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A Four-element Antenna Design well Suited for Multiple-input Multiple-output Applications

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Abstract — ***A four-element antenna design well-suited for multiple-input multiple-output (MIMO) applications in 5G millimeter-wave (mmWave) communication systems is proposed. The proposed design features an inverted E-shaped radiator on an ultra-thin Rogers RT 5880 substrate, with each single antenna element measuring $12 \times 12\ \mathrm{mm}^2$. The four antenna elements are arranged in a polarization diversity configuration to form the MIMO system, with overall dimensions of $24 \times 24\ \mathrm{mm}^2$. Notably, the simulated results reveal an impressive impedance bandwidth of 13.3 GHz from 24.3 to 37.6 GHz and isolation higher than 34 dB between adjacent elements, all without requiring any decoupling network. These results highlight the potential for the proposed MIMO antenna system to play a significant role in 5G mmWave wireless mobile communications.***

Keywords: *5G; MIMO; ECC.*

INTRODUCTION

Recently, mobile networks have faced a significant surge in traffic, therefore the demand for high capacity and low latency in these networks has increased. Currently, extensive research is being carried to create 5G technologies that can fulfill the critical demands of efficient spectral usage, reduced latency, enhanced energy efficiency, and the ability to connect numerous nodes. The shortage of available spectrum results in a bottleneck in wireless networks due to the growing demand for high data rates. The ever-increasing technology has significantly impacted human life, especially with the widespread use of internet services in daily routines. The anticipated impact of 5G is expected to be significant across various fields, leading to improvements in the lifestyle of most of the population through diverse applications.

5G wireless technology provides high-speed internet with several advantages over its predecessor, 4G. Data rate of around 20 Gbps is achieved and offers remote control with low latency over a reliable network. In addition, it supports wireless worldwide web (WWWW) of 4G while utilizing the Internet Protocol Version 6 (IPv6) protocol. With low latency, high throughput, high reliability, energy efficiency, and extremely high data rates, 5G offers users convenient access to high-speed internet. While 5G can operate on multiple frequency bands, including low, mid, and high bands, the 6 GHz and millimeter wave 5G bands are becoming more common in industry and academia. The mid-frequency band at 6 GHz strikes a balance between capacity and coverage, making it suitable for most commonly used applications by end-users. It offers high bandwidth and improved network performance, facilitating the use of continuous channels that reduce the need for network densification in the absence of mid-band spectrum. This feature enables 5G connectivity to be provided to anyone, anywhere and anytime. On the other hand, the mmWave (millimeter wave) frequency band offers significantly higher bandwidth and faster data transfer speeds, making it suitable for applications that demand ultra-high-speed connectivity. However, contemporary research studies and various service providers who have deployed 5G mmWave have found that this band is less frequently used due to its limited coverage area and high susceptibility to signal attenuation caused by obstacles such as buildings and trees. Despite the challenges associated with the mmWave frequency band, it is still considered a crucial component of the next-generation mobile networks due to its ability to offer ultra-wide bandwidths and high-speed wireless communications. Therefore, researchers and industry experts continue to work on addressing the technical challenges associated with mmWave to ensure its effective integration and use in 5G networks.

According to Ericsson's mobility report, mobile traffic is projected to constitute 69% of the total traffic by 2028, with a decline in 4G traffic. Additionally, the report estimates that the monthly data usage per smartphone in India will rise from 19 GB/month in 2023 to 46 GB by the end of 2028 [1]. In order to facilitate this expansion, 5G networks incorporating multiple input multiple output (MIMO) technology will likely play a crucial role. Furthermore, MIMO technology is expected to provide wider bandwidth compared to current mobile networks like 4G/LTE.

SINGLE ELEMENT ANTENNA DESIGN

The geometry of the proposed single antenna element is shown in Fig.1. The front side of the antenna consists of an inverted E-shaped patch radiator having its end strips inclined at an angle of 15° within the patch. The back side of the antenna features a square notch in the partial ground plane to improve impedance matching. The partial ground plane is designed to provide a sufficient return path while minimizing reflections and standing waves, resulting in a wideband response in the frequency range of interest. The antenna has been designed on Rogers $RT5880$ (lossy) substrate with relative permittivity ($\varepsilon_r = 2.2$) and the loss tangent ($tan\delta = 0.0009$). The dimensions of the substrate are $10mm \times 12mm \times 0.254\,mm$), while the size of the ground plane is $5\,mm \times 10\,mm$. The dimensions of the notch are taken to be $1.5\,mm \times 1.5\,mm$ as illustrated in the Fig. 1.

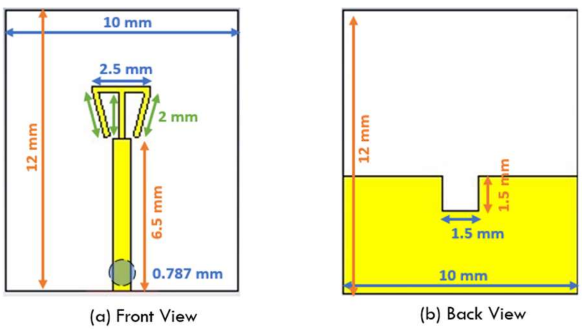

Fig. 1: Single element antenna design.

The patch is fed by a 50 Ω microstrip line whose length and width equal $6.5\,mm$ and $0.787\,mm$, respectively. Fig. 1 displays the remaining design parameters along with their corresponding values. The simulation of the proposed antenna element has been carried out in CST Microwave Studio software.

Simulated Results

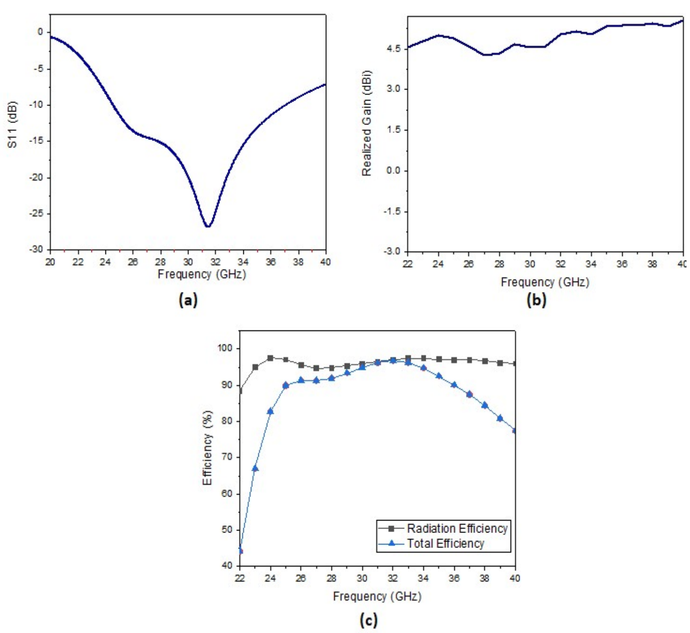

Fig. 2: Single Antenna Element - Results (a) S - Parameters (b) Realized Gain (c) Efficiency.

The simulation results, which include S-parameters (S_{11}), realized gain, and efficiency are shown in the Fig. 2. The antenna operates well in the frequency band of $23 - 37$ GHz ($|S_{11}| < -10\,dB$), providing an impedance bandwidth of $12.5\,GHz$. The desired operating bandwidth shows a radiation efficiency of over 94.5 %, while the total efficiency ranges from 87 % to 97% . The antenna's operating bandwidth enables a gain range between 2.8 and 3.7 dBi.

COMPACT MIMO ANTENNA DESIGN

Fig. 3 shows the MIMO configuration, which was designed by the transformation of the single antenna element into compact 4-element MIMO. The dimensions of the substrate are $24\,mm\ x\ 24\,mm\ x\ 0.54\,mm$. On the front side of the MIMO antenna, individual antenna elements are positioned at a 90-degree angle to one another. The back side has separate partial ground planes with square notches.

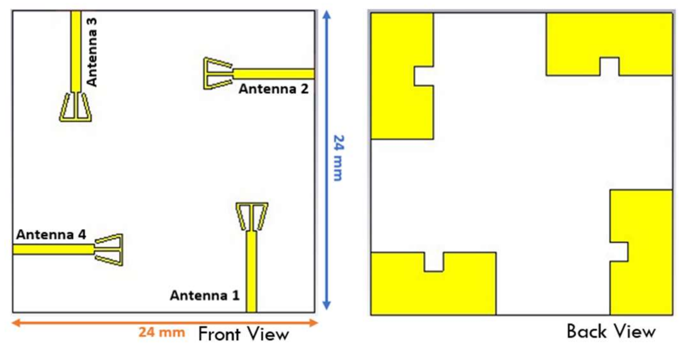

Fig. 3: MIMO Antenna Design

Simulated Results and Discussion

i. S – Parameters

Fig. 4 displays the simulated S-parameters that include the reflection coefficient (S_{mm}) and isolation (S_{mn}) between the antenna elements. It can be seen from the simulated reflection coefficients that the proposed design has an impedance bandwidth of 13.3 GHz from 24.3 to 37.6 GHz. The isolation between adjacent antenna elements is greater than $30\,dB$ across the entire operating bandwidth, which is desirable for a MIMO configuration.

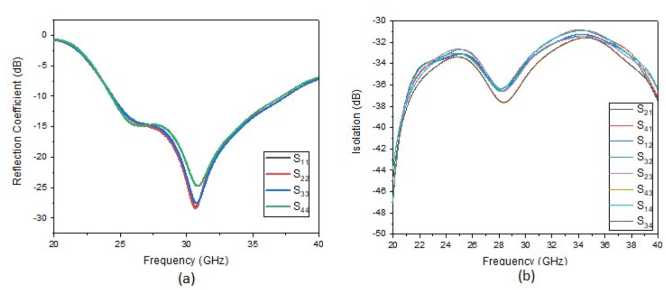

Fig. 4: S-Parameters of the proposed MIMO Antenna Design (a) Reflection Coefficient (S_{mm}), (b) Isolation (S_{mn}).

ii. Antenna Efficiency, Realized Gain and VSWR

Fig. 5 illustrates the simulated antenna efficiencies for all antenna elements and the realized gain of the proposed MIMO antenna design. The antenna elements' total efficiency fluctuates between 85–96.5% across the entire operating frequency band. Moreover, the simulated peak gain of the MIMO antenna is around $5.36\ dBi$. The proposed design has a VSWR (voltage standing wave ratio) of less than 2, as shown in the figure, indicating improved impedance matching of antenna elements.

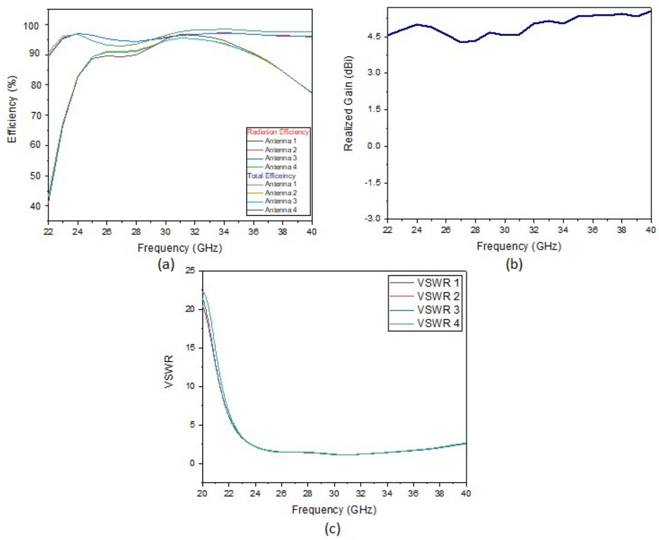

Fig. 5: (a) Radiation and Total Efficiency (b) Realized Gain, (c) VSWR of the proposed MIMO antenna design.

Radiation Patterns

The simulated three-dimensional radiation patterns for all the MIMO elements, extracted at 28 GHz, are displayed in the Fig. 6. It is evident from the radiation patterns that the proposed MIMO antenna exhibits pattern diversity in both planes along with polarization diversity.

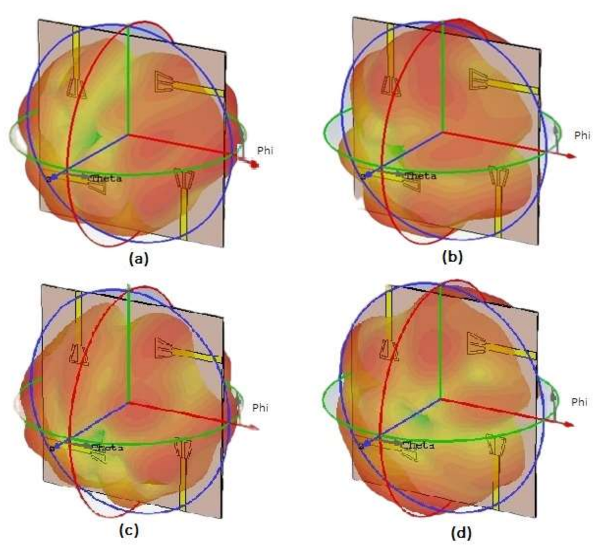

Fig. 6: Radiation Pattern (3D) of proposed MIMO antenna design at 28 GHz for (a) Antenna 1, (b) Antenna 2, (c) Antenna 3, (d) Antenna 4

MIMO Parameters

The MIMO parameters comprise various factors such as the envelope correlation coefficient (ECC) and diversity gain (DG). ECC measures the degree of isolation between antennas, and in order for MIMO applications to function efficiently, it is necessary to minimize the correlation between receiving signals. ECC can be determined by analysing the far-field radiation characteristics of the MIMO antenna. For multiple antenna systems, the ECC should ideally be ≤ 0.5 to ensure high isolation [2]. In the presented MIMO antenna system, the ECC value is found to be less than 0.001 within the desired operating band, which is considerably low, ensuring independent channel operation for the proposed MIMO system. Additionally, the diversity gain for the band of interest is approximately 10, which is considered acceptable for MIMO applications.

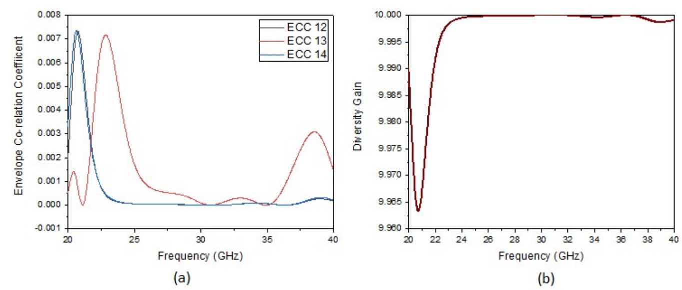

Fig. 7: Parameters of the proposed MIMO (a) ECC, (b) Diversity Gain.

CONCLUSION

The focus of this study was to propose a four-element MIMO antenna design for 5G mmWave communication systems. The proposed design achieved a -10dB impedance bandwidth of 13.3 GHz within the operating frequency range of 24.3 to 37.6 GHz. The ECC of the proposed design was found to be less than 0.001, and the diversity gain was around 10, which are both acceptable values. The isolation between adjacent and diagonal elements was greater than 30 dB and 20 dB respectively. The design also achieved a peak gain of 5.36 dBi and total efficiencies ranging from 85% to 95%. Based on these results, the proposed MIMO antenna system is a viable option for future mmWave wireless systems.

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