3. DESIGN OF MICROSTRIP ANTENNAS FOR 2×2 MIMO SYSTEMS

3.1 INTRODUCTION

In this chapter, the basic concept of MIMO system and its channel capacity model are briefly presented. The role of microstrip antennas in the current wireless scenario and different types of microstrip antennas that are used in the design of MIMO systems are presented. These antennas are narrowband elements, which limits their application in modern high data rate wireless systems. The mutual coupling is another major issue that degrades the performance of the MIMO systems, which arises due to the smaller spacing between the antennas.

In the present chapter, the problems of impedance bandwidth improvement and mutual coupling reduction are taken up and addressed. A modified E shaped patch antenna giving improved bandwidth compared to the existing E shaped patch antenna is studied. A novel Swastika shaped patch antenna that can simultaneously give improved impedance bandwidth and isolation in MIMO systems is proposed and developed physically. The empirical formulas for calculating the resonant frequencies of the proposed antenna are presented. Also, the channel capacity is calculated for a 2×2 MIMO system.
system using the proposed antenna and the improvement in channel capacity compared to the existing E shaped patch antenna and the traditional dipole MIMO system is observed. A 2×2 MIMO system is formed using a pair of rectangular patch antennas and the mutual coupling between the two antennas is analyzed using Artificial Neural Networks (ANNs).

### 3.2 MIMO SYSTEMS

In traditional communication systems, usually one antenna is used at the transmitter and receiver. This system, known as Single Input Single Output (SISO) system suffers from bottleneck in terms of channel capacity according to the Shannon-Nyquist criterion. However, the present advanced communication systems require the channel capacity to be multiplied for supporting huge data rates. The channel capacity of a SISO system can be improved by increasing either transmitter power or bandwidth of the system according to Eq. (1.1), which increase the overall cost of the system. Fortunately, recent research has proved that the MIMO systems can substantially increase the channel capacity by employing multiple antennas at both the transmitter and receiver, without increasing either transmitter power or bandwidth of the system.

A MIMO system with N number of transmitting and receiving antennas is shown in Fig. 3.1. The basic idea of this system is to
transmit various data streams using different antennas at the same carrier frequency and without additional power. When a data stream is transmitted from $p$th antenna, it is received at the $q$th antenna after travelling in different paths as shown in the Fig. 3.1. This method of propagation is known as multipath propagation, which occurs due to the reflections of signal from different objects in the path. In such systems, the signal received at the receiver is represented as

$$x_q(t) = \sum_{p=1}^{N_t} h_{qp}(t)s_p(t)$$  \hspace{1cm} (3.1)

Fig: 3.1. A schematic representation of a basic MIMO system

Where, $x_q(t)$ represents the $q$th received data, $s_p(t)$ represents the $p$th transmitted data and $h_{qp}(t)$ represents the path gain between $p$th transmitter and $q$th receiver. The same parameters can be represented using the matrix notation as given below.
The $s(t)$ and $x(t)$ matrices represent various transmitted and received data streams respectively. The $H(t)$ matrix is known as channel coefficient matrix and its elements represent the path gains from the respective transmitting antenna to the receiving antenna. The channel matrix $H(t)$ is the mathematical representation of the physical transmission path of the signal, which includes both the multipath channel characteristics of the physical environment and the antenna configurations. Hence, the multipath channel characteristics and the antenna configurations will decide the communication system performance in a MIMO system. The channel capacity of such systems is given by Eq. (1.2), which describes the channel capacity improvement in a rich scattering environment by increasing the number of antennas.

In order to study the performance of a MIMO system compared to a SISO system, four different antenna configurations like a SISO system, a $2\times2$, a $4\times4$ and an $8\times8$ MIMO systems are modeled using half wave dipole antennas with a separation of $\lambda/2$ between each antenna. The variation of channel capacity with the number of antennas is shown in Fig. 3.2. The figure clearly illustrates that the channel capacity of a
MIMO system is more compared to a SISO system and increases with the number of antennas. For example, at an SNR of 30 dB, the 2×2 MIMO system gives a channel capacity of 10 bps/Hz, whereas the 8×8 MIMO system gives a channel capacity of 80 bps/Hz. There is no restriction in using the number of antennas in MIMO systems for achieving improved channel capacity. However, more number of antennas at the transmitter and receiver increase the system complexity and the cost of implementation.

The MIMO technology can improve the reliability and Quality of Service (QoS) of a communication system, besides improving the channel capacity using two different transmission schemes known as Space Division Multiplexing (SDM) and Space Time Coding (STC), which are briefly illustrated as below.

Fig: 3.2. Comparison of channel capacity for SISO and MIMO systems
A. SPACE DIVISION MULTIPLEXING

In Space Division Multiplexing (SDM) or simply known as Spatial Multiplexing (SM), different data streams are transmitted simultaneously in parallel channels from each transmitting antenna. The basic principle of spatial multiplexing can be understood by considering a 2×2 MIMO system as shown in Fig. 3.3.

![Fig: 3.3. A 2×2 MIMO system with Spatial Multiplexing (SM) scheme](image)

Firstly, the data to be transmitted is divided into two sub streams, then modulated and transmitted simultaneously from each transmit antenna. The signals arrived at the receiver can be well separated, if the propagation channels are uncorrelated. The receiver can conveniently differentiate the arrived co-channel signals assuming that it has the knowledge of channel. The originally transmitted two data sub-streams can be combined to give the original bit stream of data after demodulating the received signals. In this way, using the parallel channels, multiple and independent data streams can be transmitted at a time to increase the channel capacity. This concept can be extended to
N number of transmitting and receiving antennas to increase the channel capacity by N times. However, this data transmitting scheme is well suited only for high SNR environments as the receiver can’t identify the uncorrelated signal paths under low SNR conditions.

B. SPACE TIME CODING

Space Time Coding (STC) is another data transmitting scheme exploiting the MIMO channel concept. However, in this method the system performance is improved using the multiple antennas for achieving diversity gain rather than for the spatial-multiplexing gain of parallel data streams. It increases the system throughput by selecting quality signal paths and by avoiding signal paths that are likely to produce packet errors and retransmissions.

The STC technique differs from SM technique in such a way that the same data stream is encoded to produce the symbol streams for each transmit element as shown in Fig. 3.4. The diversity gain is achieved at the receiver with appropriate decoding methods. This transmission technique is particularly suitable for those systems with no channel knowledge available at the transmitter. The diversity gain improves the reliability of fading wireless channels and thus improves the quality of the transmission.
The space-time coding technique does not increase the channel capacity with the number of transmit/receive elements. However, it maximizes the wireless coverage and range by improving the quality of the transmission. Hence, a MIMO system with the combination of spatial multiplexing and space time coding can improve both the reliability of the communication system and channel capacity.

Usually, in any MIMO system the antenna design plays major role in improving the system performance and channel capacity. The antenna bandwidth must support the wireless system for transmitting larger data rates. Also, the mutual coupling effect between the antennas must be taken into consideration, while designing an efficient MIMO system.
3.3 MICROSTRIP ANTENNAS

The Microstrip antennas are the most preferred one for small handheld devices and WLAN cards due to their number of inherent advantages. A microstrip antenna basically consists of a radiating patch placed on a dielectric substrate attached to a ground plane as shown in Fig. 3.5. The conducting patch is usually made with copper or gold and it can be designed in variety of shapes. The conducting patch and the feed lines are connected to the dielectric using photo etching method.

These antennas radiate primarily because of the fringing fields developed between the radiating patch and the ground plane. For achieving larger bandwidth and good radiation efficiency, usually the antennas with thick dielectric constant and low permittivity value are desired. However, it increases the antenna size. Hence, a compromise is to be reached between antenna performance and antenna size.

![Fig: 3.5. A basic Microstrip patch antenna](image-url)
These antennas are fed with different feeding mechanism like microstrip feed, coaxial feed, aperture coupled feed and proximity coupled feed. In the first two methods, the RF power is fed directly to the radiating patch and these are known as contacting schemes. In the later two methods, the electromagnetic coupling is used to transfer the power from microstrip line to the radiating patch and these are known as non-contacting schemes. The microstrip antennas are available in different shapes like square, rectangular, circular, elliptical, triangular, etc., as shown in Fig. 3.6.

![Fig: 3.6. Different shapes of Microstrip patch antennas](image)

As mentioned earlier, the microstrip antennas have many advantages compared to the traditional antennas like monopole and dipole antennas and they are very popular in the wireless applications. They are extremely compatible to embed in handheld devices like mobile phones and Personal Digital Assistants (PDA). They also find place in telemetry,
missiles and defense applications, where the antennas are to be thin and must occupy smaller volumes. The following are some of the advantages of microstrip antennas.

- Light weight, low cost and occupy smaller volumes
- Low fabrication cost
- Capable of giving multiple resonant frequencies
- Capable of operating at both linear and circular polarization

However, the microstrip antennas have several major drawbacks also. They suffer from narrow bandwidth due to the high Quality factor (Q). The value of this Quality factor Q can be minimized by increasing the thickness of the dielectric substrate. But, increase in the thickness of the substrate results in the formation of surface waves. These surface waves result in mutual coupling in the MIMO systems, deteriorating the overall system performance. Hence, in the present work the task of improving the bandwidth and reducing the mutual coupling is taken up and addressed. The impedance bandwidth improvement and mutual coupling reduction are two independent problems and usually they are handled separately. However, in the present work a novel Swastika shaped patch antenna that can solve both the problems is proposed and studied for wireless MIMO systems.
3.4 MODIFIED E SHAPED PATCH ANTENNA

The Microstrip antennas are initially available in the basic shapes like square, rectangular, circular, etc. These antennas have very narrow impedance bandwidth in the range 2-5% [42]. This narrow bandwidth is the major drawback of microstrip antennas and limits their application in the current wideband wireless communications. To improve the bandwidth of these antennas, several researchers have developed microstrip antennas of various shapes like H shaped patch antenna [45], E shaped patch antenna [46], W shaped patch antenna [53], V shaped patch antenna [55], etc. Among all these antennas, the E shaped patch antenna is popular due to its wideband characteristics.

The E shaped patch antenna discussed in [49] is shown in Fig. 3.7, which resonates at the dual band of frequencies 5.2 GHz and 5.8 GHz giving an impedance bandwidth of 7% at -10 dB return loss. The antenna is developed on an RT Duroid substrate with $\varepsilon_r = 2.2$ and thickness $h = 3.2$ mm. The various dimensions of the antenna are taken as $W = 20$, $L = 17.2$, $W_1 = 5.9$, $W_s = 1.0$, $W_t = 6.2$ and $L_s = 10$. All the dimensions are taken in mm. The simulations are carried out using the FEKO EM Simulator, which works on the principle of Method of Moments (MoM).
The reason for the E shaped antenna to give improved impedance bandwidth compared to a normal rectangular shaped patch antenna can be understood by analyzing the current paths in Figs. 3.8 (a) and (b). A normal rectangular microstrip antenna can be represented as an LC resonant circuit [47], where the values of L (Inductance) and C (Capacitance) are determined by the length of current paths from the feed location. When the narrow slots are introduced in the rectangular patch resulting in E shaped patch antenna, the path of the current changes as shown in Fig. 3.8 (b). This increased current path changes the value of inductance L to L+ΔL giving the second resonant frequency. These two resonant frequencies couple each other giving the improved impedance bandwidth [46].

Based on this idea, a modified E shaped patch antenna is proposed by incorporating additional slots to the E shaped patch antenna as shown in Fig. 3.9. In order to compare this proposed antenna with the above discussed antenna, the dimensions of the patch and substrate
material are taken same as above. The additional slot lengths are optimized using EM simulation tool to give good resonance and bandwidth characteristics and the selected values are \( d_1 = 2 \) mm and \( d_2 = 4 \) mm.

![Diagram of current paths in a rectangular patch and an E shaped patch](image)

**Fig. 3.8. Current paths in (a) Rectangular patch (b) E shaped patch**

The choice of taking the additional slots to improve the impedance bandwidth is inherited from the idea of designing a basic E shaped patch antenna by incorporating slots to a rectangular patch antenna. As explained above, the slots on the patch changes the current path resulting in the improved bandwidth. Similarly, the additional slots in the E shaped patch antenna make the current path to further increase as shown in Fig. 3.9, shifting the resonant frequency further to give improved bandwidth. The additional slots are kept at top and bottom edges of the patch so that their distance from the feed location is more,
resulting in the increased current path. However, the improved bandwidth depends on the careful selection of the parameters \( d_1 \) and \( d_2 \) and in the present case these values are optimized using the EM simulator.

![Diagram of Modified E shaped patch antenna](image)

**Fig: 3.9. Modified E shaped patch antenna**

The performance of the modified E shaped patch antenna is compared with the E shaped patch antenna in terms of return loss as shown in Fig. 3.10. The modified E shaped patch antenna resonates at 5.35 GHz and 5.81 GHz giving an impedance bandwidth of 16% at -10 dB, improving the bandwidth by an amount of 9% compared to the normal E shaped patch antenna. The impedance bandwidth or simply called as bandwidth can be calculated using Eq. (3.3), where \( f_H \) and \( f_L \) represent the upper and lower cutoff frequencies at -10 dB return loss.

\[
\% \text{ of BW} = 2 \left( f_H - f_L \right) / \left( f_H + f_L \right)
\]  

(3.3)
Fig: 3.10. Comparison of return loss between the E patch and modified E patch antennas.

Hence, the proposed modified E shaped antenna gives the improved performance in terms of impedance bandwidth compared to the normal E shaped antenna. To analyze the mutual coupling, a 2×2 MIMO system is formed using a pair of modified E shaped antennas as shown in Fig. 3.11. Here, the two antennas are taken with orthogonal polarization diversity, i.e. the second antenna is rotated by 90° w.r.t. to the first antenna. As discussed in [73], the antennas with polarization diversity yield better isolation compared to the antennas with normal orientation. The separation between the two antennas is taken as 10 mm. The performance of this antenna system is compared with the orthogonally polarized normal E shaped antenna system [49] in terms of the mutual coupling $S_{21}$ (dB) as shown in Fig. 3.12. From the results, it can be seen that both the MIMO systems give almost same mutual coupling (<-27 dB) at the two resonant frequencies. The modified E shaped antenna gives a
gain of 7 dB in the operating frequency range as presented in Fig. 3.13. The radiation patterns of the developed MIMO system at the resonant frequencies 5.35 GHz and 5.81 GHz are shown in the Fig. 3.14.

Fig: 3.11. A 2×2 MIMO system with orthogonal polarization diversity

Fig: 3.12. Comparison of mutual coupling between E shaped and modified E shaped antenna pair
Fig: 3.13. Gain plot of the proposed MIMO array

Fig: 3.14. Radiation patterns of the proposed MIMO system at
(a) 5.35 GHz (b) 5.81 GHz
3.5 SWASTIKA SHAPED PATCH ANTENNA DESIGN

The modified E shaped patch antenna discussed in the previous section provides improved impedance bandwidth without changing the mutual coupling values in the operating frequency range. In this section, a novel tri-band Swastika shaped patch antenna that can give improved impedance bandwidth and isolation simultaneously is proposed for first time, which is shown in Fig. 3.15.

![Proposed Swastika shaped patch antenna](image)

Fig: 3.15. Proposed Swastika shaped patch antenna

The Swastika shaped patch antenna can be formed by incorporating four slots at the four sides of a square patch. The feed point can be given at the corner of any arm so that the current in the patch flows in three different directions as shown in the above figure. The antenna resonates at tri-band of frequencies due to the flow of current in three different directions, where each current path corresponds to a particular resonant frequency. These three resonant frequencies couple each other resulting in higher bandwidth.
3.5.1. Development of Empirical Formulae

The resonant frequency of any patch antenna can be calculated using the following equation [59].

\[
f_r = \frac{c}{2(L_e + 2\Delta l)\sqrt{\varepsilon_e}} \tag{3.4(a)}
\]

Where, \(f_r\) – Resonant frequency; \(L_e\) – Effective electric length; \(\Delta l\) – Fringe field strength; \(c\) – speed of light; \(\varepsilon_e\) – Effective dielectric constant.

The fringe field strength and height ‘h’ of the substrate are related as

\[
\frac{\Delta L}{h} = 0.412 \left( \frac{\varepsilon_{\text{reff}} + 0.3}{\varepsilon_{\text{reff}} - 0.258} \right) \frac{(w/h + 0.264)}{(w/h + 0.8)} \tag{3.4(b)}
\]

The effective dielectric constant \(\varepsilon_e\) can be calculated as,

\[
\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{10h}{w} \right)^{-\frac{1}{2}} \tag{3.5}
\]

Where, \(\varepsilon_r\) - Relative dielectric constant; \(h\) – Height of the substrate; \(w\) – Width of the substrate.

The effective electric length ‘\(L_e\)’, given in Eq. (3.4) plays key role in determining the resonant frequency of any patch antenna. The empirical equations for calculating the effective electrical length ‘\(L_e\)’, corresponding to the three current paths of the Swastika antenna are proposed as

\[
L_{e1} = L_1 + 2L_2 + L_a
\]

\[
L_{e2} = L_1 + \frac{L_2}{3} + L_a
\]
The resonant frequencies corresponding to these lengths can be calculated using Eq. 3.4(a) and are shown as,

\[
f_{r1} = \frac{c}{2(L_1 + 2L_2 + L_a + 2\Delta l)\sqrt{\varepsilon_e}}
\]

\[
f_{r2} = \frac{c}{2\left(L_1 + \frac{L_2}{3} + L_a + 2\Delta l\right)\sqrt{\varepsilon_e}}
\]

\[
f_{r3} = \frac{c}{2\left(L_1 + \frac{2L_2}{3} + L_a + 2\Delta l\right)\sqrt{\varepsilon_e}}
\]

The concept behind the proposed empirical equations and the meaning of the lengths \(L_1\), \(L_2\) and \(L_a\) can be understood by analyzing the current paths \(P_1\), \(P_2\) and \(P_3\) as shown in Fig. 3.16. From Eq. (3.4), it can be seen that the resonant frequency mainly depends on the length of the patch ‘\(L\)’ rather than width of the patch ‘\(W\)’. Hence, the empirical equations for calculating the resonant frequencies are proposed in terms of the length of the patch \(L\) only. The current in the path \(P_1\) covers the length \(L_1\), approximately twice the length \(L_2\) in taking two turns across \(L_2\) and finally through the length \(L_a\) as shown in Fig. 3.16. Hence, the effective electric length for the path \(P_1\) is \(L_{e1} = L_1 + 2L_2 + L_a\). Similarly, the current in the path \(P_2\) covers the length \(L_1\), approximately one third of length \(L_2\) as the current here mostly flows vertically and through length
L_a. Hence, the effective electric length for path P_2 is, \( L_{e2} = L_1 + \frac{L_2}{3} + L_a \).

Similarly, the current in the path P_3 covers the length L_1, approximately two third of length L_2 as the current here mostly flows horizontally and through the length L_a. Hence, the effective electric length for path P_3 is  
\[ L_{e3} = L_1 + \frac{2L_2}{3} + L_a. \]

These three effective electric lengths correspond to the three resonant frequencies \( f_{r1}, f_{r2} \) and \( f_{r3} \) respectively, which can be calculated using Eq. (3.6(b)). The validity of these empirical equations is verified by comparing the simulated resonant frequencies with the calculated frequencies using the proposed empirical formulae for various Swastika antennas with different sizes and substrate materials.

![Fig: 3.16. (a) Current paths in the Swastika antenna (b) Surface current distribution](image)
The dimensions of the proposed antenna are generalized using the following relations to give a symmetrically oriented Swastika shaped patch antenna.

\[ L = W; \ L = 2.75 \ L_a; \ W = 2.75 \ W_a; \ L = 11 \ L_s; \ W = 11 \ W_s \]

To validate the above geometrical relations and the proposed empirical formulae, initially a Swastika antenna with \(22 \times 22\ \text{mm}^2\) size is taken. The antenna is formed on an RT Duroid substrate with \(\varepsilon_r = 3.2\) and thickness \(h = 2.2\ \text{mm}\). In such case, various dimensions of the antenna according to the above relations are given as, Length of the antenna \(L = 22\ \text{mm}\); Width of the antenna \(= 22\ \text{mm}\); Length of the arm \(L_a = 8\ \text{mm}\); Width of the arm \(W_a = 8\ \text{mm}\); Length of the slot \(L_s = 2\ \text{mm}\); Width of the slot \(W_s = 2\ \text{mm}\).

A comparison between the simulated and calculated resonant frequencies is given in Table 3.1. The results show the close resemblance between EM simulated resonant frequencies and resonant frequencies calculated using the proposed empirical formulae. The simulated and calculated values almost match with a maximum error of 6%. The obtained results indicate that, though the width of the arm is not taken into consideration, resonant frequency is not changing much. Hence, it can be concluded that the length of Swastika arm plays key role in deciding the resonating frequency rather than the width of the arm.
Table 3.1. Comparison of simulated and calculated resonant frequencies for 22×22 mm² Swastika shaped patch antenna

<table>
<thead>
<tr>
<th>Resonant frequency ($f_r$)</th>
<th>Simulated</th>
<th>Calculated</th>
<th>% of error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{r1}$ (GHz)</td>
<td>3.8</td>
<td>3.9</td>
<td>2.5</td>
</tr>
<tr>
<td>$f_{r2}$ (GHz)</td>
<td>6.6</td>
<td>6.2</td>
<td>6.0</td>
</tr>
<tr>
<td>$f_{r3}$ (GHz)</td>
<td>7.6</td>
<td>8.0</td>
<td>5</td>
</tr>
</tbody>
</table>

Further to validate the proposed empirical formulae and to evaluate the dependence of length of Swastika arm on resonant behavior, Swastika shaped patch antennas with sizes 33×33 mm² and 44×44 mm² are taken and the three resonant frequencies are simulated and calculated. In this case, the substrate material is also changed from RT Duroid substrate to air substrate with $\varepsilon_r = 1$ and thickness $h = 2.2$ mm. The comparison of resonant frequencies is shown in Tables 3.2 and 3.3 respectively. Here also, the simulated and calculated results closely match with a maximum error of 8.7% in the case of 33×33 mm² antenna and a maximum error of 6.8% in the case of 44×44 mm² antenna. Hence, using the proposed empirical formulae, the three resonant frequencies of the antenna can be calculated with minimum error. Also, using the proposed dimensions, the Swastika shaped patch antenna with desired resonant frequencies can be designed conveniently.
Table 3.2. Comparison of simulated and calculated resonant frequencies for 33×33 mm\(^2\) Swastika shaped patch antenna

<table>
<thead>
<tr>
<th>Resonant frequency (f_r) (\text{GHz})</th>
<th>Simulated</th>
<th>Calculated</th>
<th>% of error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_{r1})</td>
<td>3.2</td>
<td>3.4</td>
<td>5.8</td>
</tr>
<tr>
<td>(f_{r2})</td>
<td>5.7</td>
<td>5.2</td>
<td>8.7</td>
</tr>
<tr>
<td>(f_{r3})</td>
<td>7.0</td>
<td>6.7</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 3.3. Comparison of simulated and calculated resonant frequencies for 44×44 mm\(^2\) Swastika shaped patch antenna

<table>
<thead>
<tr>
<th>Resonant frequency (f_r) (\text{GHz})</th>
<th>Simulated</th>
<th>Calculated</th>
<th>% of error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_{r1})</td>
<td>2.49</td>
<td>2.59</td>
<td>3.8</td>
</tr>
<tr>
<td>(f_{r2})</td>
<td>4.4</td>
<td>4.1</td>
<td>6.8</td>
</tr>
<tr>
<td>(f_{r3})</td>
<td>5.2</td>
<td>5.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Now, the impedance bandwidth of Swastika shaped patch antenna of size 22×22 mm\(^2\) is compared with the E shaped patch antenna discussed in the previous section. The size of this antenna is taken as 17.2×20 mm\(^2\), which is close to the dimensions of the proposed Swastika shaped patch antenna. Both the antennas are taken on RT Duroid substrate with \(\varepsilon_r = 3.2\) and height of the substrate \(h = 2.2\) mm. The simulated return loss comparison of both the antennas is shown in Fig. 3.17.
The E shaped patch antenna resonates at a dual band of 5.2 GHz and 5.8 GHz with an impedance bandwidth of 7%, whereas the proposed Swastika shaped patch antenna resonates at a tri-band of 3.7 GHz, 6.6 GHz and 7.6 GHz frequencies with an impedance bandwidth of 20%. The tri-band antennas are highly useful in several applications like mobile phone, GPS, Wi-Fi, etc.. Hence, the proposed antenna gives a wideband performance in addition to its tri-band operation compared to the present widely studied E shaped patch antenna. This improvement in the bandwidth is achieved only with the change in the shape of the patch and without changing the substrate material. Now, a 2×2 MIMO system is formed using the proposed Swastika shaped patch antenna with air as substrate and the mutual coupling between the two antennas is studied in the following sub-section.

![Comparison of return loss between E shaped patch antenna and proposed Swastika shaped patch antenna](image.png)

**Fig: 3.17.** Comparison of return loss between E shaped patch antenna and proposed Swastika shaped patch antenna
3.5.2 A 2×2 MIMO System Using Swastika Antenna

To analyze the isolation performance of the proposed Swastika shaped patch antenna, a 2×2 MIMO system is formed as shown in the Fig. 3.18. The size of each antenna is 33×33 mm² and both the antennas are separated by a distance of 10 mm. The entire antenna system is formed on air substrate with εᵣ = 1 and height h = 5 mm. The antenna system is simulated using the FEKO EM simulator and the simulated return loss (S₁₁) and mutual coupling (S₂₁) of the proposed MIMO system are shown in Fig. 3.19.

The proposed MIMO system resonates at a tri-band of 3.3 GHz, 5.8 GHz and 7.1 GHz with an impedance bandwidth of 37% in the frequency range 5.6 GHz to 8 GHz. The obtained bandwidth is very high compared to the bandwidth of a normal E shaped patch antenna discussed in [68], which gives a bandwidth of 14% designed with same size (approximately) and same substrate (air). The mutual coupling (S₂₁) of the proposed Swastika antenna is also found to be very low due to the multipath current propagation on the patch and the amount of isolation at the operating frequency range is 33 dB, whereas for the antenna system in [82] the obtained isolation is 25 dB. Hence, the proposed Swastika patch antenna gives both improved impedance bandwidth and isolation.
In order to validate the performance of the proposed antenna, a comparative analysis is made between the proposed Swastika shaped patch antenna and the existing patch antennas like E shaped, H shaped, and U shaped patch antennas as shown in Fig. 3.20 (a) & (b). For the better comparison, all the antennas are formed on air substrate ($\epsilon_r=1$) with almost same dimensions. The return loss of the Swastika antenna is shown in Fig. 3.20(a), which gives higher bandwidth compared to the other patch antennas. Similarly, Fig. 3.20(b) shows the good isolation characteristics of the proposed Swastika antenna MIMO system.
compared to the remaining patch antenna MIMO systems, where the antennas are separated with same separation (10 mm) in all the cases. The impedance bandwidth and mutual coupling comparison between various antenna systems are given in Tab.3.4. The proposed Swastika antenna MIMO system gives better bandwidth and isolation compared to E shaped, H shaped, and U shaped patch antenna MIMO systems.

![Comparison of return loss](image1)

(a) Comparison of return loss

![Comparison of mutual coupling](image2)

(b) Comparison of mutual coupling

Fig: 3.20. Comparison between the Swastika antenna and other patch antennas
Table 3.4. Bandwidth and mutual coupling comparison

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Obtained Impedance Bandwidth (%)</th>
<th>Mutual Coupling at Resonant Frequency (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swastika shaped Antenna</td>
<td>37</td>
<td>-33</td>
</tr>
<tr>
<td>E shaped Antenna</td>
<td>14</td>
<td>-25</td>
</tr>
<tr>
<td>U shaped Antenna</td>
<td>5</td>
<td>-23</td>
</tr>
<tr>
<td>H shaped Antenna</td>
<td>4</td>
<td>-23</td>
</tr>
</tbody>
</table>

The amount of isolation between the antennas in a MIMO system can be studied using the correlation coefficient parameter, which can be calculated using the Eq. (3.7)

\[
\rho = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1-|S_{11}|^2 - |S_{21}|^2)(1-|S_{22}|^2 - |S_{12}|^2)}
\]  

(3.7)

where, \( \rho \) is the correlation coefficient; \( S_{11}, S_{22} \) represent the return loss of both the antennas in the array; \( S_{12}, S_{21} \) represent the mutual coupling between the two antennas with energy from antenna 2 to antenna 1 and from antenna 1 to antenna 2 respectively; \( S_{11}^*, S_{21}^* \) are the complex conjugates of \( S_{11}, S_{21} \) respectively.
The correlation coefficient vs. frequency plot is shown in Fig. 3.21, from which it can be observed that the correlation coefficient values are -140 dB, -175 dB and -180 dB at the three resonant frequencies, indicating a very low amount of correlation between the two antennas in the array.

![Fig: 3.21. Correlation coefficient plot](image)

The directivity radiation patterns of the proposed two element MIMO system using the Swastika shaped patch antenna are shown in Fig. 3.22. The radiation patterns are obtained by varying the elevation angle θ and keeping the azimuthal angle Ø at 0° and 180°. From the figure, it can be observed that at 3.3 GHz resonant frequency, the main lobe is directed at an angle of 12° with an angular width of 92.4° and at 5.8 GHz resonant frequency, the main lobe is directed at an angle of 25° with an angular...
width of 57.8° and at the 7.1 GHz resonant frequency, the main lobe is directed along 1° with an angular width of 69.9°.

Fig: 3.22. Radiation patterns of the developed MIMO antenna system at (a) 3.3 GHz (b) 5.8 GHz (c) 7.1 GHz
3.5.3 A 2×2 MIMO System Using Swastika Antenna With Reduced Ground Plane

In the present sub-section, a wideband MIMO antenna system with good isolation characteristics is discussed. The antenna system is developed using the Swastika patch antenna on a reduced ground plane as shown in Fig. 3.23. The size of each antenna is $30 \times 45 \text{ mm}^2$ and the size of the MIMO system is $90 \times 45 \text{ mm}^2$ with a separation of 10 mm between the edges of two elements. A co-axial feed of impedance 50 Ω is given at $(X_1, Y_1) = (14, 4)$ for the first element and $(X_2, Y_2) = (54, 4)$ for the second element.

![Fig: 3.23. Proposed 2×2 MIMO system (a) Top view (b) Bottom view](image)

There are various techniques proposed in the literature to improve the bandwidth of microstrip antennas by altering the ground structure
According to these studies, the alteration of ground structure changes the path of ground surface currents resulting in the improvement of impedance bandwidth. In the present work, the ground plane is reduced as shown in Fig. 3.23 (b) to improve the impedance bandwidth of the proposed MIMO system. In order to study the effect of ground plane area reduction on the impedance bandwidth of the MIMO system, a parametric study is performed by changing the dimension of ground width ‘d’ as shown in Fig. 3.24. The return loss of the proposed antenna is analyzed for different values of ‘d’ and from the characteristics it is evident that, a good resonant behavior with improved bandwidth is observed for d= 13 mm. Hence, the ground plane is reduced to d=13 mm to give wideband operation.

![Simulated return loss for various values of ‘d’](image)

**Fig: 3.24.** Simulated return loss for various values of ‘d’

The antenna array is printed on a glass epoxy substrate of permittivity $\varepsilon_r = 4.3$ and thickness $h = 1.6$ mm. The developed antenna system...
resonates at tri-band of frequencies 2 GHz, 4.2 GHz and 5.5 GHz giving an impedance bandwidth of 51%, which is considerably a good impedance bandwidth for a substrate of thickness 1.6 mm and permittivity value $\varepsilon_r = 4.3$. The fabricated antenna can handle more than 50 W of power. The physical realization and measurement set up of the developed antenna system are shown in Figs. 3.25(a) and 3.25(b) respectively. The measurements were carried out using the Agilent 8719ES Vector Network Analyzer (VNA). The comparison between the simulated and measured values of the return loss and mutual coupling are shown in Figs. 3.26(a) and 3.26(b) respectively. The measured results are found in good agreement with the simulated results with a slight shift in the resonant frequency, which is due to the fabrication tolerances at the feed point.

(a) Fabricated 2×2 MIMO system
(b) Measurement setup for the fabricated antenna system

Fig: 3.25. Photographs of the fabricated MIMO array

(a) Return loss comparison
Mutual coupling

(b) Mutual coupling

Fig: 3.26. Comparison between the simulated and measured values

The designed system is shown to exhibit an isolation of 40 dB over the operating frequency range 3.5 GHz to 6 GHz with a maximum isolation of 50 dB at the resonant frequency 4.2 GHz. This isolation is achieved only with a separation of 10 mm between the two antennas. The reason for the reduction of mutual coupling between the antennas can be understood by analyzing the surface current distribution of the developed antenna system as shown in Fig. 3.27.

(b) Mutual coupling

Fig: 3.26. Comparison between the simulated and measured values

The designed system is shown to exhibit an isolation of 40 dB over the operating frequency range 3.5 GHz to 6 GHz with a maximum isolation of 50 dB at the resonant frequency 4.2 GHz. This isolation is achieved only with a separation of 10 mm between the two antennas. The reason for the reduction of mutual coupling between the antennas can be understood by analyzing the surface current distribution of the developed antenna system as shown in Fig. 3.27.
The amount of mutual coupling developed between two adjacent antennas depends on the distance between the two antennas and the directions of the current flowing on the surface. If the directions of the currents on adjacent sides of both the antennas are in same direction, the coupling is more and if the currents are in opposite directions, the induced mutual coupling cancels or is minimized [130]. Due to the unique structure of the proposed antenna, the surface currents flow in the opposite directions at the adjacent sides of both the antennas (right portion of the first antenna and left portion of the second antenna), resulting in lower mutual coupling.

The correlation coefficient is calculated using Eq. (3.7) and its variation with frequency is shown in Fig. 3.28. From the figure, it can be observed that the correlation coefficient values at the three resonant frequencies are very small and are less than -100 dB. The measured gain of the fabricated antenna system is shown in Fig. 3.29, where the realised average gain is 7 dB and a maximum gain of 8 dB is observed at the 4.2 GHz resonant frequency. The directivity of the antenna at the three resonant frequencies 2 GHz, 4.2 GHz and 5.5 GHz is found to be 5.5 dBi, 8 dBi and 6 dBi respectively. This measured gain meets well the requirements of mobile and WLAN applications.
The measured radiation patterns at the resonant frequencies 2 GHz, 4.2 GHz and 5.5 GHz are shown in Fig. 3.30. At 2 GHz, the main lobe with magnitude 5.5 dBi is directed along 180° with an angular width of 54°. At this frequency, the minor lobe magnitude is observed to be -2.3 dBi. At 4.2 GHz the main lobe with magnitude 8 dBi is directed along 178° with a 3 dB angular width of 71.8°. At this frequency, the minor lobe magnitude is found to be -9.4 dBi. At 5.5 GHz the main lobe with magnitude 4.6 dBi is directed along 118° with a 3 dB angular width of 76.4° and having minor lobe of magnitude -1.9 dBi. Hence, the developed antenna system gives considerably good angular widths making it suitable for applications in handheld devices like mobile phones and laptops.

Fig: 3.28. Correlation coefficient of the proposed MIMO System
Fig: 3.29. Measured gain of the fabricated antenna system

(a)  

(b)  

(c)  

Fig: 3.30. Radiation patterns of the developed MIMO system at

(a) 2 GHz (b) 4.2 GHz (c) 5.5 GHz

On overall, the comparison is made between the different types of patch antennas and the reduced ground plane Swastika shaped patch antenna in terms of impedance bandwidth and mutual coupling as shown in Table 3.5. From the obtained values, it can be seen that the reduced ground plane Swastika antenna is better in terms of impedance bandwidth and isolation compared to the remaining patch antennas and hence, it is more suitable for the practical MIMO applications.
Table 3.5. Bandwidth and mutual coupling comparison

<table>
<thead>
<tr>
<th>Parameters</th>
<th>H shaped MIMO system</th>
<th>U shaped MIMO system</th>
<th>E shaped MIMO system</th>
<th>Swastika shaped MIMO system</th>
<th>Swastika Antenna with Reduced ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Bandwidth</td>
<td>4</td>
<td>5</td>
<td>14</td>
<td>37</td>
<td>51</td>
</tr>
<tr>
<td>Mutual Coupling (dB)</td>
<td>-23</td>
<td>-23</td>
<td>-25</td>
<td>-33</td>
<td>-50</td>
</tr>
</tbody>
</table>

3.5.4 Channel Capacity Calculations

The main objective of the MIMO systems is to improve the channel capacity by employing multiple antennas at both the transmitter and receiver side. In this sub-section, the channel capacity of a 2×2 MIMO system using the proposed reduced ground plane Swastika shaped patch antenna is calculated. The channel capacity of a 2×2 MIMO system is found to be more compared to a 1×1 SISO system and also the channel capacity of the Swastika shaped MIMO system is observed to be more by 1 bps/Hz compared to the existing E shaped MIMO system.

A ray tracing simulator namely, Wireless Insite is used in the present work for carrying the channel capacity calculations and to construct realistic realizations of the channel matrix $H$ in an indoor wireless environment. The simulator helps in creating an artificial environment of
a communication system with transmitter, receiver and channel by defining the transmitted power, channel bandwidth, number of transmitting and receiving antennas, etc.. The transmitter and receiver can be designed by importing any of the designed antennas into the wireless simulator. In the present case, the proposed Swastika shaped patch antenna is imported into the environment. The channel capacity of a MIMO system can be calculated using Eq. (1.2)

Channel parameter matrix or the $H$-matrix is computed using Eq. (3.8)

$$h_{ij} = \sum_{k=1}^{M} \sqrt{P_k} e^{i\frac{2\pi}{\lambda}l_k} e^{i2\pi n_k}$$  

Where, $h_{ij}$ is complex path gain from $j^{th}$ transmitter to $i^{th}$ receiver; $f$ is carrier frequency; $P_k$ is received power from $k^{th}$ ray; $l_k$ is path length of the $k^{th}$ ray; $t_k$ is time taken by the $k^{th}$ ray to reach the receiver; $M$ is number of rays between transmitter and receiver.

The measurements are carried out using the simulator in an indoor propagation environment with multipath propagation, which is shown in Fig. 3.31. The transmitters and receivers are placed at various locations and channel coefficient matrix for each of the MIMO configurations is calculated for different values of Signal to Noise Ratio (SNR) using the wireless simulator. The calculations are performed for the proposed
Swastika shaped MIMO system, existing E shaped MIMO system and the traditional dipole antenna, as it is a common practice to compare the channel capacities of any proposed antenna with the existing dipole antenna. The results in Fig. 3.32 show the improvement of channel capacity with the increase in the number of antennas. At an SNR of 10 dB, the 1×1 Swastika antenna gives a capacity of 1.5 bps/Hz and 2×2 Swastika MIMO array gives 4.2 bps/Hz. This capacity is compared with 2×2 E shaped MIMO array and a 2×2 MIMO array employing dipole antennas separated by λ/2 spacing, which are calculated as 3.2 bps/Hz and 3 bps/Hz respectively. Hence, the channel capacity of the proposed Swastika MIMO array is better compared to the E shaped and dipole MIMO arrays.

The improved channel capacity using Swastika shaped patch antenna is achieved mainly due to its lower mutual coupling compared to the E shaped and dipole antenna MIMO systems. The antenna arrays with lower mutual coupling always give better channel capacity due to the minimum interference between the antennas [131]. Hence, the proposed Swastika shaped MIMO antenna is a good choice for the applications requiring higher data rates.
Fig: 3.31. Indoor propagation environment    Fig: 3.32. Channel capacity results
3.6 MUTUAL COUPLING ANALYSIS USING ANN

The importance of analyzing and reducing the mutual coupling is discussed in the previous sub-sections. This mutual coupling mainly depends on the distance between the antennas in the MIMO array. More the distance between the antennas, lesser is the mutual coupling and the lesser the distance between the antennas, more is the mutual coupling. Any MIMO antenna system can be designed with a specific spacing between the antennas and the mutual coupling can be calculated for that particular separation between the antennas only. To estimate the mutual coupling for various separations between the antennas, the antenna system is to be redesigned again and again, which is practically difficult. The process of calculating mutual coupling for a set of separations is very time consuming even with the advanced EM simulation tools.

This problem can be easily solved with another powerful simulation tool known as Artificial Neural Networks (ANNs). Artificial Neural Network is one of the powerful computational tools that processes the information with its design inspired by the ability of the human brain to learn from experience, observations and to generalize by abstraction [132]. This important feature of ANN makes it useful in number of areas such as speech processing, pattern recognition, control, biomedical
engineering, etc.. The beauty of ANN is its versatile use in solving RF and microwave Computer-Aided Design (CAD) problems [133]. A neural network model for microwave devices can be developed from simulated/measured or calculated microwave data through a process called training. Once the ANN model is fully developed, the computation time is negligible and much faster than any EM simulator. Though a considerable effort is required in developing an ANN model, it is worthy doing so if repeated design analysis and optimization is required.

Though ANNs do not help in designing the antenna systems, they are very helpful in calculating variable parameters like mutual coupling. To understand how ANNs can be used to calculate mutual coupling for various separations between the antennas, a $2\times2$ MIMO system is developed using a simple rectangular antenna as shown in Fig. 3.33. The various dimensions of the antenna are given as $W=50$ mm, $L=45$ mm, $W_p=30$ mm, $L_p=30$ mm, $P=5$ mm. The antenna system is formed on a substrate of permittivity value $\varepsilon_r=3$ and thickness $h=1$mm with reduced ground plane for giving improved bandwidth. For this particular antenna system, the main interest of study is the analysis of mutual coupling between the two antennas using ANNs.

To analyze the mutual coupling between the two antennas using ANN, the neural network model shown in Fig. 3.34 is taken. The
operating frequency ‘f’ and the separation between the two antennas ‘D’ are given as inputs to the neural network structure. The mutual coupling $S_{21}$ is taken as the output from the neural structure. ANN models are a kind of black box models and their performance and accuracy depends on the amount of training data presented to it during the training process. An accurate, sufficient and well distributed data is the basic requirement to obtain a good model. The selection of training parameters during training process depends on experience besides the type of problem to be solved [134]-[135]. After several trials, it has been found that the three layered network shown in Fig. 3.34 achieved the task with high accuracy. The three layers shown in the figure represent input layer, hidden layer and output layer with variable number of neurons. The number of neurons in the hidden layer depends on the complexity of the problem to be solved.

Fig: 3.33. A 2×2 rectangular MIMO system
To model the mutual coupling between the elements of the designed rectangular MIMO array, a total of 6000 samples are taken from the FEKO EM simulator. Out of these samples, 4000 samples are used for training the neural model and remaining 2000 samples are used as the test data. The main goal of the training process is to minimize the error between the actual output and target output of the ANN. The neural network is trained with a learning rate of 0.25 for 1000 epochs. The neural network model for modeling the mutual coupling is trained with different learning algorithms namely, Back Propagation (BP), Adaptive Back Propagation (ABP), Sparse Training (ST), Quasi-Newton (QN), Quasi-Newton MLP (QN-MLP), Huber-Quasi-Newton (HQN), Conjugate Gradient (CG), Auto Pilot (MLP3) and Simplex Method (SM) using the Neuromodeler 1.5 simulator.
The training and testing errors obtained in modeling the mutual coupling of the MIMO array are given in Table 3.6. The results show the better performance of QN (Quasi Newton) and QNMLP (Quasi Newton Multi Layer Perceptron) algorithms in terms of minimum training and testing errors with maximum correlation coefficient. The correlation coefficient gives the amount of correlation between the trained and tested data.

Table 3.6. Comparison of training and testing errors

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Learning Algorithms</th>
<th>Training Error</th>
<th>Testing error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Avg. Error</td>
<td>Worst Case Error</td>
</tr>
<tr>
<td>1</td>
<td>ST</td>
<td>0.0465572</td>
<td>4.8357515</td>
</tr>
<tr>
<td>2</td>
<td>CG</td>
<td>0.0454214</td>
<td>4.8626294</td>
</tr>
<tr>
<td>3</td>
<td>ABP</td>
<td>0.0454341</td>
<td>4.8626294</td>
</tr>
<tr>
<td>4</td>
<td>QN (MLP)</td>
<td>0.03662274</td>
<td>3.8217053</td>
</tr>
<tr>
<td>5</td>
<td>QN</td>
<td>0.0366226</td>
<td>3.8217053</td>
</tr>
<tr>
<td>6</td>
<td>HQN</td>
<td>0.0356824</td>
<td>3.706239</td>
</tr>
<tr>
<td>7</td>
<td>SM</td>
<td>0.0366248</td>
<td>3.8213212</td>
</tr>
</tbody>
</table>
To analyze the mutual coupling between the antennas of proposed MIMO system, the QN algorithms are selected as they are giving minimum error and maximum correlation coefficient. The distance ‘D’ between the two antennas is varied from 0 to 30 mm and the mutual coupling is calculated for different values of frequency using the ANN structure as shown in Fig. 3.35 (a). From the results, it can be observed that the ANN structure predicts the mutual coupling between the two antennas for the entire set of ‘D’ values i.e. from 0 to 30 mm. The accuracy of prediction depends on the total number of samples used for training process. Similarly, the mutual coupling obtained by varying the frequency from 1 to 9 GHz with a set of specified values of D is shown in Fig. 3.35 (b).
In order to validate the performance of the selected neural network structure, a comparison is made between the EM simulated mutual coupling and neural network generated mutual coupling for an antenna separation of $D = 10$ mm as shown in Fig. 3.36. From the figure, it is evident that the neural network generated and the EM generated data are almost similar except at the sudden peaks giving a variation of $\pm 3$ dB.
In this way, the ANN structures can be used to model the mutual coupling between the antennas in any MIMO system with more accuracy and higher computational speeds. From the obtained mutual coupling values using ANN, we can easily predict the values of ‘D’ for which the minimum mutual coupling can be obtained and for that particular spacing between the antennas, the MIMO antenna system can be designed conveniently.

3.7 SUMMARY

The methods of improving the impedance bandwidth and isolation of microstrip antennas are presented in this chapter. The E shaped patch antenna is popularly studied due to its higher bandwidth and isolation compared to the other patch antennas like rectangular, H shaped and U shaped antennas. However, the bandwidth and isolation of this antenna are not sufficient for the current advanced MIMO wireless systems. This antenna is modified resulting in the modified E shaped antenna giving an improvement of 9% in the bandwidth without changing the mutual coupling level at the resonant frequencies.

A novel tri-band Swastika shaped Microstrip antenna giving improved impedance bandwidth and isolation simultaneously is developed. The main contribution in the present chapter is the development of empirical formulae for calculating the resonant frequencies of the proposed
antenna. The simulated and calculated resonant frequencies using the proposed formulae are almost similar with a maximum error of 8.7%.

The bandwidth and isolation of the proposed Swastika shaped MIMO system are further improved using the ground plane reduction concept. This MIMO system is shown to give an impedance bandwidth of 51% and a reduced mutual coupling of 50%. These results are remarkably good compared to any antenna system designed with FR4 substrate and with a thickness of only 1.6 mm. The proposed MIMO antenna system is fabricated for the experimental validation and both the simulated and measured results are compared. The main objective of any MIMO system is to improve the channel capacity. Hence, in the present work the channel capacity of the proposed 2×2 Swastika shaped antenna is compared with the existing E shaped patch antenna and a traditional dipole MIMO system and the improvement in channel capacity is observed.

A 2×2 MIMO system is developed using a pair of rectangular microstrip antennas and the mutual coupling between the two antennas is calculated for various separations using the computational tool, Artificial Neural Networks (ANNs).