Optimizing Geometric Shapes for a Compact Planar Multiband MIMO Antenna in Vehicular Communications

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Abstract

The purpose of this study is to investigate and comprehend the performance analysis of a compact planar multiband multiple-input-multiple-output (MIMO) antenna, accomplished as a part of the ECE 533: Advanced Antenna Design course at Washington State University, Vancouver during the Fall 2022 semester. This study has introduced two symmetrical radiating elements joined by a neutralizing line to nullify the reactive coupling that makes up the MIMO antenna’s basic structure. The basic MIMO antenna occupies an overall three dimensions of 60x80x0.8mm$^3$ volume on a FR4 substrate with relative permittivity $e_r=4.40$ and loss tangent of $\tan\delta=0.02$. Coplanar waveguide (CPW) transmission lines of 50 have been used to feed the MIMO antenna. Furthermore, the base plane of the basic MIMO antenna has four slits and two compact rectangles of 2x12mm$^2$ cut into it to compensate the mutual coupling. The slit width, neutralizing line, substrate material, and its thickness have all been tuned in the proposed techniques to analyze different antenna parameters. The operating frequency band has been set to 500MHz-3500MHz for all the four cases. By employing simulation results obtained from the ANSYS HFSS environment, the performance of the fundamental MIMO antenna is evaluated and assessed against the optimized models. The optimized versions of the conventional MIMO antenna design have been thoroughly discussed in separate case studies. From our software simulation analysis, we find that optimized geometric shapes of the compact planar MIMO antenna show significant improvement in the isolation parameter of $|S_{21}|$, from $\leq 14.9$ dB to $\leq 18.44$ dB, $\leq 20$ dB and up to $\leq 27.68$ dB for ease of understanding, no servicing frequencies have been predetermined.
Optimizing Geometric Shapes for a Compact Planar Multiband MIMO Antenna in Vehicular Communications

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Abstract—The purpose of this report is to investigate and comprehend the performance analysis of a compact planar multiband multiple-input-multiple-output (MIMO) antenna, accomplished as a part of the ECE 533: Advanced Antenna Design course at Washington State University, Vancouver during the Fall 2022 semester. This study has introduced two symmetrical radiating elements joined by a neutralizing line to nullify the reactive coupling that makes up the MIMO antenna’s basic structure. The basic MIMO antenna occupies an overall three dimensions of 60x80x0.8mm³ volume on a FR4 substrate with relative permittivity εᵣ = 4.40 and loss tangent of tanδ=0.02.

Coplanar waveguide (CPW) transmission lines of 50Ω have been used to feed the MIMO antenna. Furthermore, the base plane of the basic MIMO antenna has four slits and two compact rectangles of 2x12mm² cut into it to compensate the mutual coupling. The slit width, neutralizing line, substrate material, and its thickness have all been tuned in the proposed techniques to analyze different antenna parameters. The operating frequency band has been set to 500MHz-3500MHz for all the four cases. By employing simulation results obtained from the ANSYS HFSS environment, the performance of the fundamental MIMO antenna is evaluated and assessed against the updated models. Each revamped version of the conventional MIMO antenna design has been thoroughly discussed in separate case studies. While the comprehensive case study findings show significant improvement in the isolation parameter of |S21|, from <-14.9 dB to <-18.44 dB, <-20 dB and up to <-27.68 dB for ease of understanding, no servicing frequencies have been predetermined.

Keywords—2-element MIMO antenna, neutralizing line, monopole, coplanar waveguide (CPW) transmission lines, double a-slots, four slits, long term evolution (LTE)

I. INTRODUCTION

With the onset of the growing demands in wireless technologies and wearable devices tracking after the late 2015s, scientific studies on wireless channels in the 5G bands have also seen equal substantial expansion. In recent times, utilizing multiple-input multiple-output (MIMO) devices and wider frequency bandwidths in wireless communication technologies have resulted in a significant transition in data transmission rates too. The adoption of a multiband MIMO antenna improves the overall antenna performance in terms of link capacity, spectral efficiency, and data rate even though designing a MIMO antenna is quite challenging and the single radiation element within a single-input-single-output (SISO) system shows optimum efficiency [1]. The contemporary and recent research trends that have analyzed MIMO antenna are centered on Global Positioning Systems (GPS), Global Systems for Mobile Communication (GSM), Long Term Evolution (LTE), Wireless interoperability for Microwave Access (WiMAX), Wireless Local Area Network (WLAN) and Ultra-Wide Band (UWB) applications [2-8].

In [2], authors have reported a 2x2 MIMO antenna based on 4 rectangular nested loops that provides five narrow band applications for GSM, WiMAX and WLAN applications. Similar research [3] has been done that have introduced a 4-element 2x2 planar MIMO antenna which is developed from a modified elliptical monopole with parasitic elements added on the feed-line for GPS applications. Another study [4], have covered MIMO antenna applications in the sub-6 GHz range, proposing a 2-element multi-wide-band MIMO antenna system with high isolation in the bands of 1.2 GHz–3 GHz, 4.5 GHz – 5.7 GHz and 7.2 GHz – 7.9 GHz. In order to explore the MIMO antenna performance for UWB applications, another study [5] have reported a 4-port UWB-MIMO antenna by employing layout with symmetrical shapes, Defected Ground Structure (DGS), 4 staircase-structured decoupling, and orthogonal structure. However, to understand the MIMO antenna performance, it’s also vital to grasp the antenna efficiency factors, e.g., the antenna radiation pattern. To analyze the radiation pattern in a MIMO antenna array, authors have reported a novel configuration of an L-band cascade comb dipole antenna with cross-band mutual coupling dedicated for 5G MIMO base station developments [6]. Furthermore, efficiency of a multiband MIMO antenna also depends on the orientation of the radiation element. Finding the sweet spot when constructing a multiband is challenging yet crucial. Addressing the orientation challenge of the multiband MIMO antenna, authors have reported a novel orthogonal multiband diversity antenna with a common ground plane that has a pair of slits and strips which radiates within a wider impedance bandwidth of S₁₁ and S₂₂ <- 10 dB [7]. Another crucial aspect of developing multiband MIMO antennas is expanding the bandwidth. In order to increase bandwidth, a novel design strategy [8] to excite multiple useful modes under
an inverted-L antenna (ILA) is described. This ILA has successfully acquired the targeted upper 5G band (3.3-4.2 GHz) as well as the lower 4G band (1.71-2.69 GHz). All these recent literatures establish that MIMO technology is a compelling candidate for various applications.

In [9], authors have proposed a robust and compact small MIMO antenna for multiband indoor applications which is the reference antenna for my report. The versatile feature of different bands is obtained in this design structure by utilizing the folded monopole and the beveled rectangular metal patch as the antenna element. By employing neutralizing line and creating four slits in the back of the ground plane, it was possible to produce high isolation $|S_{21}| < -30$ dB in the working bands. Firstly, in this report, I have tried to describe the replication of the reference multiband MIMO antenna. Next, I have made significant changes in the reference antenna design in terms of slit width, neutralizing line, substrate material and its thickness to understand its performance in different conditions. The reference antenna design including all the other designs have been elaborately explained in the later sections via four case studies.

With a special focus in the mathematical modeling of the antenna design in Section II; the following sections of this report are organized as: the antenna design process for all the four cases and the layout have been discussed in Section III, the simulation results and in-depth analysis are described in Section IV, a comparative summary of the four case studies in tabulated form is presented in Section V. Finally, the work is concluded in Section VI.

II. MATHEMATICAL MODELLING OF PROPOSED ANTENNA

The reference multiband MIMO antenna is incorporated by a beveled rectangular metal patch. To calculate the dimensions of the rectangular metal patch, several mathematical equations have been incorporated [10].

\[
L = \frac{(2N+1) \lambda}{\sqrt{\varepsilon_{\text{eff}}} \times \frac{\lambda}{2} - \Delta L} \quad (1)
\]

\[
W = \frac{(2N+1) \lambda}{\sqrt{\varepsilon_{\text{eff}}} \times \frac{\lambda}{2}} \quad (2)
\]

Equations (1-2) have been used in order to calculate the length and width of the rectangular patch, where $N = \text{integer}$, $\varepsilon_r$ is the relative dielectric constant of the projected substrate and $\varepsilon_{\text{eff}}$ is the effective dielectric constant, which is computed using Eq. (3).

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[1 + 12 \left(\frac{h}{W}\right)^{1/2}\right] \quad (3)
\]

In the feeding line, the effect of fringing has been taken into account, which is further represented in Eq. (4).

\[
\Delta L = 0.412h \left(\varepsilon_{\text{eff}} + 0.3 \left(\frac{W}{h} + 0.264\right)\right) - 0.258 \left(\frac{W}{h} + 0.8\right) \quad (4)
\]

Lastly, for the feeding line, the width and length can be calculated via Eq. 5 and 6 respectively.

\[
W_{\text{feed}} = \frac{1}{0.8} \left[9.5138 \times h - t\right] \quad (5)
\]

\[
L_{\text{feed}} = \left(2M + 1\right) \times \frac{\lambda}{2} \quad (6)
\]

III. DESIGN PROCEDURE AND LAYOUT STRUCTURE

The main design process of the four design models has a common structure in the fundamental building block. The MIMO antenna consists of two symmetric radiating elements using the folded monopole and the beveled rectangular metal patch. In the following subsections, all the design models are briefly described.
A. **Design Model I:** This model represents the *reference multiband MIMO antenna configuration.* Apart from the two common symmetric radiating elements, the reference multiband MIMO antenna has four slits in the ground place. The slit width is 1.5mm. Additionally, it has two rectangular vacuums in the ground plane of 2\(\times\)12mm\(^2\) dimension. The substrate is composed of a 60x80x0.8mm\(^3\) dimension made of FR4_epoxy. The ground plane’s dimension is 60x56x0.8mm\(^3\). Therefore, the reference design has three parasitic elements. Their dimensions are 19.2x56mm\(^2\), 14.4x56 mm\(^2\) and 19.2x56mm\(^2\) respectively.

B. **Design Model II:** This model is quite similar to that of the previous model. Except all the features, this model has no neutralizing line connecting the two antenna radiation elements and no external rectangular vacuums in the ground plane. Apart from that, the substrate width has been set to 1.3mm.

C. **Design Model III:** This model has a different substrate material which is Arlon AR100 with a relative permittivity of \(\varepsilon_r=4.40\) and loss tangent of \(\tan\delta=0.003\). It has also a substrate dimensions of 60x80x10mm\(^3\). The thickness of the substrate has been increased from 0.8mm to 10mm with a difference of 9.2mm. Similar to that of the previous design, it has the same parameter for the slit width and there is no neutralize line introduced. Except this, all the other parameters are quite similar according to the Design Model II.

D. **Design Model IV:** Likewise, the Design Model III, this model has similar substrate material and relative permittivity. The substrate dimensions are also similar to that of the previous design. However, the slit width has been set to 1.5mm. The interesting design aspect of this model is that, it has a similar neutralizing line connecting the two radiation element. However, two additional double u-slot has been introduced to observe the performance of the multiband MIMO antenna. It has no rectangular vacuums in the ground plane.

In the basic reference, the concept of meandering has been introduced. It’s a conventional technique for antenna miniaturization. This technique boosts the current to flow through a longer path at the cost of an increased dimensions in the patch. Meandered lines are quite common for basic PIFA antenna applications.

![Fig. 2. Geometries of the Design Model II: Revamped multiband MIMO antenna showing the Top View and the Rear View of the Ground Panel.](image)

![Fig. 3. Geometries of the Design Model IV: Revamped multiband MIMO antenna showing the Top View.](image)

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<tr>
<th>TABLE I. COMPARISON OF THE LAYOUT OF FOUR DESIGN MODELS</th>
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IV. **Simulation Results & Discussions**

A. **Design Model I:** The simulation results of the Design Model I are shown in graphical forms below.

![Graph a](image)

![Graph b](image)

The loss function of \(|S_{11}|\) is \(<-10\) dB for 1GHz, 2.1GHz, 2.3GHz and 2.6GHz. While the \(|S_{21}|\) \(<-14.99\) dB for 6
resonant frequencies. The isolation is deteriorated seriously in 2GHz frequency.

On the X-Z plane, the antenna radiation pattern shows bidirectional pattern like a ‘bean-shape’. While, in the Y-Z plane, the radiation pattern looks like an 8-shaped bidirectional pattern. The gain for this reference antenna is averaged to -2dB up to -0.03dB. Low gain antenna shows pattern in the omnidirectional way.

B. Design Model II: The simulation results in the Design Model II is quite different as I have eliminated the neutralizing line and also fixed the slit width to 1.3mm. Also, the differences are caused by removing the rectangular vacuums from the ground plane. The simulation results of the Design Model II are shown in graphical forms below.

The VSWR of this design model is below 2 for each resonating frequencies over the band of 5MHz to 3500MHz.
Here, on the Y-Z plane, the antenna radiation pattern shows bidirectional pattern like a ‘bean-shape’ but with a mirror reflected version than that of the Design Model I. While, in the X-Z plane, the radiation pattern looks like a perfect 8-shaped bidirectional pattern. The gain for this reference antenna is averaged to -2.5dB up to -0.03dB. Similar omnidirectional characteristics can be seen in the Design Model II.

C. Design Model III: The simulation results in the Design Model III has been affected with the change of the substrate material and an increased dielectric constant of 10. Therefore, the results have taken into account of the increased substrate thickness and elimination of neutralizing lines and the rectangular vacuums in the ground plane. The simulation results of the Design Model II are shown in graphical forms below.

Here, on the Y-Z plane, the antenna radiation pattern shows bidirectional pattern like a ‘bean-shape’ but with a mirror reflected version than that of the Design Model I. While, in the X-Z plane, the radiation pattern looks like a perfect 8-shaped bidirectional pattern. The gain for this reference antenna is averaged to -2.5dB up to -0.03dB. Similar omnidirectional characteristics can be seen in the Design Model II.

The value of $|S_{11}|$ has been improved to $\leq -13.22$ dB for multiple frequency bands of 0.8GHz, 1.1GHz, 2.6GHz, 3.0GHz and 3.4GHz. On the contrary, the $|S_{21}| \leq 20.01$ dB is fixed to 3 resonant frequency bands of 2GHz, 2.7GHz and 3.2GHz respectively. There is a significant improvement in the $|S_{21}|$ parameter. The VSWR is below 2 for these resonant frequencies, except for 1.6GHz and 2.1GHz which are 2.12 and 2.95 indicating a lossy match between the two antenna.
The X-Z plane and Y-Z plane radiation patterns are quite identical ‘bean-shaped’ but mirror opposite. The average gain ranges from -3dB up to -2dB.

D. Design Model IV: The last design of the multiband mimo antenna has seen significant difference in the both of $|S_{11}|$ and $|S_{21}|$ parameter. One of the main reasons for this difference is the introduction of a dual u-slot in the neutralizing lines. Also, changes in the substrate material, elimination of the rectangular vacuums and also the increment in the slit width to 1.5mm are equally responsible for this effect. The simulation results of the Design Model IV are shown in graphical forms below.

The $|S_{11}|$ parameter has been deteriorated to $\leq 7.5$ dB for two frequency bands of 2.0GHz and 2.6GHz. But, the $|S_{21}|$ has been improved to $\leq 27.65$ dB for two frequency bands 1.4GHz and 2.8GHz.
Similar characteristics can be seen in the X-Z and Y-Z plane radiation pattern. Both the radiation patterns are quite identical in shape. The average gain is ranged -2dB up to -0.02dB.

V. COMPARATIVE ANALYSIS OF THE FOUR CASE STUDIES

A comparative analysis of the antenna features extracted from the simulation results has been tabulated in the Table II. Major comparison parameters are the peak directivity, peak gain, peak system gain, radiated power, radiation efficiency and total efficiency.

<table>
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<tr>
<th>TABLE II. COMPARISON OF THE SIMULATION RESULTS OF THE FOUR DESIGN MODELS</th>
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<td><strong>Antenna Features</strong></td>
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The maximum values of the peak directivity, peak gain, peak system gain, accepted power, radiation efficiency and total efficiency can be seen for the Design Model IV. With having a maximum efficiency, this design shows optimum result in terms of a great receiver. The second efficient multiband MIMO antenna was the Design Model II. It works as a great transmitter and a receiver. Although, the peak system gain of this antenna is quite low. Hence, the peak directivity for this design model is almost closer to that of the Design Model IV. The Design Model III was nowhere comparable to that of the reference multiband MIMO antenna. The Design Model III demonstrates low peak directivity, low peak gain, very low peak system gain, lowest radiated power and accepted power. The radiation efficiency and the total system efficiency for the Design Model III was also the poorest. After analyzing all the parameters of the four design cases, I can conclude that the best efficient design model among the four case studies was the Design Model IV with neutralizing lines and dual u-slots. The single u-slot is a technique to increase antenna bandwidth up to 10%-40%. This is basically the product of a double resonance effect with two different modes. While, the dual u-slot increases the antenna bandwidth up to 44% [11].

CONCLUSIONS

Investigating and understanding the performance analysis of a compact multiband MIMO antenna is the goal of this study. The performance of the basic MIMO antenna is tested and compared to the updated models using simulation results from the ANSYS HFSS environment. In independent case studies, each updated variation of the traditional MIMO antenna design has been thoroughly covered. No servicing frequencies have been set, despite the thorough case study findings showing a considerable improvement in the isolation parameter of $|S_{21}|$, from $<-14.9\text{ dB}$ to $<-18.44\text{ dB}$, $<-20\text{ dB}$ and up to $<-27.68\text{ dB}$.

REFERENCES


