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# Dual-Band Flexible MIMO Antenna for Sub-6 GHz

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***Abstract*—Current 5G communications significantly utilise the Sub-6GHz frequency range to achieve both fast data rates and good coverage. Spatial diversity is achieved by implementing MIMO (Multiple-Input Multiple-Output) antennas which improve communication capacity and also minimise interference. With wireless technology evermore being utilised in "Internet of Things" (IoT) and wearable devices, it has become essential to develop adaptable antennas. Compared to conventional inflexible circuitry, adaptable antennas can mould themselves around non-planar objects e.g. body parts or collapsible casings and still maintain good functionality. Here we investigate the design of a dual-band adaptable MIMO antenna, capable of working at two different Sub-6GHz frequencies.**

***Index Terms*—MIMO, Flexible, Antenna, Dual-Band**

## I. Introduction

Wireless communication is now fundamental to many communication systems. Wireless communication can be found in a wide range of areas including mobile communications, wireless local area networks (WLAN), Internet of Things (IoT), satellite and vehicle communications etc. Constant innovation within wireless systems has led to the need for faster data transmission, improved network performance and better reliability. Furthermore, the radio spectrum should also be utilised effectively. The 5th generation (5G) wireless communication system fulfils this need by employing advanced communications technology and a variety of different frequency spectrum bands. Of particular importance is the Sub-6GHz band which provides good trade-off between range, transmission behaviour and data throughput. Typically the 3.5GHz vicinity is recognised for Sub-6GHz 5G wireless communication. In addition, the 5.8GHz spectrum is pertinent to both high speed and Wi-Fi wireless communications. Antennas for these wireless systems should therefore exhibit effective transmission performance and also be small in size. Appropriate impedance matching is also necessary.

Multiple-Input Multiple-output (MIMO) is currently extensively used in wireless systems to enhance data rate, and improve system reliability and space diversity. A MIMO system comprises of several transmit and/or receive antennas so that more than one transmission path can be utilised. In some cases the antennas are arranged closely together and may therefore become electromagnetically coupled, potentially leading to diminished MIMO performance. Good inter antenna isolation is therefore an important aspect of a MIMO antenna. Reflection and transmission coefficients ($S_{11}$ and $S_{21}$ respectively), Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) are often analysed to assess the performance of MIMO antennas.

Alongside size and MIMO operation, flexibility is now also considered to be a key feature in the design of antennas for wearable and IoT technologies and other conformal applications. Antennas may be shaped and manipulated to fit around curved and non-planar surfaces. Flexible materials such as polyimide allow the fabrication of light weight, flexible antennas. However, the act of bending can impact on both the physical shape and surrounding electromagnetic field of an antenna. This in turn can influence various aspects of antenna performance including resonance, impedance, gain and radiation. Consequently, it is key that an antenna can maintain good performance when being bent. Here a flexible material is employed in order to ensure that the antenna retains good electromagnetic properties through a variety of bending scenarios.

Dual band functionality can improve an antenna's utility by providing two separate frequency bands of operation for one antenna. Here, a dual band functionality is aimed for at 3.5 GHz and 5.8 GHz. A U-slot is added to the radiating element and is used to alter the surface current flow so that a second resonance can be produced. Alongside dual band and flexible properties, MIMO functionality can also be provided, to form a small multi-functional antenna for various wireless applications.

A dual band flexible MIMO array antenna has been designed and analysed for use in Sub-6 GHz wireless communications. This antenna is able to provide dual band, flexible and MIMO properties in a small form factor. Impedance match, return loss, element isolation, gain and radiation efficiency are analysed in addition to the antenna's radiation pattern. ECC and Diversity Gain are also analysed. Furthermore, the influence of bending on the antenna's performance is analysed to determine its appropriateness for flexible and conformal wireless applications.



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## II. METHODOLOGY

A dual-band 2x2 multiple-Input Multiple-output (MIMO) antenna with U-slot monopole patches was developed and optimized. This antenna was designed using Ansys High Frequency Structure simulator (HFSS) and has been designed to function at both 3.5 and 5.8GHz. The process used in designing this antenna includes: theoretical patch development, physical MIMO layout, simulation and optimisation, followed by analysis.

### *A. Theoretical Design of the U-Slot Antenna*

Starting dimensions for a rectangular radiating patch can be found using standard microstrip antenna theory. Patch width can be found using

$$W = \frac{c}{2f_r} + \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

where c is the velocity of light in free space, $f_r$ is the resonant frequency and r is the relative permittivity of the substrate.

The effective permittivity of the substrate takes into account the effect of fringing fields and is given by

$$\varepsilon\text{eff} = \frac{\varepsilon_r + 1}{2}\frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{W}/\right) - 1/2 \tag{2}$$

where h is the substrate height and W is the patch width.

The effective patch length is

$$L\text{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{\text{eff}}}} \tag{3}$$

The increase in the patch length caused by fringing fields is

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{\text{eff}} + 0.3)(W/h + 0.264)}{(\varepsilon\text{eff} - 0.258)(W/h + 0.8)} \tag{4}$$

Patch length is then calculated by;

$$L = L\text{eff} - 2\Delta L \tag{5}$$

This gives starting dimensions for the rectangular patch. A U-slot is then added to the patch to alter both the surface current and effective length of the patch. The U-slot provides a further current loop and allows the antenna to operate at two resonances. The U-slot dimensions are then fine-tuned through electromagnetic simulation so that the required resonant frequencies are achieved.

### *B. Geometrical Configuration of the Proposed MIMO Antenna*

This antenna is made up of a 2x2 array of identical U-slot radiators. It is mounted on a shared dielectric material which has an overall size of 80 x 75 x 0.508mm³ cube. A metal ground plane has a size of 80 x 75 x 0.035mm³ cube.

Each radiator is a rectangular patch with dimensions 25.7 x 20.2 x 0.035mm cube containing a U-slot. This is made up of a horizontal bar of area 6.7 x 0.53mm² square together with two vertical bars each of area 0.8 x 7.05mm² square. Individual radiators can be excited by one of four feeding mechanisms. These have dimensions 0.7 x 7.2 x 0.035mm cube.

| Parameter | Dimensions (mm) |
|---|---|
| Substrate | $80 \times 75 \times 0.508$ |
| Ground Plane | $80 \times 75 \times 0.035$ |
| Radiating Patch | $25.7 \times 20.2 \times 0.035$ |
| Feed Line | $0.7 \times 7.2 \times 0.035$ |
| U-slot Horizontal Section | $6.7 \times 0.53$ |
| U-slot Vertical Arms | $0.8 \times 7.05$ |
| Number of Radiating Elements | 4 |
| Number of Excitation Ports | 4 |
| Array Configuration | $2 \times 2$ |

The array is symmetrically laid out on the PCB. The position of each array element is given in HFSS. The 4-port allows analysis of both element excitation and coupling between array elements. Figure 1 shows a schematic representation of the design of the antenna. Table I summarises the antenna dimensions.

### *C. HFSS Modelling and Simulation*

This antenna is simulated using Ansys HFSS, which applies a FEM approach to analyse electromagnetic behaviour. The dielectric, ground plane and patch, U-slot and feed sections are designed to match the required physical dimensions. Correct material properties are allocated to each section.

Air is then introduced around the antenna and radiation boundary conditions are added, so that the antenna can radiate into free space. Four excitation ports are added to the feed sections allowing individual excitation of each of the radiating sections.

The simulation is run for a frequency range that includes the required frequency bands. An interpolation function is used to generate frequency dependent scattering parameters. Analysis of the electromagnetic behaviour is then undertaken to investigate the antenna's impedance match, mutual coupling, radiation pattern, gain and radiation efficiency.

### *D. Parametric Optimization*

Parameters defining the antenna are optimised by carrying out electromagnetic simulations and modifying the shape of the radiating patch, U slot and feeding system, as well as inter-element separation. Mainly, the U slot is analysed and modified with respect to arm length, arm width, lower section length and lower section width.

Reflection coefficient is analysed to assess the resonant behaviour and impedance match of the antenna. Parameters are then modified so that the antenna is resonant at the target frequencies of 3.5GHz and 5.8GHz. Inter-element spacing and layout is also analysed so that coupling can be reduced and element isolation increased.

The optimum geometry is then decided upon, taking into account both the simulated frequency behaviour and electromagnetic performance of the 4 element MIMO antenna.

### *E. Performance Evaluation*

The performance of the designed antenna is investigated using the scattering parameter and radiation information produced by HFSS. Reflection coefficient data is analysed to



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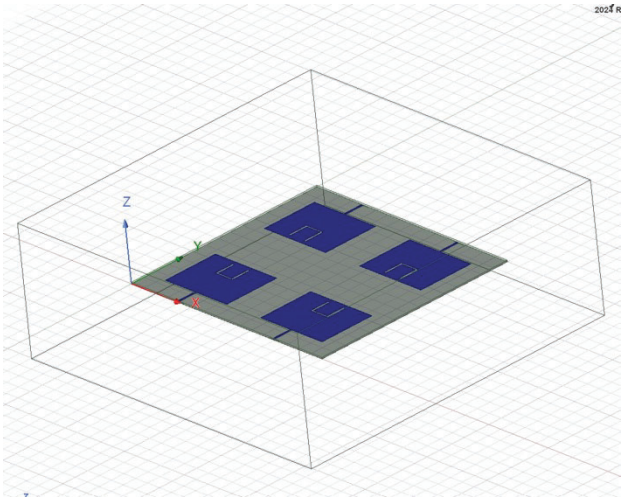



Fig. 1. Geometry of the proposed U-slot MIMO antenna.

assess both the matching and resonance properties of an antenna. Mutual coupling information is then investigated to understand an antenna's element isolation.

The reflection coefficient is expressed as

$$S_{ii}(\text{dB}) = 20\log_{10}|S_{ii}| \tag{6}$$

The mutual coupling between antenna elements is represented by

$$S_{ij}(\text{dB}) = 20\log_{10}|S_{ij}| \tag{7}$$

where $i$ and $j$ represent different excitation ports.

The isolation between antenna elements is calculated as

$$I_{ij} = -20\log_{10}|S_{ij}| \tag{8}$$

The Envelope Correlation Coefficient (ECC) is used to evaluate the correlation between antenna elements. For a two-port approximation based on scattering parameters, ECC is expressed as

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1-|S_{11}|^2-|S_{21}|^2)(1-|S_{22}|^2-|S_{12}|^2)} \tag{9}$$

The Diversity Gain (DG) is calculated using

$$DG = 10\sqrt{1-\rho_e^2} \tag{10}$$

The radiation efficiency is determined from the ratio of radiated power to accepted power and is expressed as

$$\eta_{\text{rad}} = \frac{P_{\text{radiated}}}{P_{\text{accepted}}} \times 100\% \tag{11}$$

The realised gain was analysed along with the influence of impedance and antenna loss on the radiation pattern. These data can then be used to define the antennas' dual band operation and MIMO performance.

## III. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

A four port 2x2 U slot MIMO antenna was simulated using Ansys HFSS in order to investigate its dual band functionality and impedance match. Good impedance matches and high levels of element isolation are shown in the simulation results for each of the two operating bands.

### A. Return Loss Characteristics

Reflection coefficient data (S-parameters) are analysed for each of the four antenna ports, S11 , S22 , S33 and S44 in order to assess impedance matching properties. From Fig. X it can be seen that the antenna has two distinct resonant frequency ranges; a low and high frequency band.

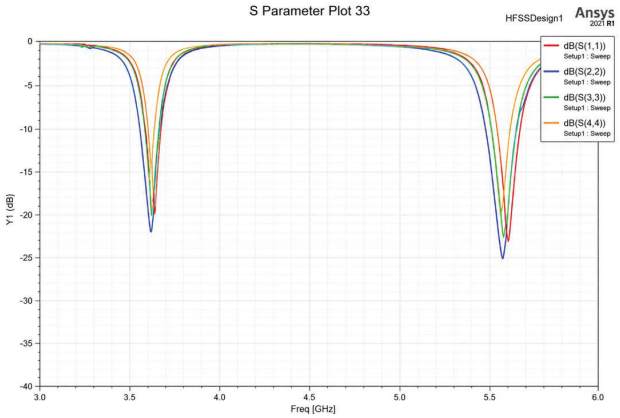



Fig. 2. Return Loss Characteristics of the Four Antenna Ports

The low frequency band is found to be active between 3.60 and 3.63 GHz. Corresponding return losses in this band range between -17 and -22dB. The higher frequency band is active at around 5.56-5.60 GHz, and has corresponding return loss values in the region of -18 to -25dB. This is appropriate for standard impedance matching (-10dB), so good power delivery can occur in both bands.

Whilst the reflection coefficient resonances for each port are broadly comparable, this highlights good uniformity of the antenna radiation components. Small shifts in resonant frequency of up to 20-30MHz can also be seen for some ports. A small difference in level of impedance matching is additionally apparent. In comparison to Port 2, Port 4 appears to have less optimal impedance matching. Differences in component positioning and coupling effects could be responsible for these differences in performance in the limited extent ground plane.

### B. Mutual Coupling and Isolation Characteristics

Transmission parameters were used to analyse the mutual coupling behaviour of the MIMO antenna. Simulated S-parameters such as $S_{21}$, $S_{31}$, $S_{41}$ together with additional inter-port coupling information is shown in Fig. X.

It can be seen that the transmission parameters are predominantly less than -30dB. Isolation between various ports is also found to be good with values lying between -30dB and



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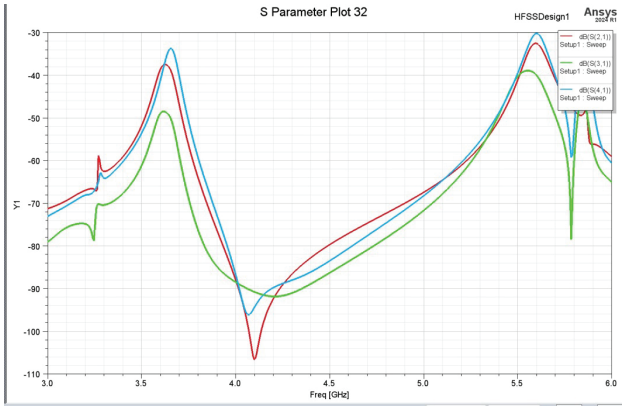



Fig. 3. Transmission Coefficients Between Port 1 and the Remaining Ports

-48dB. Therefore good mutual coupling reduction between the antennas is achieved.

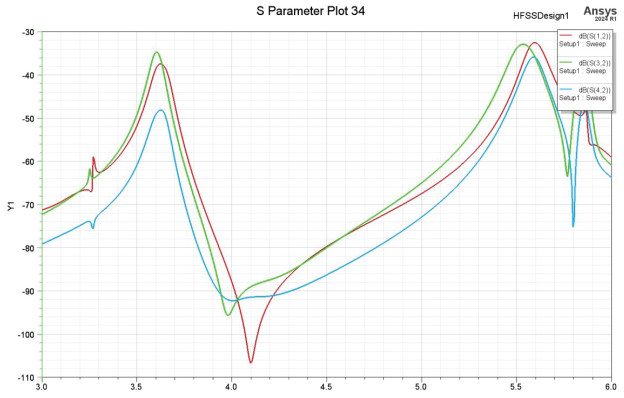



Fig. 4. Transmission Coefficients Between Port 2 and the Remaining Ports

The level of isolation that has been achieved is greater than the typically desired -15dB to -20dB isolation for MIMO antennas. Beneficial effects of the geometry and perpendicular positioning of the U-slotted antenna sub-elements results in a reduction in neighbouring port coupling.

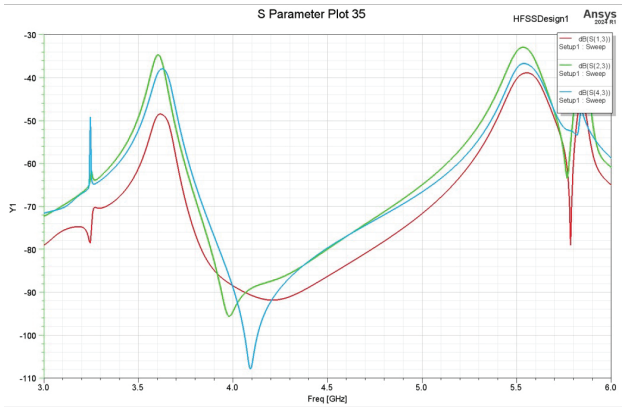



Fig. 5. Transmission Coefficients Between Port 3 and the Remaining Ports

Furthermore, the simulated transmission coefficients exhibit reciprocal behavior, with $S_{ij}$ approximately equal to $S_{ji}$, consistent with the reciprocity characteristics of passive antenna structures.

There are small fluctuations in the transmission coefficient around 3.25GHz and 5.8GHz. As these fluctuation occur for low coupling values further analysis is advised, ideally with an improved frequency sampling rate and mesh refinement to ensure that numerical artefacts can be separated from actual electromagnetic behaviour.

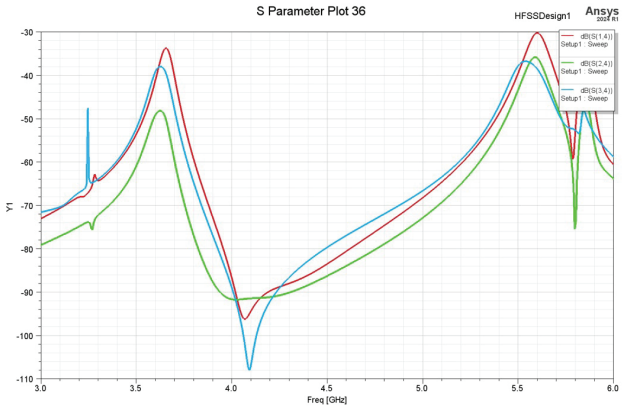



Fig. 6. Transmission Coefficients Between Port 4 and the Remaining Ports

### C. Discussion of Simulation Characteristics

The obtained S-parameter results establish the dual-band impedance matching and isolation characteristics of the proposed antenna.

### D. Radiation Pattern and Gain Characteristics

The radiation pattern describes how an antenna emits electromagnetic energy. It can be used to determine both the angular emission properties and behaviour of an antenna. Typically an antennas radiation pattern is analysed in both the electric (E) and magnetic (H) plane and also in 3D.

The E plane comprises the electric field vector and the main lobe and the H plane comprises the magnetic field vector and main lobe. Analysis can then be performed on these planes to assess both the angular emission profile and properties of the antenna.

The 3D gain profile demonstrates how an antennas gain differs depending on direction. Gain is measured in decibels with reference to an isotropic radiator (dBi). It is a measure of how much an antenna focuses its emitted energy. Both the radiation pattern and gain are key factors in determining whether an antenna is appropriate for use in a wireless communications system.

Fig. 7 shows the simulated radiation patterns of the proposed antenna at 3.6GHz and 5.6GHz. Both E- and H-plane patterns are shown and describe the angular radiation behaviour of the antenna. The 3D gain graphs further show the variation in antenna gain. Radiation is mainly emitted in the positive z direction. The simulated maximum antenna gain is approximately 6dBi at both 3.6GHz and 5.6GHz as illustrated by



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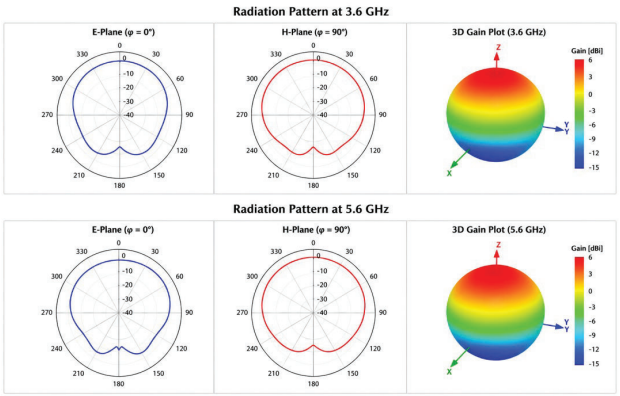



Fig. 7. Simulated Radiation Patterns and 3D Gain Distribution at 3.6 GHz and 5.6 GHz

the 3D gain graphs. Furthermore, the radiation behaviour exhibits wide-beam radiation at both operating frequencies, thus confirming that the antenna is appropriate for application within dual-band wireless systems.

### *E. Impedance Bandwidth Characteristics*

The impedance bandwidth of the designed antenna is investigated according to the -10 dB return loss definition. This is defined as the frequency interval where the return loss is larger (i.e. more negative) than -10 dB and can be written as

$$BW = f_H - f_L$$

where $f_H$ and $f_L$ represent the upper and lower cutoff frequencies of the operating band, respectively. The fractional bandwidth is calculated as

$$BW(\%) = \frac{f_H - f_L}{f_c} \times 100$$

where $f_c$ denotes the center frequency of the operating band.

As can be seen from the simulated return loss, the designed antenna is dual-band and is matched at frequencies of approximately 3.6GHz and 5.6GHz. It has a bandwidth of around 150MHz for the lower frequency band, and an approximate bandwidth of 370MHz on the higher frequency band. Thus, the U-slot MIMO antenna is indeed dual-band and appropriate for wireless communications.

### *F. Radiation Efficiency Characteristics*

The radiation efficiency describes the ability of an antenna to convert absorbed power into electromagnetic waves. It can be defined as the ratio of radiated power to that of absorbed power, and is given by

$$\eta_{\text{rad}} = \frac{P_{\text{rad}}}{P_{\text{accepted}}} \times 100$$

The radiation efficiency of the four port MIMO antenna has been investigated within Ansys HFSS. It has a simulated radiation efficiency of around 14% and 42% for the 3.6GHz and 5.6GHz bands respectively. It can be seen that the upper band has a greater radiation efficiency than the lower band; therefore suggesting that the antenna has better radiation characteristics at higher frequencies. These findings inform us of the power radiation properties of the proposed antenna within both of its bands.

| Frequency (GHz) | Radiation Efficiency (%) |
|---|---|
| 3.6 | 13.88 |
| 5.6 | 41.75 |

### *G. Envelope Correlation Coefficient (ECC)*

The Envelope Correlation Coefficient (ECC) is a key performance metric for analysing the diversity behaviour of a MIMO antenna array. It provides an assessment of how correlated two antennas are. A smaller value of ECC yields less correlation and so enhanced diversity. For this investigation, the ECC has been calculated for the 6 distinct port pairs of the four-port proposed MIMO antenna. These have been generated from complex far-field data acquired via HFSS simulation.

The far field ECC can be determined by means of:

$$\rho_{e,ij} = \frac{\left| \int_0^{2\pi} \int_0^{\pi} \left( E_{\theta i} E_{\theta j}^* + E_{\phi i} E_{\phi j}^* \right) \sin\theta \, d\theta \, d\phi \right|^2}{\left[ \int_0^{2\pi} \int_0^{\pi} \left( |E_{\theta i}|^2 + |E_{\phi i}|^2 \right) \sin\theta \, d\theta \, d\phi \right] \times \left[ \int_0^{2\pi} \int_0^{\pi} \left( |E_{\theta j}|^2 + |E_{\phi j}|^2 \right) \sin\theta \, d\theta \, d\phi \right]} \quad (6)$$

Here, $E_{\theta i}$ and $E_{\phi i}$ represent the complex far-field components corresponding to the $i$-th antenna port, while the asterisk denotes complex conjugation. The integration is performed over the complete spherical radiation domain.

TABLE I
SIMULATED ECC FOR ALL SIX PORT COMBINATIONS

| Port Pair | 3.6 GHz | 5.6 GHz |
|---|---|---|
| 1–2 | $3.740 \times 10^{-3}$ | $4.991 \times 10^{-3}$ |
| 1–3 | $1.812 \times 10^{-3}$ | $1.088 \times 10^{-3}$ |
| 1–4 | $1.083 \times 10^{-1}$ | $6.280 \times 10^{-3}$ |
| 2–3 | $9.644 \times 10^{-2}$ | $4.994 \times 10^{-3}$ |
| 2–4 | $2.256 \times 10^{-3}$ | $9.20 \times 10^{-4}$ |
| 3–4 | $8.385 \times 10^{-3}$ | $6.125 \times 10^{-3}$ |

Various 2-ports are analysed for the multiple-input multiple-output (MIMO) antenna comprising 4 ports: 1-2, 1-3, 1-4, 2-3, 2-4 and 3-4. ECC is then computed for these port-pairs within both 3.6 GHz and 5.6 GHz frequency bands.

The simulated ECCs for each of the above mentioned ports are shown in Table I. Between 3.6 GHz, the ECCs are found to lie in the range $1.812 \times 10^{-3}$ to $1.08258 \times 10^{-1}$. Maximum and minimum ECC are seen to occur for the 1-4 and 1-3 port-pairs respectively. Between 5.6 GHz, the ECCs are obtained in the range $9.20 \times 10^{-4}$ to $6.280 \times 10^{-3}$. The 2-4 port-pair has the smallest correlation, and the 1-4 port-pair has the greatest ECC of those investigated. As all ECCs are less than the generally accepted limit of 0.5, it can be concluded



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that there is little correlation between the radiation patterns of the antenna elements. It is also evident from the results that the degree of correlation is influenced by both the frequency-band and the port-pair under investigation. It is shown that the investigated antenna provides good radiation pattern diversity properties at both 3.6 GHz and 5.6 GHz. Moreover, the smaller ECCs at 5.6 GHz suggest that the investigated port-pairs have less correlation than at 3.6 GHz.

### *H. Diversity Gain (DG)*

Diversity Gain (DG) is a measure of the diversity performance of a MIMO antenna array. It quantifies the improvement in signal reception achieved by using several antennas. It can be obtained from the Envelope Correlation Coefficient (ECC) according to: (where denotes the average value)

$$DG_{ij} = 10\sqrt{1 - \rho_{e,ij}^2}\ \text{dB}. \tag{7}$$

For each of the 6 different port pairs, the diversity gains were also determined from the derived ECC values. These are shown in Table II. Between 3.6GHz and 5.6GHz, the diversity gains are within approximately 9.9412dB to 9.99998dB. The pair of ports that provides the least diversity gain is that of Ports 1 and 4, which has the highest ECC value (0.108258). For the other port pairs, the diversity gains are near to 10dB. Between 5.6GHz, the diversity gains range between approximately 9.99980dB to 9.999996dB. Again, all port pairs produce a diversity gain very near to 10dB; therefore, good diversity properties can be seen to exist for the higher frequency band. As previously mentioned, there is good agreement between the diversity and ECC results. Port pairs with smaller ECC values give rise to greater diversity gains near to 10dB. In general then, it can be concluded that the novel four-port MIMO antenna provides good diversity properties at both frequencies.

TABLE II
SIMULATED DIVERSITY GAIN FOR ALL SIX PORT COMBINATIONS

| Port Pair | 3.6 GHz (dB) | 5.6 GHz (dB) |
|---|---|---|
| 1–2 | 9.99993 | 9.99988 |
| 1–3 | 9.99998 | 9.99999 |
| 1–4 | 9.94123 | 9.99980 |
| 2–3 | 9.95339 | 9.99988 |
| 2–4 | 9.99997 | 10.00000 |
| 3–4 | 9.99965 | 9.99981 |

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