient theories. The proposed antenna and a 12x12 MIMO system using four tri-port antennas are designed, manufactured, and measured. The results demonstrate high isolation, low envelope correlation, good total efficiency, and favorable calculated channel capacity.

II. Problem Statement

Traditional MIMO systems, while offering improved communication performance, suffer from significant mutual coupling between antennas. This coupling leads to interference and signal degradation, reducing the overall system efficiency. The challenge is to design a compact antenna array that offers improved isolation without increasing complexity, making it suitable for space-constrained environments. Moreover, the solution should maintain the simplicity of the antenna design to enable widespread adoption in commercial applications.

III. Objective

The primary objective of this work is to design, simulate, and validate a self-decoupling tri-port antenna design that utilizes a shared radiator to enable a compact 12x12 MIMO antenna system for 5G smartphone applications. The goals are:

- High isolation among the antenna ports.
- High total efficiency.
- Low envelope correlation coefficients for good diversity performance.
- Favorable calculated channel capacity.

IV. Literature Survey

Research into MIMO antenna systems has consistently highlighted the issue of mutual coupling. Coupling between antennas can degrade system performance, affecting both signal integrity and overall throughput. Traditional decoupling methods such as metamaterials, parasitic elements, and neutralization lines provide solutions but often increase the complexity and size of the antenna array. These methods involve additional structures that may not be suitable for compact designs in modern wireless systems.

Recently, methods like equivalent transmission line theory, neutralization lines, and mode cancellation have been employed to achieve high isolation and self-decoupling in compact MIMO designs. Symmetric dual-port antennas can use mode cancellation based on common mode and differential mode, while asymmetric dual-port antennas require active reflection coefficient analysis for self-isolation.

V. Methodology

The approach integrates principles of substrate selection, ground plane design, radiator configuration, and impedance matching, ensuring optimal electromagnetic behavior and power transfer. By employing a symmetrical design and precise component arrangement, the proposed methodology aims to achieve multi-band functionality while minimizing reflection losses, ultimately enhancing the antenna's overall efficiency and effectiveness in real-world operational settings.

A. Antenna Design

To construct a tri-port antenna, start by preparing an FR4 substrate with a relative permittivity of 4.4 and a loss tangent of 0.02, ensuring it provides a balance of cost-effectiveness and performance. Etch a metal ground plane on the back of this substrate to serve as a reference for electromagnetic waves, influencing radiation patterns and impedance matching. Simulate the smartphone's frame using a vertical FR4 substrate, which is critical in defining the antenna's radiation characteristics. Design the radiator with two symmetrical U-shaped bent structures to support multiple resonant modes, allowing for broad bandwidth and multi-band functionality. Maintain precise ground clearance between the radiator and frame to optimize coupling and efficiency. Implement microstrip feed lines to connect the ports with the radiators; Ports 2 and 3 are symmetrically connected to enhance balanced signal distribution, while Port 1 connects centrally. Introduce -type impedance matching networks at each port to ensure efficient power transfer by minimizing reflection losses, using tailored inductors and capacitors to achieve this; Ports 2 and 3 share identical matching configurations owing to their symmetrical design. Ensure precise alignment of feed lines on the substrate's upper surface for consistent performance, with line widths carefully chosen to maintain desired impedance. Symmetry in design supports balanced radiation patterns, while the -network refines VSWR and enhances antenna efficiency through fine-tuning of reactive components, making this methodology apt for compact mobile applications.

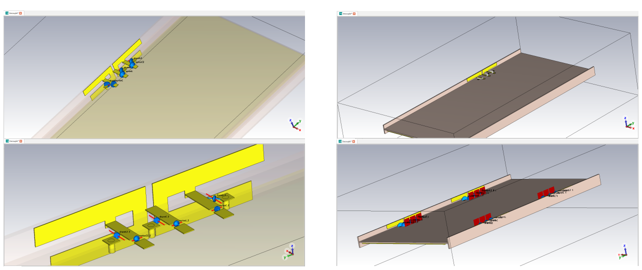


Fig. 1: CST Schematic Design

B. Simulation Setup

Simulations were conducted using CST Microwave Studio to validate the design. The simulation environment was set up to analyze the current distribution, as well as the H-field and E-field distributions at key frequencies. The antenna parameters, including the dimensions of the patch and feeding structure dimensions, were optimized to achieve maximum isolation and performance.

C. Performance Metrics

Key performance metrics for the antenna design include:

- **S-Parameters:** S-parameters, or scattering parameters, are a cornerstone of antenna design analysis in CST software, providing crucial information about how RF signals are reflected and transmitted through an antenna system. They offer insights into key aspects like return loss, gain, and isolation between antenna elements, which are vital for ensuring efficient signal transmission and reception.
- **Y-parameters:** Y-parameters, or admittance parameters, are crucial for understanding the relationship between voltage and current in the system, especially at varying frequencies. They provide insights into the input and transfer admittance, helping designers assess bandwidth performance and the effect of different loading conditions. Analyzing Y-parameters is essential for optimizing network designs, particularly in high-frequency applications where accurate admittance characterization ensures proper system integration.
- **Z-parameters:** Z-parameters, or impedance parameters, on the other hand, focus on the impedance properties of the antenna by relating voltage and current. These parameters help in determining the reflection and transmission characteristics, crucial for optimizing matching networks and ensuring effective power transfer, especially in scenarios where specific impedance values (like 50 ohms) are targeted. Understanding Z-parameters enables designers to diagnose and address impedance mismatches, ensuring that antennas operate efficiently across their intended frequency range.
- **Surface Current:** Analyzing surface current distributions is critical in antenna design as it provides insights into how current flows across the antenna's surface. This analysis helps identify areas with high current concentration, which can influence the radiation pattern, efficiency, and overall performance of the antenna. By visualizing surface currents, designers can pinpoint potential issues such as unexpected resonances or loss hotspots that might degrade performance. Adjustments based on surface current insights can lead to design improvements, such as altering shapes, sizes, or materials to enhance gain, directivity, or bandwidth.

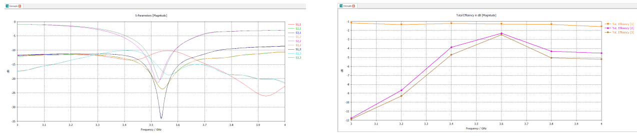
VI. Results

The results of the simulations demonstrate the effectiveness of the self-decoupling mechanism in reducing mutual coupling between antennas.

A. Simulated Results of the Tri-Port Antenna

The simulated S parameters for the proposed tri-port antenna are illustrated in Fig. 2(a). Port 1 offers an exceptionally wide 10 dB impedance bandwidth, surpassing the targeted 3.4–3.6 GHz range. Port 2 shows a 6 dB impedance bandwidth of 270 MHz, spanning 3.37–3.64 GHz, while Port 3 covers 280 MHz, from 3.35–3.63 GHz. The isolation between the three ports exceeds 11 dB within the 3.4–3.6 GHz frequency range.

The MIMO antenna system's diversity performance is effectively assessed by the envelope correlation coefficient (ECC). As shown in Fig. 2(b), the simulated ECCs for the tri-port antenna are below 0.14, indicating excellent diversity. Additionally, Fig. 2(b) reveals that the simulated total efficiency of the tri-port antenna ranges from 59.6% to 88.6%.

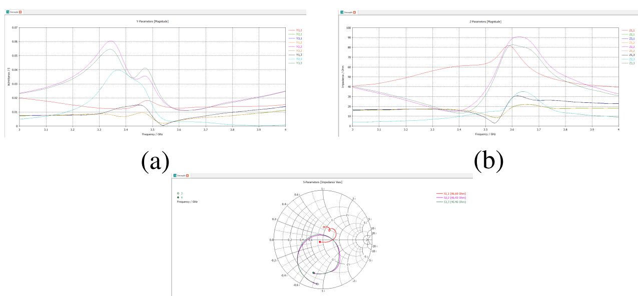


(a) (b)

Fig. 2: Simulated performance of the proposed tri-port antenna. (a) S parameters. (b) Total efficiency

B. S, Y and Z Parameters

The Y and Z parameters in CST are both complex values that describe the relationship between voltage and current at a given port in a simulation model - the Y parameter represents the admittance or conductance, while the Z parameter represents the impedance. These parameters are crucial in the analysis and characterization of various electronic, microwave, and electromagnetic systems, as they provide information about the behavior and performance of the simulated structures.



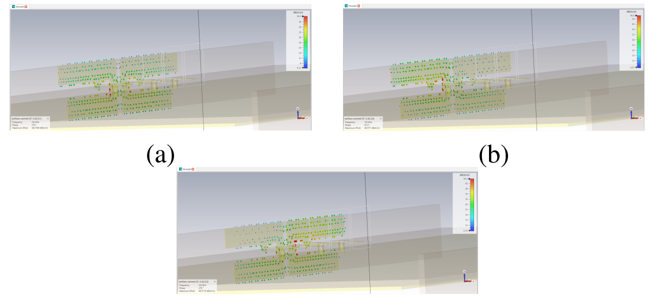
(a) (b)

(c)

Fig. 3: Impedance Parameters. (a) Y parameters (b) Z parameters (c) S parameters(Impedance View)

C. Simulated Vector Surface Current

CST simulations provide a visualization of the vector surface current, which represents the direction and magnitude of current flow on the surface of a simulated electromagnetic structure. Analyzing the simulated vector surface current allows users to identify regions of high or low current density, which is crucial for understanding the underlying electromagnetic phenomena and optimizing the design of devices such as antennas, microwave circuits, and components for electromagnetic compatibility (EMC) studies. The vector surface current analysis is a powerful feature of CST, as it enables a comprehensive evaluation of the electromagnetic behavior of the simulated structure.



(a) (b)

(c)

Fig. 4: Surface Current (a) Port 1 (b) Port 2 (c) Port 3

VII. PROPOSED 12 × 12 MIMO ANTENNA SYSTEM

A. Geometry and Fabrication of the 12 × 12 MIMO Antenna System

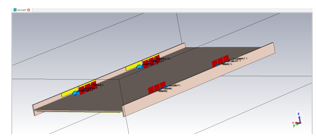
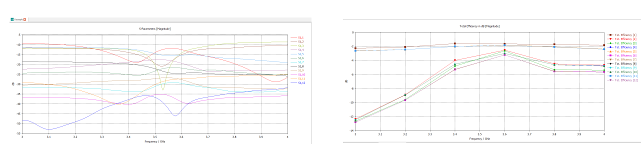


Fig. 5: Details of the proposed 12 × 12 MIMO antenna system.

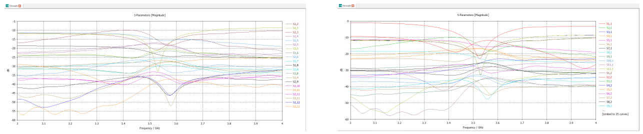
Fig. 5 shows a schematic of the proposed 12 × 12 MIMO antenna system. A metal ground (150 × 70 mm 2) is etched on the back face of the horizontal FR4 substrate (r = 4.4, tan = 0.02, and size: 150 × 75 × 0.8 mm 3). The vertical FR4 substrate (150 × 7 × 0.8 mm 3) represents the frame of the smartphone. Four tri-port antennas are symmetrically distributed on the inner surface of the frame, and the distance between the two antennas on the same side is 30 mm to obtain acceptable isolation. The ground clearance is 2.5 mm away from the edge of the frame of the smartphone. Fig. 9 shows the photograph of the fabricated 12 × 12 MIMO antenna system. Twelve 50 semirigid cables are connected to 12 ports for testing.

B. Simulated Results of the 12 × 12 MIMO Antenna System



(a) (b)

Fig. 6: Simulated and measured (a) reflection coefficients and (b) total efficiency of the proposed 12 × 12 MIMO antenna system.



(a) (b)

Fig. 7: Isolation of the proposed 12 × 12 MIMO antenna system. (a) Simulated. (b) Measured.

The simulated and measured reflection coefficients of the proposed 12 × 12 MIMO antenna system are shown in Fig. 6(a). Since the 12 × 12 MIMO antenna system is composed of four tri-port antennas with mirror symmetry, the results of Ports 4–12 are not listed. The simulated and measured reflection coefficients of the three ports in the 3.4–3.6 GHz band are all less than 6 dB. The slight deviation of frequency between simulation and measurement is caused by manufacturing errors and test cables. The measurement result of Port 1 differed marginally from the simulation result because of manual errors. The simulated and measured total efficiencies are shown in Fig. 6(b). The simulated and measured total efficiencies of Port 1 are 76.9%–84.8% and 65.0%–71.0%, respectively; the simulated and measured total efficiencies of Port 2 are 60.4%–72.1% and 51%–66%, respectively; the simulated and measured total efficiencies of Port 3 are 57.0%–74.0% and 53.0%–67.0%, respectively. The measured total efficiency is lower than the simulated total efficiency probably because of the loss of the lumped element and coaxial line. Fig. 11 shows the simulated and measured transmission coefficients of the proposed 12 × 12 MIMO antenna system. Fig. 7(a) and (b) shows that the isolation among 12 ports is higher than 10 dB. Fig. 12 shows the simulated and measured radiation patterns of the three ports on phi = 0 ○ , phi = 90 ○ , and theta = 90 ○ at 3.5 GHz. The trends of the simulation and measurement curves are coincident, which verifies the feasibility of this structure. The measured antenna gains are listed in Table I. The antenna gain is 3.11–4.66 dBi when Port 1 is excited, 2.34–3.66 dBi when Port 2 is excited, and 2.36–3.41 dBi when Port 3 is excited.

VIII. Conclusion

The results indicate that the proposed self-decoupling tri-port antenna design offers significant improvements in isolation for 5G MIMO smartphone applications. The use of mode cancellation and active reflection coefficient techniques is an effective method for reducing coupling between the antenna ports, making it a promising solution for compact mobile device configurations.

Future work could involve further optimizing the design for different frequency bands and testing the antenna in real-world environments. Additionally, exploring the use of this design in other wireless applications, such as 5G or IoT systems, could broaden its applicability.

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