A Compact CPW-Fed Ultra-Wideband Multi-Input-Multi-Output (MIMO) Antenna for Wireless Communication Networks

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ABSTRACT In this article, a compact coplanar waveguide (CPW) technique based ultra-wideband multiple-input-multiple-output (MIMO) antenna is proposed. The design is characterized by a broad impedance bandwidth starting from 3 GHz to 11 GHz. The overall size of the MIMO design is 60 × 60 mm² (1.24 × 1.24 λg @ 3 GHz) with a thickness of 1.6 mm. To make the design ultra-wideband, the proposed MIMO antenna design has four jug-shaped radiating elements. The design is printed on a FR-4 substrate (relative permittivity of εr = 4.4 and loss tangent of tanδ = 0.025). The polarization diversity phenomenon is realized by placing four antenna elements orthogonally. This arrangement increases the isolation among the MIMO antenna elements. The simulated results of the ultra-wideband MIMO antenna are verified by measured results. The proposed MIMO antenna has a measured diversity gain greater than 9.98, envelope correlation coefficient (ECC) less than 0.02, and good MIMO performance where the isolation is more than −20dB between the elements. The group delay, channel capacity loss (CCL), and the total active reflection coefficient (TARC) multiplexing efficiency and mean effective gain results are also analyzed. The group delay is found to be less than 1.2ns, CCL values calculated to be less than 0.4 bits/sec/Hz, while the TARC is below −10dB for the whole operating spectrum. The proposed design is a perfect candidate for ultra-wideband wireless communication systems and portable devices.

INDEX TERMS Multi-input-multi-output (MIMO), ultra-wideband, envelope correlation coefficient (ECC), channel capacity loss (CCL), group delay, total active reflection coefficient (TARC).

I. INTRODUCTION

Ultra-wideband (UWB) technology is a telecommunications technology that enables high-speed bandwidth connections with low energy consumption in wireless communication networks. The UWB was designed within commercial radar applications in mind at first. Nowadays, UWB technology has two primary applications: wireless personal area networks (PANs) and consumer electronics. After its initial success in the mid-2000s, UWB radio evolved into a technology within unique smart structures such as radar, wireless communications, and medical applications [1]. Up until 2001,
UWB was used in military applications only. The Federal Communications Commission (FCC) permitted the general public’s use of UWB capacity for commercial purposes after 2002. Furthermore, the FCC permitted the use of the UWB spectrum, which in the United States lies between 3.1 and 10.6 GHz [2]. Short-range transmission of UWB is due to its low spectral density. However, high gain antennas with relatively constant radiation characteristics are necessary for this function [3]. Planar antennas, particularly monopoles, are used in UWB equipment [4] due to their compact size, low profile, low cost and ultra-wide impedance bandwidth. Additionally, positioning these antennas near metallic surfaces may cause a considerable impedance mismatch. When transmitting restricted frequency signals, low-profile antennas have low gain and poor directivity [5].

In future wireless network systems, the ultra-wideband MIMO technology has received a lot of attention. Ultra-wideband MIMO technology considerably improves the efficiency of wireless communication systems due to its high data rate transmission, high precision range, low density of power spectra, and channel capacity [6]. In condensed broadcast contexts, the combination of MIMO with UWB technology expands the range of ultra-wideband systems without requiring any more band or multiple pathways fading. MIMO technologies need MIMO antennas with lower mutual coupling for portable devices with limited space. Many techniques to reduce the mutual coupling impact and inter-element distance in these antennas have therefore been developed. Compact size printed antennas are of major interest for UWB MIMO antenna designs because of their many qualities such as low cost, low profile, easy integration and manufacturing [7].

Several UWB MIMO-antenna designs have recently been reported in the literature. For UWB MIMO antennas in multi-functional portable devices, a high isolation is required. Designing a highly isolated compact size ultra-wideband MIMO antenna, on the other hand, is extremely difficult. To address this issue, many solutions have been proposed to increase the isolation between the elements of MIMO antennas. In [8], by etching the slits inside the ground plane and eliminating the defined band helps to achieve the high isolation. The isolation between the MIMO antenna elements can also be achieved by maintaining a spacing of $\lambda/2$ between the adjacent antenna elements. Unfortunately, this results in an increase in the antenna size. Mutual coupling between the components of a MIMO antenna is developed due to electromagnetic interactions between the closely placed antenna elements [9]. The UWB MIMO antenna’s densely packed components create strong mutual coupling, impedance mismatches, small radiations, and antenna correlation. Various solutions are proposed to reduce mutual coupling between the components of the MIMO antenna, in particular to reduce mutual coupling in a MIMO antenna system to closely situated parts. Some of the most frequently used techniques include parasitic elements (PE), electromagnetic band gap (EBG) structures, decoupling and matching networks, and neutralizing lines. In a study provided in [10], [11], it has been shown that employing UWB MIMO techniques, the channel capacity of the systems may be enhanced. L-shaped and Z-shaped strip MIMO antennas with distinct ground are presented in [12]. Such antennas have bandwidths of 3.4-3.6 GHz with dimensions of 150 $\times$ 75 mm$^2$. In [13] a 44 MIMO antenna with a bandwidth of 4.8-5 GHz for fifth-generation wireless applications is presented. A transparent glassy MIMO antenna with operating bandwidth between 4.5 and 5.3 GHz (800 MHz) is presented in [14]. The antenna is made with transparent glass substrate. The MIMO antenna has a gain of 2.3 dBi and isolation of $-15$ dB. This particular design has low efficiency of 55% and a large size. According to the manufacturer, the size of this antenna is 150 mm $\times$ 70 mm. Another broadband highly isolated MIMO antenna based on a FR-4 substrate is described in [15]. A mm-wave MIMO antenna for fifth generation (5G) applications is described in [16]. The bandwidth of this antenna is between 2 to 6 GHz (4 GHz), and its peak gain is 4.5 and 7.5 dBi. The antenna size is 110 $\times$ 114 mm$^2$, with a reported isolation of less than $-15$ dB. The envelope correlation coefficient of the design is not calculated. A characteristic mode theory-based MIMO antenna array for applications in 5G smartphones is presented in [14]. The size of the antenna is 145 $\times$ 75 $\times$ 1.6 mm$^3$, and it is used in the 3.4-3.6 GHz (200 MHz) frequency band. The gain of this MIMO antenna ranges from 1.6 to 4.5 dBi, and the isolation is more than $-15$ dB, with 0.16 ECC. The substrate is made of FR-4 and measured 1.6 mm in height. A MIMO antenna for 5G millimeter-wave applications and 4G wireless communication networks is reported in [18]. Rogers RT5880 is used as the substrate, and the antenna has a frequency range of 1.8 to 2.6 GHz, as well as 25 to 40 GHz. The antenna’s gain ranges from 5.8 dBi to 7.2 dBi. The isolation of the design is greater than $-17$ dB and the ECC of the design is found to be 0.001. Quad elements MIMO antennas with dual notched band for wireless applications, as well as a printed Yagi Uda array MIMO antenna with sub-5GHz frequency bands, are presented in [19], [20]. A UWB MIMO antenna, with a planar decoupling structure to decrease the mutual coupling, is described in [21]. The radiator is made up of circular patch pieces that are printed on FR-4. This proposed antenna has a size of $47 \times 93 \times 1.6$ mm$^3$. Despite the fact that the antenna has achieved the UWB spectrum from 3.1 to 10.6 GHz, the envelope correlation coefficient is more than 0.2. Another wideband MIMO antenna array based on electromagnetic bandgap (EBG) structures with good gain and low mutual coupling, is introduced in [22]. The antenna has a total size of $55 \times 79$ mm$^2$ and operates in the 5.42-5.95 GHz band. In this design ECC and efficiency are not calculated. In [23], a metamaterial-based MIMO antenna is presented for gain increase and mutual coupling reduction. The antenna is claimed to be $60 \times 60$ mm$^2$ in size, with a 2.35-2.45 GHz working bandwidth. The antenna design is large enough with narrow bandwidth. FR-4 is used as the substrate, with a typical thickness of 1.6 mm. A dual-notched flower-shaped H-slotted CPW-fed UWB MIMO antenna is demonstrated.
TABLE 1. Comparison of the stated UWB MIMO antennas within recent research.

| Ref. No.  | Area (mm$^2$) | Frequency Range (GHz) | Peak Gain (dBi) | Isolation (dB) | Peak Efficiency (%) | ECC | Substrate Material | Proposed Technique |
|-----------|---------------|-----------------------|-----------------|----------------|---------------------|-----|-------------------|-------------------|
| [12]      | 150x75 (3.5x2.1.76) | 3.4-3.6/4.5-8.5 | <5.1 | 16.5 | <82 | 0.01 | FR-4 | L-shaped strip |
| [13]      | 150x75 (3.5x2.1.76) | 3.4-3.66 | <1.6 | >20 | >47 | <0.3 | FR-4 | M-shaped strip |
| [14]      | 150x70/ (3.525x1.64) | 4.5-5.3 | 2.3 | 15 | >5 | Glass ITO conductive films |
| [15]      | 110x114/ (1.52x1.28) | 2-6 | 4.8-7.5 | <15 | >75 | — | FR-4 Stepped Ground in Each Element |
| [16]      | 145x75/ (3.4x1.76) | 3.4-3.6 | 1.6-4.5 | >15 | 42-73 | <0.16 | FR-4 | L-shaped slots inside ground plane |
| [17]      | 158x77.8/ (1.4x0.692) | 1.8-2.6 & 25-40 | 5.8-7.2 | >17 | >75 | <0.001 | RT/duroid-5880 | Tapered slot antenna |
| [18]      | 100x100/ (2.45x2.45) | 3.55, 5.5 | <2 | >20 | >60 | <0.1 | FR-4 | Notches technique |
| [19]      | 154 x 154/ (5.32x5.32) | 5-5.3 | 5 | >40 | — | — | FR-4 | Printed Yagi Uda |
| [20]      | 263 x 263/ (2.63x2.63) | 1.45-2.55 & 3.7-4.7 | 7 | 18 | 65 | <0.1589 | FR-4 | Circular Quasi Yagi |
| [21]      | 47 x 93 (1.1x1.99) | 3.1-10.6 | 3.5 | >31 | >75 | <0.2 | FR-4 | Decoupling Ground Stub |
| [22]      | 55 x 79 (2.06x2.97) | 5.42-5.95 | <5.3 | >30 | — | — | FR-4 | Neutralization Line |
| [23]      | 60 x 60 (0.98x0.98) | 2.35-2.45 | — | >18 | — | — | FR-4 | Metamaterial |
| [24]      | 80x80 (1.16x1.16) | 2.1-3.3, 4.1-8.2, 8.6-20 | 5.8 | >25 | 80 | 0.02 | FR-4 | CPW-technique |
| [25]      | 50x50 (0.7x0.7) | 2.4-9.1, 6.41-12 | 3.3 | >17 | — | <0.15 | FR-4 | Stubs inside ground |
| [26]      | 60x60 (1.24x1.24) | 3.4, 5.2-16.2 | 6 | >17.5 | — | <0.3 | FR-4 | Electromagnetic Bandgap |
| [27]      | 50x30 (0.8x0.55) | 2.5-14.5 | <3 | >20 | — | <0.04 | FR-4 | F-shaped parasitic elements inside ground |
| [28]      | 33x48 (0.59x0.78) | 2-13.7 | <4.3 | >20 | — | 0.15 | FR-4 | Slotted stub inside ground |
| [29]      | 40x40 (0.67x0.67) | 1.8-3.1 | <2.36 | >20 | — | <0.2 | FR-4 | G-shaped ground plane for each antenna element |
| [This work] | 60x60/ (1.24x1.24) | 3-11 | >3.4 | >20 | >68 | <0.02 | FR-4 | Self-decoupling due to orthogonal placement of elements |

In [24], with a total size of 80 × 80 mm$^2$ the MIMO antenna functions in the band ranges of 2.1-3.3 GHz, 4.1-8.2 GHz, and 8.6-20 GHz. In [25], another UWB MIMO antenna with WLAN band rejection characteristics is presented. The operational bandwidth is 2-4.91 GHz, 6.41-12 GHz, and the substrate used is FR-4 Duroid material with an overall dimension of 50 x 50 mm$^2$. A four-port element UWB MIMO antenna with band notching and low mutual coupling, based on EBG, is reported in [26]. With a total area of 60 x 60 mm$^2$ and an ECC of less than 0.3, the antenna achieved operational bandwidths of 3-4 GHz and 5.2-16.2 GHz. In Table 1, we provide a comparison of the antenna proposed in this paper, as described below, with the comparable antennas from earlier research. From Table 1, it is clear that our proposed design has much better features, compared to the state-of-the-art antennas from the literature. It is also superior with its compact size.

In the present paper, we propose a compact self-isolated CPW-fed ultra-wideband MIMO antenna with an impedance bandwidth of 8 GHz. This UWB MIMO antenna can be useful for ultra-wideband wireless communication networks. Because of the symmetry of the MIMO elements and the disconnected ground plane, the proposed antenna has several features that makes it strongly positioned compared to the antennas proposed in previous research. These features includes self-isolation, compact size, ultra-wideband
coverage, minimal ECC, enhanced gain and efficiency, and less mutual coupling. This can be helpful to provide a possibility to an additional decoupling technique. The proposed MIMO antenna has a 60mm $\times$ 60 mm $\times$ 1.6 mm overall size. The radiating elements are made of FR-4, which is a low-cost material.

II. UNIT CELL DESIGN FOR THE ULTRA-WIDEBAND (UWB) MIMO ANTENNA

A. ANTENNA DESIGN STEPS

The reflection coefficients for the different design steps of the proposed antenna are shown in Fig. 1. Initially, the basic design consists of a simple rectangular monopole radiator excited by a CPW feedline (see ANT I). In the next step, the rectangular radiator is truncated from its upper and lower sides in order to keep the return loss close to $-10$dB. In step three, a semi-circular shape is added in the ANT II in order to keep some portion of the UWB band below $-10$dB as seen in ANT III (Fig. 1). In step four, a C-shaped resonator is introduced to make the design jug shaped which keeps the whole UWB band below $-10$dB perfectly as shown in ANT IV.

The following is a description of the patch antenna’s design process:

The primary antenna design includes a 50$\Omega$-CPW feedline, a jug-shaped patch, and a ground plane. (ANT I) depicted in Fig. 1(a). The length and width of the patch are computed using equations (1) and (2) below [23].

$$W_P = \frac{\lambda_o}{2\sqrt{0.5(\varepsilon_r + 1)}}$$ \hspace{1cm} (1)

In (1), $\varepsilon_r$ and $\lambda_o$ are the substrate’s relative permittivity and free-space wavelength at the operating frequency. The optimal choice of $W_P$ results in an excellent impedance matching. The patch’s length can be calculated using

$$L_P = \frac{c_o}{2f_o\sqrt{\varepsilon_{eff}}} - 2\Delta L_p$$ \hspace{1cm} (2)

where $c_o$, $\Delta L_p$, and $\varepsilon_{eff}$ are the speed of light, change in the size of the patch owing to its fringing effect, and the effective dielectric constant, respectively. The effective relative permittivity can be calculated as follows

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + \frac{12h_s}{W_P}}}\right)$$ \hspace{1cm} (3)

where ‘$h_{sub}$’ is the height of the substrate. Finally, the change in the size of the patch, due to its fringing effects, can be calculated using following equation

$$\Delta L_p = 0.421h_s\left(\frac{\varepsilon_{eff} + 0.300}{\frac{W_P}{h_s} + 0.264}\right) - \left(\frac{\varepsilon_{eff} - 0.258}{\frac{W_P}{h_s} + 0.813}\right)$$ \hspace{1cm} (4)

The rectangular patch’s starting parameters are $L_P = 16$ mm and $W_P = 10$ mm, based on $\varepsilon_r = 4.3$ and $h_s = 1.6$mm in Eqs. (1)-(4). As illustrated in Fig. 2, the antenna only operates at 3.5 GHz and 9.98 GHz using a basic rectangular patch (ANT I). The antenna’s bandwidth is increased by ANT II, but it is still unable to achieve the UWB band. The antenna achieved the UWB band in the third step (ANT III), with the help of a semi-circular patch on top of the truncated patch. Thereafter, the antenna was able to cover a frequency range of 3 to 11 GHz. Fig. 2 shows a comparison of the $S_{11}$ for the design steps.

A schematic illustration of the orthogonal MIMO antenna’s unit cell is shown in Fig. 3. The suggested UWB antenna’s design consists of a jug-shaped patch with a handle on the right side of the radiator. Because of the antenna’s Jug-like shaped construction, it has a larger bandwidth. A coplanar waveguide (CPW) microstrip line feeds the patch. The antenna elements are made on an inexpensive FR-4 substrate with a loss tangent (tan $\delta$) of 0.025 and a relative permittivity ($\varepsilon_r$) of 4.4. This antenna design is simulated in the Computer simulation technology (CST-2018) Software. The antenna’s optimized design parameters are listed in Table 2.
B. PARAMETRIC ANALYSIS
The proposed design is finalized after performing several parametric studies on different variables as shown in Fig. 4. The first parametric analysis is performed on the length and width of the ground plane. When the length of the ground plane \( L_g \) is extended from 10mm to 12mm, the antenna’s impedance matching improves with acceptable bandwidth, and when the width of the ground plane \( W_g \) is altered from 9mm to 11mm, the antenna’s bandwidth increases from 5.5GHz to 8GHz. The next parametric study is performed on the width of the feedline \( W_f \), gradually increasing the width of the feedline improves the impedance bandwidth from 5.8 GHz to 8 GHz. A parametric study on the C-shaped radiator is also performed. By varying the lengths \( L_6 \) and \( L_3 \) the bandwidth of the antenna increases as can be seen in Fig. 4.

III. DESIGN OF THE QUAD PORT MIMO ANTENNA
The schematic diagram of the quad port ultra-wideband MIMO antenna is presented in Fig. 5. A low-cost FR-4 substrate is used to construct the proposed ultra-wideband MIMO antenna with relative permittivity of \( \varepsilon_r = 4.4 \), loss tangent of \( \tan \delta = 0.02 \), and thickness \( t_s = 1.6 \text{mm} \). All the four radiating elements of the MIMO antenna are placed in an orthogonal pattern which can be seen in Fig. 5. This orthogonal geometry of the unit cells helps to enhance the isolation between ports, thus improve the mutual coupling without using any specific decoupling technique. This helps to keep the design simple. Any additional decoupling technique will further enhance the port isolation. The complete spacing among the two successive radiating patches is \( S = 5.5 \text{ mm} \). The width and position of the feedline is adjusted after several optimizations. The overall size of the
quad port UWB MIMO antenna is $60 \times 60 \times 1.6 \text{ mm}^3$. Thus, the proposed design has a very compact electrical length at the operating bandwidth. Although the ground plane is disconnected, the design symmetry does not disturb the performance and system reliability. All the modeling and simulation of the stated MIMO antenna configuration are performed using CST MW Studio Suite software.

A. FINAL SIMULATED AND MEASURED S-PARAMETERS
To evaluate the scattering parameters of the proposed prototype, the two ports of the prototype are connected to the vector network analyzer (VNA), while the remaining ports are terminated with terminators. Since all the ports have identical responses, Fig. 6(a) shows a comparison of simulated and measured reflection coefficients ($S_{11}$) for a single port of the proposed antenna. Due to tolerances in the fabrication process and surrounding noises, there are some variations in the measured results. It is also noticed that the measured operating bandwidth is almost the same.

The simulated and measured mutual couplings among all ports are given in Fig. 6(b). It can be shown that the mutual coupling between any two elements is less than $-20\text{dB}$ across the entire operating band, indicating strong isolation between closely positioned parts. It can be shown that over the full working band, the mutual coupling between any two components is less than $-20\text{dB}$, showing high isolation between closely spaced portions. Furthermore, there is a slight degradation in the isolation between port 2, 3 and 4. The simulated mutual coupling between port 2, 3 and 4 is less than $-20\text{dB}$. However, the measured mutual coupling has attained more than $20\text{dB}$.

B. SURFACE CURRENT DENSITY
It is important to evaluate the surface current density of the UWB MIMO antennas. Surface current distribution of a MIMO antenna shows which part of the radiator has major role in resonating in the desired frequency band. This implies that current distribution has a substantial impact on the antenna’s ability to resonate at the required frequency ranges. The proposed antenna’s surface current distribution at 3.5 GHz is shown in Fig. 7. When port 1 is excited, a current flows from the transmission line (TL) to the CPW ground edges, and the maximum current is distributed across the Jug-shaped radiator, as shown in Fig. 7(a). The current flows also from TL towards the curves of the CPW ground, when port 2 is simulated and the current path is alongside the patch (x-axis), suggesting that the antenna is still linearly polarized, as shown in Fig. 7(b). The coupling analysis of the current density among the ports is presented in Fig. 7. It can be observed that the first antenna excited by port 1 is showing surface density while its coupling effect on the other antenna elements is negligible. Similarly, if the other antenna elements are excited then they will not have much coupling effect on the other antenna elements.

C. FARFIELD MEASUREMENT
In this section, the far field radiation pattern and peak gain of the UWB MIMO antennas are investigated in detail. The radiation patterns of the abovementioned port 1 are examined in the respective planes. Fig. 8 shows that evaluation setup is made in an anechoic chamber to measure the radiation pattern. Fig. 9 depicts the antenna’s simulated and observed 2D radiation pattern in free space along the E-plane and H-plane at 2.4GHz, 3.2GHz, 5.8GHz, and 10.3GHz, respectively. At the E-planes, and H-planes, the red-pink colored lines depict the observed radiation pattern, while the blue-green
colored lines represent the simulated radiation pattern. The antenna’s activity is described by the two-dimensional (2D) far-field. At 2.4 GHz and 4.5 GHz, the suggested antenna exhibits an elliptical pattern in the E-plane, whereas in the H-plane, the antenna exhibits an Omni-directional radiation pattern. At frequencies 5.8 GHz and 10.3 GHz, it acts as an omni-directional pattern in both planes. The antenna’s peak gains are 3.1 dBi at 2.4 GHz, 3.21 dBi at 3.2 GHz, 3.25 dBi at 5.8 GHz, and 3.2 dBi at 10.3 GHz, respectively. The radiation patterns of the port 1 in different frequency bands are illustrated in Fig. 9. Over the whole band, the antenna’s efficiency is greater than 68%, with an average peak gain of more than 3.4 dBi. The differences between the simulated and observed outcomes of peak gain and radiation efficiency, as illustrated in Fig. 10, are due to fabrication imperfections, soldering, and connection losses. In Table 3, we show a comparison of the proposed MIMO antenna to comparable antennas from previous research.

It is clear from the Table 3 that the proposed design is compact with good isolation. No additional decoupling technique is used. The proposed design has good isotropic gain, ECC, TARC and DG.

IV. MIMO ANTENNA PERFORMANCE
In this section, the MIMO antenna parameters, such as the envelope correlation coefficient, diversity gain, and the total active reflection coefficient (TARC), are discussed in more detail.

A. ENVELOPE CORRELATION COEFFICIENT
The envelope correlation coefficient is used to calculate the diversity gain between the MIMO antenna parts. Less ECC
and higher diversity gain are achieved by using a variety of radiation patterns and less mutual coupling in a single plane. The calculated isotropic ECC values for the whole operating band are shown in Fig. 11. The computed ECC values are less than 0.02 which are very good for the target wireless application. The ECC of the broadband MIMO antenna is calculated using the equation (5), as shown at the bottom of the page, from [23].

### B. DIVERSITY GAIN ANALYSIS

The amount of diversity gained is normally reported in decibels, although it can also be expressed as a power ratio. The simulated and measured diversity gain for the whole operating band is shown in Fig. 12. The diversity gain of the proposed design is calculated after determining the value of ECC. The equation (6) below gives the diversity gain [24], and it shows that the value of DG is dependent on the value of ECC. The simulated value of the diversity gain throughout the operating band is 10. There is a slight decrease in the measured value due to the fabrication tolerances.

\[
DG = 10 \sqrt{1 - |ECC|^2}
\]  

### C. TOTAL ACTIVE REFLECTION COEFFICIENT (TARC)

The TARC curves determine the effective operating bandwidth of a MIMO antenna system. The entire bandwidth is less than −10dB, as seen in Fig. 13. Equation (7) provides an expression for calculating TARC using obtained S-parameters for a two-port network [21], (7), as shown at the bottom of the next page, where \( \theta \) is the phase of the input feeding.

### V. MIMO DIVERSITY ANALYSIS

In this section, the diversity parameters, such as the channel capacity loss, group delay analysis, multiplexing efficiency, and the mean effective gain, are discussed in detail.
A. CHANNEL CAPACITY LOSS (CCL)

The suggested MIMO design’s channel capacity loss demonstrates the quality of information transmission over the operational spectrum. A low CCL value enables a high data transfer rate and is highly preferred. A CCL value of 0.5 bits/sec/Hz indicates excellent data transmission, whereas values more than 0.5 bits/sec/Hz imply lossy and poor data transfer. From Fig. 14 we see that CCL is less than 0.4 bits/sec/Hz in the whole working band. Thus, over most of the working range, the suggested design has an excellent CCL, demonstrating the proposed design’s efficient and less lossy data transmission. It can be calculated using the formulas given below [24]:

\[ C(\text{los}) = -\log_2 \det(a) \]  

where, ‘a’ is the correlation matrix.

\[ a = \begin{bmatrix} \sigma_{ii} & \sigma_{ij} \\ \sigma_{ji} & \sigma_{jj} \end{bmatrix} \]  

(9)

\[ \sigma_{ii} = 1 - (|S_{ii}|^2 - S_{ij}^2) \]  

(10)

\[ \sigma_{ij} = -(S_{ii} \ast S_{ij} - S_{ji} \ast S_{jj}) \]  

(11)

B. GROUP DELAY ANALYSIS

The temporal delay between the amplitude envelopes of the multiple sinusoidal components of a signal, as they pass through a device under test, is called a group delay. It is a function of frequency for each component, such that it will maintain the same form as the original, but the envelope will be delayed. Thus, the temporal lag between the envelope of the input burst and the envelope of the amplitude of the output burst is referred to as group delay. Group Delay of the proposed MIMO design is shown in Fig. 15. Group delay (1,1) signifies the delay from port 1 to port 1, Group delay (1,2) means the delay from port 1 to port 2, and Group delay (1,3) defines the delay from port 1 to port 3. Group delay (1,2) and Group delay (1,4) are practically same in the proposed MIMO antenna since the elements are identical and symmetrical. Certain delays are noticed below 5 GHz. The change in group delays is higher between 6.5 GHz and 7.5 GHz. However, they all get minimized before and beyond 6.5 GHz. The overall group delay values for the proposed MIMO antenna are less than 1.2 ns.

C. MEAN EFFECTIVE GAIN (MEG)

MEG is the capacity of an antenna to accept electromagnetic power in a multipath situation. The MEG for real time conditions for acceptable diversity performance should be

\[ \Gamma_a = \sqrt{\frac{|(S_{11} + S_{12}e^{j\theta})|^2 + |S_{22} + S_{21}e^{j\theta}|^2(|S_{33} + S_{31}e^{j\theta})|^2 + |S_{44} + S_{41}e^{j\theta})|^2}} \]  

(7)
−3 ≤ MEG (dB) < −12. We therefore validate the MEG values of all MIMO antennas in the proposed architecture as shown in Fig. 16. Equation (12) below is used to compute the mean effective gain [25]:

\[
MEG_i = 0.5\mu_{\text{rad}} = 0.5(1 - \sum_{j=1}^{K} |S_{ij}|)
\]

The number of antennas is ‘K’, the antenna under observation is ‘i’ and the radiation efficiency is ‘\(\mu_{\text{rad}}\)’.

D. MULTIPLEXING EFFICIENCY

Multiplexing efficiency specifies the power efficiency losses or degradation necessary while using the MIMO antenna under test. It is a vital metric of a MIMO antenna system that is examined not only in terms of overall antenna efficiency, but also in terms of correlation and efficiency difference. The MIMO antenna’s multiplexing efficiency (\(\eta_{\text{MUX}}\)) is computed as

\[
\eta_{\text{MUX}} = \sqrt{1 - |\rho_c|^2\eta_1\eta_2\eta_3}\eta_4
\]

and its functional form is shown in Fig. 17. In (13), \(\rho_c\) is a complex correlation between two side by side antennas, i.e. \(\text{ECC (\rho_{ee}) = } \rho_c^2\) and \(\eta_1, \eta_2\) are the total efficiencies of the two MIMO antenna elements.

VI. CONCLUSION

This paper presented a jug-shaped UWB MIMO antenna. The proposed design was simulated, fabricated and measured. The designed UWB MIMO antenna works over the whole UWB band (3–11 GHz) with overall good gain and radiation efficiency of 3.4 dBi and 68%, respectively. The simulated and measured reflection coefficients, as well as the radiation pattern are determined and found quite similar. The single element is then extended to four elements UWB MIMO design. The MIMO elements are arranged in an orthogonal pattern for self-decoupling. Couple of circular and rectangular slots have improved the impedance matching. The suggested UWB MIMO antenna has a diversity gain (DG) of more than 9.98, an ECC of less than 0.02, and strong MIMO performance with isolation of more than 20dB between adjacent and other components. The group delay, channel capacity loss, and total active reflection coefficient (TARC), multiplexing efficiency and the mean effective gain values have also been analyzed. The group delay is found to be less than 1.2ns, CCL values calculated to be less than 0.4 bits/sec/Hz, while the TARC is below −10dB for the whole operating spectrum. Based on the acquired results and compact size, the proposed design is an ideal candidate for the targeted wireless applications.

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