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A Review of MIMO Antennas With Various Mutual Coupling Reduction Techniques.

Komal Dudam[1], Priyanka Nayak[2], Sonali Raut[3], Poorti Kulkarni[4] and Prof. Sheetal Bukkawar[5]
Saraswati College of Engineering

Abstract: *The high demand of wide bandwidth, high channel capacity and high data rate in wireless communication is achieved with the help of MIMO Antennas. The level of performance of the MIMO antenna is very high and steep if represented graphically but due to the use of many antennas the issue of mutual coupling exists which deteriorates the performance of MIMO antennas. The problem of multipath propagation can be solved using MIMO systems. Here in this paper we discussed the various types of monopole, fractal and hybrid antennas which can be chosen to make a MIMO system. The requirements such as high bandwidth, high data rate, omnidirectional characteristics, etc are achieved with the various types and designs of the antennas.*
Keywords: *high data rate, multiple input multiple output (MIMO), mutual coupling.*

I. Introduction

In wireless communication an antenna is the interface between radio waves propagating through space and electric currents moving in metal conductors, used with a transmitter or receiver. Antennas can be designed to transmit and receive radio waves in all horizontal directions equally or preferentially in a particular direction. There are many applications for which mainly two types of antennas are designed namely: SISO and MIMO antennas.SISO (single input single output) antenna, it is very simple and can be designed easily but has some disadvantages like, in some conditions it will be exposed to the issues like multipath effect and fading. In order to reduce the problem caused by SISO antenna, smart antenna technology is required. Therefore we design MIMO (Multiple input multiple output) antennas.In this, multiple antennas are used at the transmitter as well as at the receiver. The antenna used at the each end of the system is required to reduce errors and to enhance the speed.Multiple-input multiple-output, or MIMO, is a radio communications technology or RF technology that is being mentioned and used in many new technologies these days.Wi-Fi, LTE; Long Term Evolution, and many other radio, wireless and RF technologies are using the new MIMO wireless technology to provide increased link capacity and spectral efficiency combined with improved link reliability using what were previously seen as interference paths.Even now many there are many MIMO wireless routers on the market, and as this RF technology is becoming more widespread, more MIMO routers and other items of wireless MIMO equipment will be seen. In this smart antenna technology type, difference set of data symbols are transmitted in order to achieve high data rate compare to SISO.The importance of MIMO has increased due to its favourable applications in WLAN, digital television, metropolitan area network and in wireless compatibility of microwave access.The antenna elements are spaced by $\lambda/2$ between the elements to have suitable isolation and low correlation. In various wireless communication environments, there are many obstacles and scatters, like building, mobile terminals and offices. A problem that is encountered in such environments is multipath fading. This phenomenon limits the capacity of the antenna system. There is one way to limit that multipath fading is to use multiple antennas at either transmit, receive or both ends. In MIMO systems, more than two antennas are frequently used. Thus, for better performance of the MIMO antenna system correlation between any two antennas are required.

II. Mathematical Aspects Of Mimo Antenna

In this section the mathematical aspect of MIMO antenna in relation with the SISO antenna is introduced.

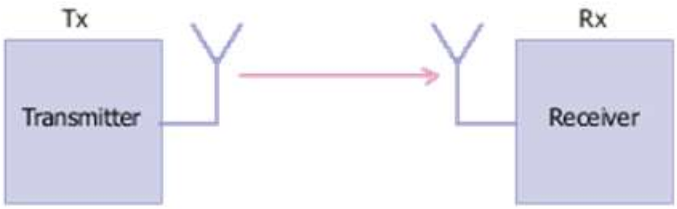


Fig.1. SISO Antenna System

The SISO system has single transmitting antenna and single receiving antenna whereas the MIMO has multiple transmitting antennas and multiple receiving antennas. The accurate information send by the entire transmitter is simultaneously received at the receiver accurately.

The capacity equation of SISO is given by expression (1),

$$C = B.\log_2\left(1+\frac{S}{N}\right) \text{bit/sec}, \qquad (1)$$

Where, C= capacity,
B= channel bandwidth in Hz
S= signal power in Watt
N= noise power in watt
The capacity of SISO is logarithmic function of S/N.

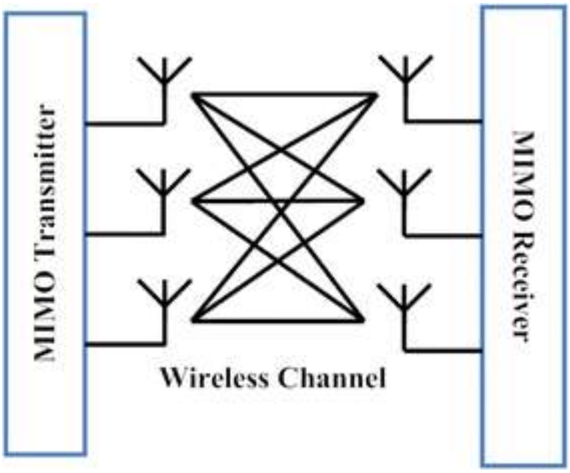


Fig.2. MIMO Antenna System

The capacity of MIMO system is given by expression (2),

$$C = E\left[\log_2 \det\left(I_{Nr} + \frac{E_t}{\sigma_n^2 + N_t}\right) H.H^H\right], \qquad (2)$$

Where, H= channel matrix
H^H= the hermitian transpose of the channel matrix
E_t= total input power
σ_n^2= noise power
I_{Nr}= identity matrix
The capacity of MIMO is a linear function of S/N.

Due to close proximity of radiating elements results in mutual coupling or correlation, the isolation is reduced and performance is achieved. The isolation parameter S_{12} or S_{21} between the ports couldn't include the effect of all S-parameters, therefore, correlation co efficient is required. By using S parameters and far field radiation patterns of the MIMO antenna, the correlation can be measured. The diversity performance of the MIMO antenna is given by expression (3),

$$|\rho_e(i,j,N)| = \frac{\left|\sum_{n=1}^{N} S_{i,n}^* S_{n,j}\right|}{\sqrt{\left|\prod_{k(=i,j)}\left[1-\sum_{n=1}^{N} S_{i,n}^* S_{n,k}\right]\right|}}, \qquad (3)$$

Where, i, j are the antenna elements and
N is the number of antennas.
For the two element antenna system, ECC can be given as equation (4),

$$\rho_{12} = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{\left(1-|S_{11}|^2-|S_{21}|^2\right)\left(1-|S_{22}|^2-|S_{12}|^2\right)}, \qquad (4)$$

Where, S_{11},S_{22} are the return losses at two ports
S_{21} and S_{12} are the isolation parameters.
Using far field radiation pattern the ECC can be measured as shown in expression (5),

$$\rho_e = \frac{\left| \int\int_{4\pi} d\Omega F_1(\theta,\phi)^{*} .\ F_2(\theta,\phi) \right|^2}{\int\int_{4\pi} d\Omega |F_1(\theta,\phi)|^2 . \int\int_{4\pi} d\Omega |F_2(\theta,\phi)|^2}, \qquad (5)$$

Where, F_i (θ, φ) is radiation field of the i^{th} antenna
The envelop correlation coefficient for two element antenna is given in expression (6),

$$\rho_e = 1 - \frac{\eta_{mux}^2}{\eta_1 \eta_2}, \qquad (6)$$

III. Different Antennas with their Geometry

A. E-shaped MIMO Antenna

A triband E-shaped printed monopole antenna is shown in fig.3. This antenna is loaded with narrow slots, suitable for MIMO applications, operating at 2.4, 5.4, 5.8GHz bands.

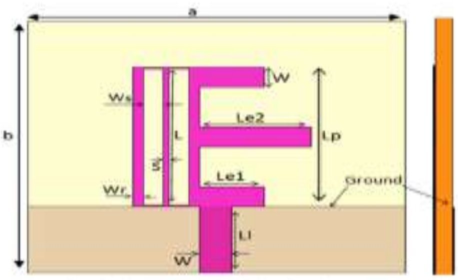


Fig.3. Configuration of the Microstrip-fed printed monopole triband antenna.

Antenna Design

The E-shaped patch is used in monopole antenna to design the E-shaped antenna. Fig.3 shows the geometry of the designed triband printed monopole antenna which is suitable for WLAN applications. To design this antenna they considered a rectangular monopole antenna with dimension $L_p \times W_p$ operating at resonant frequency of 2.4GHz. The dimensions of the rectangular patch are L_p=21mm ≊ $\lambda_g/4$ and w_p=16mm. To obtain E-shaped antenna, they have cut two small L-shaped pieces from the rectangular patch. The extra resonant modes are added to the basic E-shape antenna to create multiple bands within the frequency range. These modes are introduced through U-shaped current paths of odd multiples of $\lambda_g/4$ length.

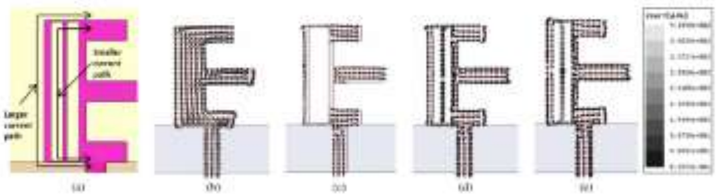


Fig.4. (a) U-shaped current path around the slots and surface current distribution on the E-shaped antenna structure
(b) With no slot at 2.4GHz, (c) With single slot at 5.4GHz,
(d) With double slots at 5.4 GHz and (e) with double slots at 5.8GHz

Figure 4 shows the result of the simulated E-shape antenna with single slot and the simulated and measured E-shape antenna with two slots. For tuning of each of the three frequency bands various parameters of the antenna are adjusted. The creation of second and third resonances do not affect the return loss behaviour of the antenna. The E and H-plane radiation patterns of this antenna at 2.4, 5.4, and 5.8GHz are shown in fig 4. It is observed that the omnidirectional E-plane pattern varies within ± 1dB throughout the WLAN range while H-plane pattern does not change with frequency change. The radiation patterns confirms that this antenna is good for use in MIMO applications.

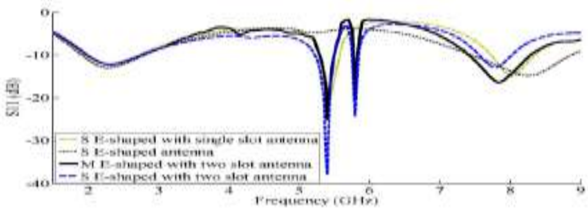


Fig.5. Simulated (S) and measured (M) return loss of the E-shaped antenna, E-shaped antenna with single slot and simulated and measured E-shaped antenna with two slots.

A triband E-shape printed monopole antenna loaded with narrow slots. The antenna parameters covers the 2.4, 5.4 and 5.8GHz bands for WLAN applications. A combination of two E-shape monopole antenna is suitable for MIMO applications. This MIMO antenna gives better than -14dB mutual coupling, envelope correlation of lower than 0.002, efficiency of higher than 90% and stable omnidirectional patterns at all three frequencies. These performances can be achieved even at low element spacing of $\lambda_g/10$.

B. PIERS PIFA MIMO Antenna

The design of a dual band internal F-PIFA is introduced in this paper. This antenna is used for dual band WLAN applications. To design a single compact antenna with dual band resonant behaviour, the 4th iteration of Koch's fractal geometry is applied to the edges of the conventional rectangular patch which is printed on a substrate with permittivity of 4.1 and thickness of 0.9mm and it is been fed to 50 Ohms probe.

The size of multiple element antenna array should be as small as possible when it embeds into a small mobile terminal. The antenna should also met other requirements such as compact structure, robustness, low profile, light weight. In MIMO antenna system, the antenna elements are present at both transmitter and receiver side. This provides the multipath fading environment. The design of multiple antenna in a MIMO system is more complicated than the design of a single antenna. The fractal is a self-similarity structure that means the small fragment of the structure can represent the original structure. Few researches are there on combination of PIFA and fractal. A miniaturized PIFA is designed for dual band mobile applications using Hilbert geometry. A fractal PIFA antenna is based on the Sierpinski carpet and it is used to obtain a multiband antenna. This antenna has achieved -6dB return loss for the required GSM, UMTS and Hiper LAN frequencies. By using PIFA structure the multiband behaviour is obtained.

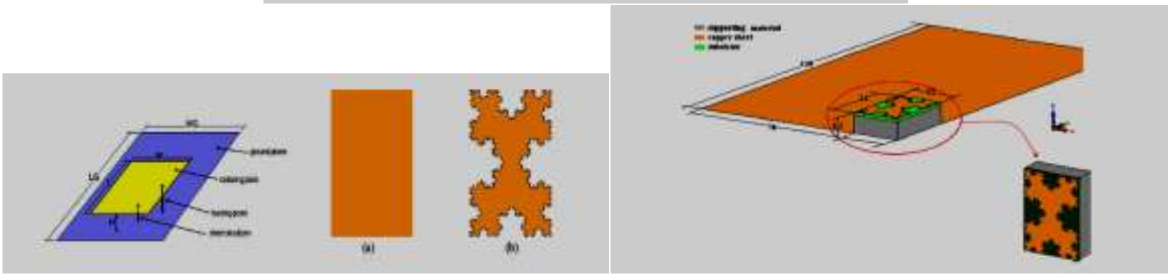
Antenna Structure

The resonant length of the antenna structure is affected due the use of Koch fractal geometry. The design of this antenna is mainly based on the PIFA antenna. The performance of this antenna depends on the antenna height H, radiating plate length L and radiating plate W. The optimized dimensions of the modified PIFA are shown below (Table 1). Using fractal geometry in PIFA antenna they obtained the fractal antenna (FPIFA). The FPIFA antenna on a ground plane is shown below (Fig.6).

The radiation patterns of the designed antenna for the two resonant frequencies;2.4GHz and 5.8GHz are given below(Fig.6).These patterns are given for two elevation planes ;XZ(ψ=0^o) ,YZ(ψ=90^0)and for the azimuth XY plane(θ=90^0). The higher band has approximately equal electric field at all the points in XY plane than the lower band. The highest values in the upper band are confined in the direction of 60^0 to 90^0 in YZ plane. They obtained the good omnidirectional radiation patterns and that are same at the two resonant frequencies.

Table 1. Dimensions of the reference PIFA Antenna

Parameter	L	W	H	L_G	W_G
Value (mm)	21	15	6.2	110	70



(A) (B) (C)

Fig 6. (A) Schematic Diagram of PIFA Antenna
(B) (a) The rectangular radiating plate
(b) The Koch fractal based radiatng plate
(C) Schematic diagram of FPIFA Antenna

Four-Element Diversity Fpifa Design

This four element diversity antenna is based on the FPIFA design. This involves four elements of FPIFA antennas in each corner of the ground plane. This is designed to achieve low correlation between the antennas. The mutual coupling between the antennas can be reduced by arranging the antennas by using the dual polarization property of the designed FPIFA. The design of the diversity antenna array is shown in fig.8. The antennas 1 and 2 (3 and 4) are spaced 40mm apart that corresponds to 0.32λ at 2.4GHz while antennas 1 and 4 (2 and 3) are spaced 68mm apart which corresponds to 0.54λ at 2.4GHz.The simulated return loss performance of each antenna of the four element diversity antenna is given in fig.4. The bandwidths of these four antennas are same .The simulation result shows the isolation between the elements is low which is a good diversity performance. The isolation between each pair of antennas is shown in fig.8. The isolation for antenna pairs (1, 3) and (2, 3) is more than 12dB in the lower band and more than 20dB in the higher band. Due to this the mutual coupling is very low and a low correlation between the antennas.

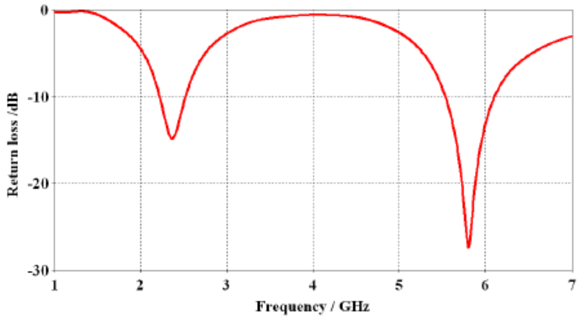
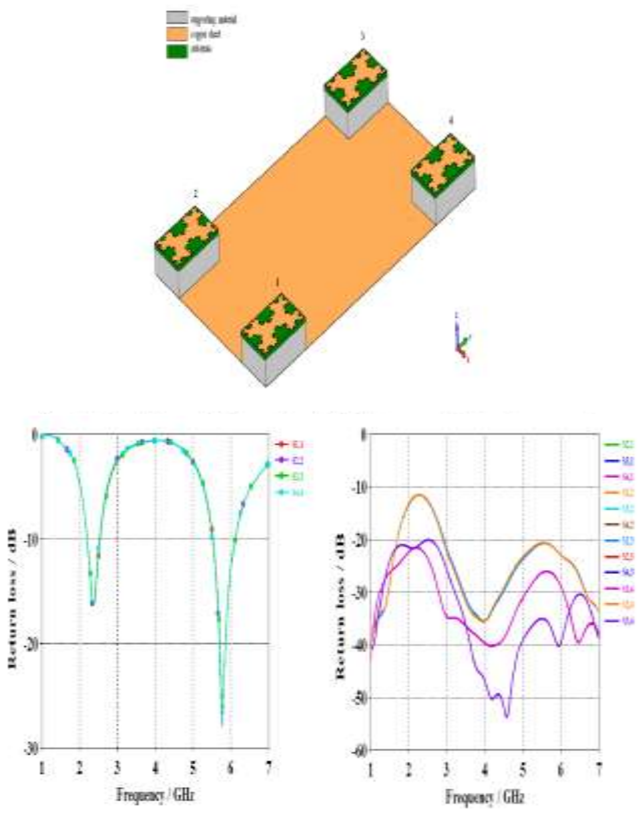


Fig.7. Simulated return loss of the FPIFA antenna



(A) (B) (C)

Fig 8. (A) Schematic of four element diversity FPIFA Antenna array placed on the same ground plane (B) Return loss characteristics of the FPIFA antennas 1, 2, 3 and 4 and (C) Isolation between each pair of antennas on the diversity FPIFA antenna array.

The designed MIMO antennas is for 2.3GHz and 5.8GHz bands. Antenna size is reduced by applying Koch's fractal geometry. This reduces the size of radiating patch of antenna by 33%. The designed system offers <=-10dB impedance bandwidths of about 300MHz with an isolation of 12dB for lower band and 570MHz with an isolation of higher than 22dB for the upper band.

C. UWB MIMO Antenna with Novel Stub

MIMO is an important technology. This technique uses multiple antennas on the terminals. System's capacity or range can be increased significantly by using this technology. The UWB technology is also in the race of wireless world since Federal Communications Commission (FCC) has approved the use of UWB devices operating in the 3.1-10.6GHz frequency range. Due to extremely low transmitted power this technology is limited to short range communications. The solution for this is the combination of MIMO techniques with the UWB technology. Also the problems like poor isolation and strong mutual coupling arises in MIMO technique. These problems can be solved by increasing the distance between the antenna elements but the compact size of the device limits this approach. The diversity performance is increased using matching and decoupling networks. The isolation is obtained by adding a coupling element between two closely packed antennas. To reduce mutual coupling between the antennas, a slotted pattern based ground plane is used.

This antenna uses the approach of using stubs on the ground plane in order to improve isolation. This antenna has a compact structure and gives good impedance characteristics in 3.2-10.6GHz band and good isolation characteristics hence provides good diversity performance. Due to the use of the proposed stub, the distance between radiating elements in compact UWB-MIMO antenna. The antenna is miniaturized from $43 \times 80mm^2$ to $40 \times 63mm^2$.

Antenna Geometry And Design

This antenna consists of two radiating elements. A circular disc monopole fed by 50Ω Microstrip line is used to design UWB-MIMO antenna. This antenna is printed on FR4 substrate having r elative permittivity of 4.4, thickness of 0.8mm and 0.02 dielectric losses. To enhance the isolation between the access ports of the radiating elements, an inverted Y shaped stub is inserted on the middle of the ground plane. The dimensions of the substrate are : width(W)=68mm, length of substrate(L)=40mm, length of ground plane(L_g)=11.5mm, feed gap(h)=0.3mm, radius of each radiating element®=12mm and the distance between two elements(d)=34mm.

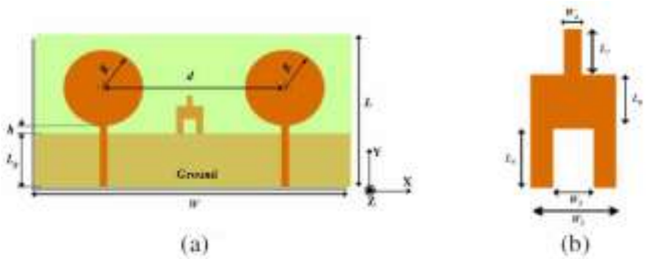


Fig.9. (a) Layout of UWB MIMO Antenna (b) Detailed layout of inverted Y-shaped stub

The dimensions of inverted Y stub are given below.

Table 1. Dimensions of inverted Y stub

W_2	W_3	W_4	L_5	L_6	L_7
6	4	1.5	6	4	2

Fig (10) illustrates the simulated as well as the measured S-parameters of the designed UWB-MIMO antenna with And without stub. These curves indicate that isolation is significantly increased in the higher band of the operating Range.

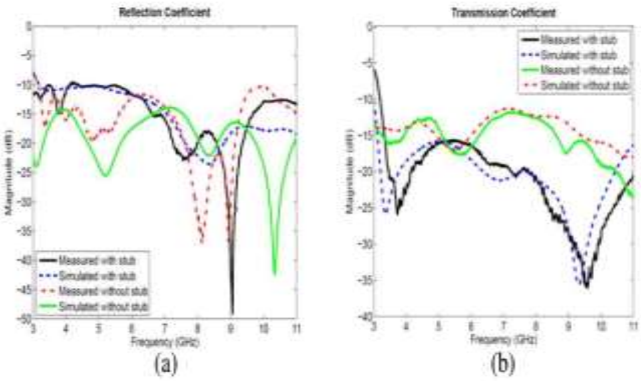


Fig (10). Measured and simulated (a) reflection coefficients and (b) transmission coefficients of the designed antenna with and without stub.

Fig (11) shows the current distributions with and without stub at three frequencies 3.5GHz, 7GHz and 9.5GHz when

Left radiating element is excited while the right radiating element is terminated with a load impedance of 50Ω.

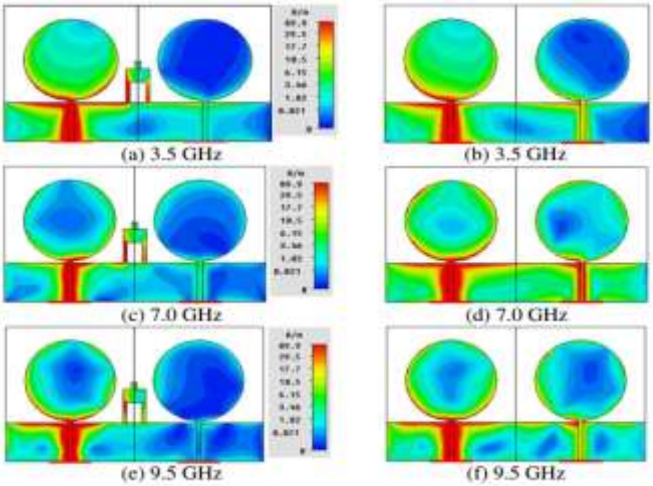


Fig (11). Surface current distributions of antenna: (a), (c) and (e) with stub (b), (d) and (f) without stub.

Performance Of Uwb-Mimo Antenna

1. Radiation Characteristics

The results shows that antenna behaves nearly omnidirectional in H-plane. Fig (12) gives the maximum absolute gains and the total efficiencies of the designed antenna.

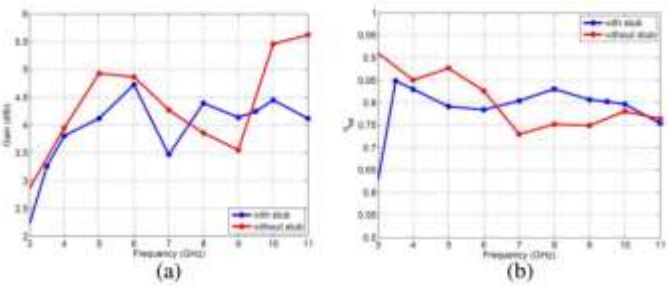


Fig (12). Simulated (a) absolute gains and (b) total efficiencies of the designed antenna.

2. MIMO Characteristics

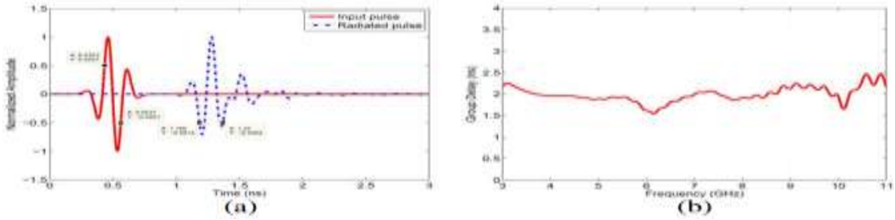


Fig (13). Time domain characteristics.

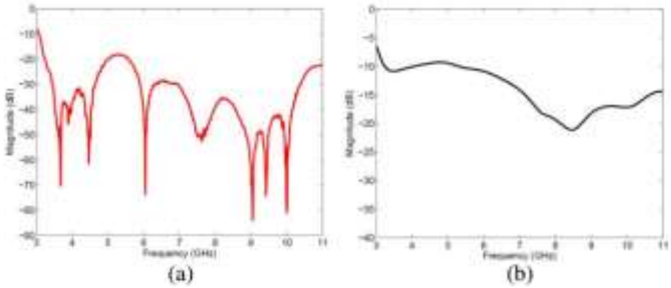
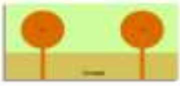


Fig (14). MIMO characteristics (a), envelope correlation and (b) TARC.

Table 2. Performance comparisons of antenna with and without stub.

Parameters	Ref. [13]	This article
Layout		
Constituent Elements	Circular disc	Circular disc
Feeding configuration	Parallel	Parallel
Impedance BW (GHz)	3.1 – 10.6	3.1 – 10.6
Gain variation (dBi)	< 3.5	< 2.5
Total efficiency	> 75 %	70 % – 85 %
Group delay (ns)	2.2	1
Isolation (dB)	> 11	> 15
Correlation coefficient (dB)	< - 15	< - 20
TARC (dB)	< -10	< - 9.5
Size (mm²)	43 × 80	40 × 68

D. Compact Co-Radiator UWB-MIMO Antenna with Dual Polarization

Here a two- and a four element co-radiator UWB MIMO antennas with dual polarization is proposed.

Two element UWB MIMO Antenna

Here co-radiator is used as the co-radiator are the best system size reducers for the MIMO antennas. The perpendicular taper Microstrip feeding structures are used to feed the pentagonal radiators. The dual polarization is used to reduce the mutual coupling, increase transmission capacity and improving the reliability of the system. The diversity gain and mean effective gains that is (DG) and (MEGs) respectively.

The design of antenna-I is given in the fig 15. The simulated and measured S parameters of antenna-I is shown in fig. 16 where in the impedance matching and isolation characteristics of the UWB is achieved.

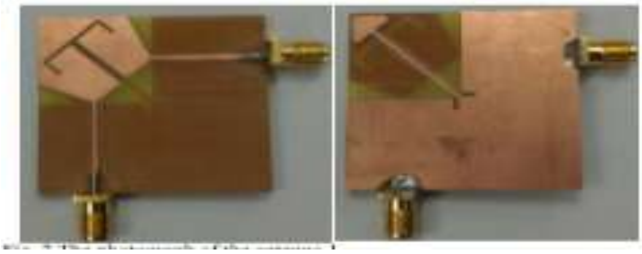


Fig. 15. The design of antenna-I

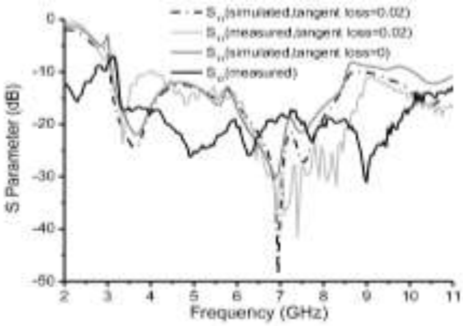


Fig. 16. The simulated and measured S-parameter

Here, the achievement of the UWB MIMO antenna is to get high isolation between the elements. So to observe that we refer the current distribution patterns of the antenna-I in fig.17 and this proves the achievement of mutual decoupling and here the higher resonant frequency can be used for the improvisation in the isolation.

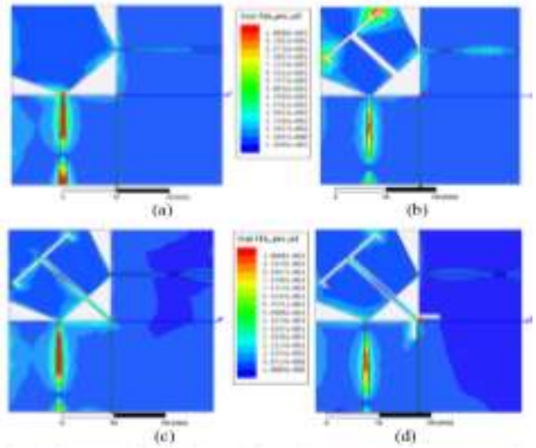


Fig.17. Current distribution in antenna-I

But later for different excitation of different ports the results were different and the above mentioned achievements were reduced to further levels as shown in fig. 18 the current distribution of simulated S_{21} antenna and then the corresponding far field distribution in them shows that the mutual decoupling increases and also the poor isolation is achievement. However from fig.19 the dual polarization is achieved is observed. But it is at the cost of poor isolation and poor mutual decoupling.

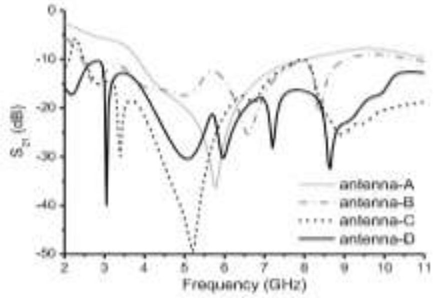


Fig.18. Simulated S-parameter graph

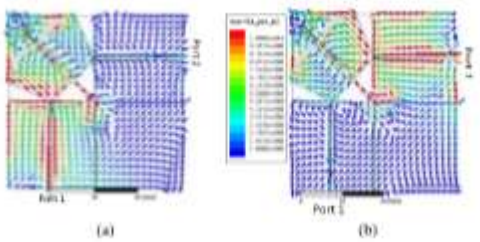


Fig.19. Current distribution when (a) port1 is excited and (b) When port 2 is excited

Four element UWB MIMO Antenna

The channel capacity and the reliability of a system depends on the number of elements used in it. The fig. 20 shows the picture of the four element antenna-II with the size of 48mm x 48 mm. Here too, we get the S-parameter graph (fig.21) and the simulated current distribution patterns (fig.22) which depicts that the isolation is achieved greatly and also that the antenna has diversity characteristics due to its radiating nature in many directions.

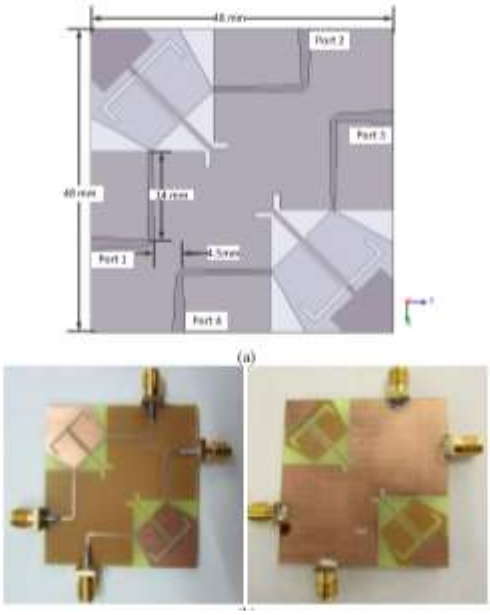


Fig.20. picture of four element antenna

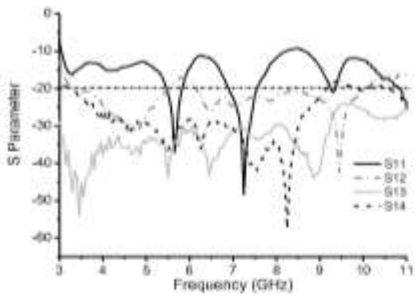


Fig.21. S parameter graph

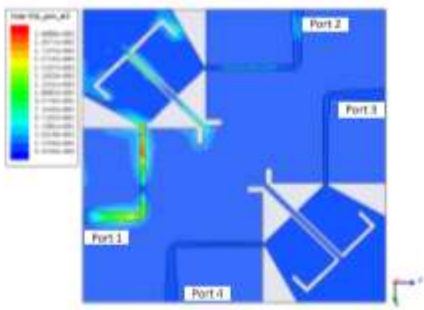


Fig.22. Current Distribution of antenna-II

We have the plotted graph for the measured gains in the two antennas and the simulated radiation efficiency graph through which we observe that the UWB gain in both the antennas are high for many frequencies leaving the higher ones. (fig.23)

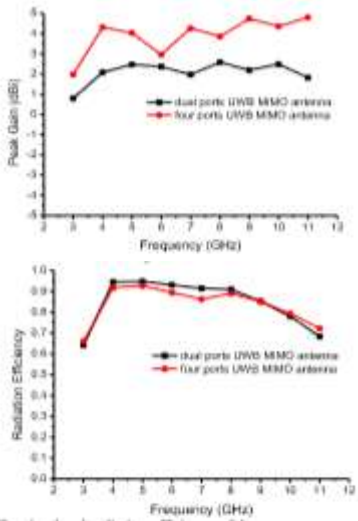


Fig23. The measured gains in the two antennas and the simulated radiation efficiency graph

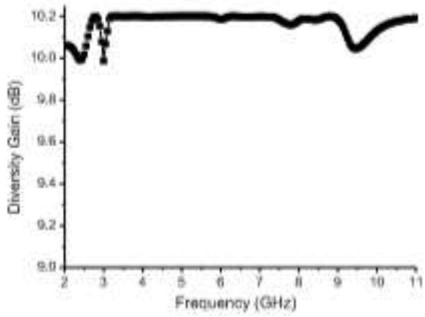


Fig.24. Diversity graph of two Antennas

The diversity graph of the antenna shows that the gain of the antennas is very well in the UWB. (fig.24)

E. UWB MIMO Challenges

UWB communication have received a lot of publicity in terms of future technology regarding high data rate and short-range transmission. This research proposes a compact MIMO antenna with two port symmetrical radiating elements on the same substrate. The antenna's radiating element consists of seven small circles surrounding the centre single circle with a 50 Ω Microstrip line feed. This seven-small circle works as a filter. Such filters increase the antenna's complexity and dimensions.

MIMO antenna has successfully functioned for UWB operating frequency of 2.8 GHz to 8 GHz, with good impedance matching of −54 dB. As compared to conventional antenna, gain of UWB MIMO's is high i.e. 6dBi. Due to high bandwidth and compact size UWB MIMO is accessible for wireless communication system. Hence, this research focuses on the minimization of the mutual coupling and the correlation coefficient since a lower mutual coupling increases radiation efficiency while a lower correlation coefficient improves antenna diversity.

Antenna Structure And Experimental Setup

Figure 26 and Figure 27 illustrate the proposed UWB-MIMO antenna's geometry and prototype, respectively. The UWB-MIMO antenna consists of a combination of two identical antennas on the same substrate. Novel antenna is developed by integrating seven small circles surrounding the centre circle. The circles have a diameter of Rs and Rin, respectively. With the feed width of W_f, the impedance of Microstrip feed lineis fixed to 50Ω. The structure of the antenna element has been fabricated on the Taconic TLY-5 substrate with a thickness of 1.5748 mm, dielectric permittivity, $\varepsilon_r$of 2.2 and tangent loss, tan δ, of 0.0009.

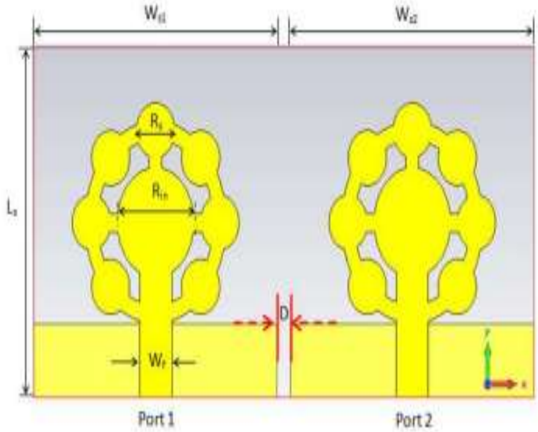


Figure 26. The simulated geometry of the proposed UWB MIMO antenna.

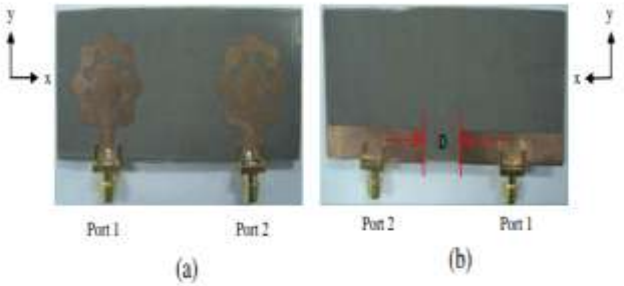


Figure 27. The fabricated geometry of the proposed UWB MIMO antenna. (a) Front view. (b) Back view.

The UWB antenna basically comes from a single circle structure, therefore more current is distributes near the edge of the circle. This research reduces the inner circle diameter and introduces a ring with 1 mm size surrounding the circle.

The single antenna with the dimensions of Ls × Ws1 is developed. The second antenna is drawn by replicating the first antenna structure on the same substrate. The geometrical values are: Ls = 38 mm, Wf = 5 mm, Rin = 12 mm, Rs = 6 mm, Ws1 = 38 mm, and Ws2 = 38 mm. The distance between both the antennas symbolized by D. All measurement processes have been carried out in the research cluster of the University Malaysia Perlis (UniMAP) with the help of Agilent Technologies E83628 PNA Network Analyser and 2D Anechoic Chamber as visualized in Figure 28. The horn antenna performed as a transmitter is competent to function from 1 GHz to 18 GHz. The antenna being tested (UWB-MIMO antenna) executes as a receiver. Both antennas are placed about 1 m apart.

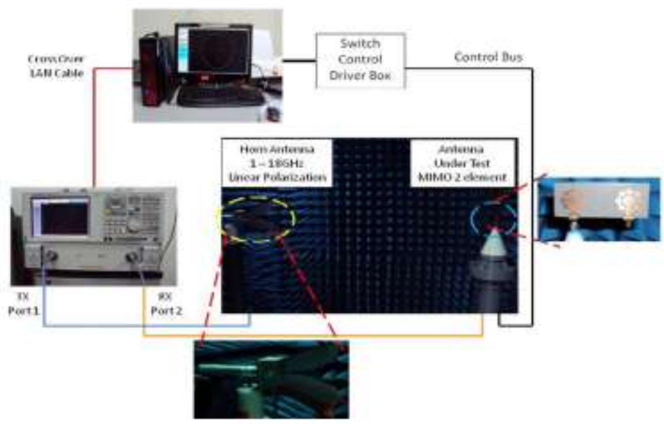


Figure 28. Agilent 2D PNA antenna test system.

Figure 29. Shows the simulated UWB MIMO antenna's return loss with a variety of 7-filters dimension; 5 mm, 6 mm, 7 mm and 8 mm. It shows that, the 7-filter has a major influence on the upper frequency and minor influence on the lower frequency.

A study on the effect of IES represented by D towards the input reflection coefficient is performed. From Figure 30, all D variables have three dominant frequencies that successfully function between 3.1 GHz and 10.6 GHz. The impedance matching is optimum at a particular frequency of 6GHz, as D=0mm. The relation between correlation coefficient and diversity gain is mathematically expressed as in equation (7),

$G_{app} = 10 * \sqrt{(1 - |\rho|)}$ (7)

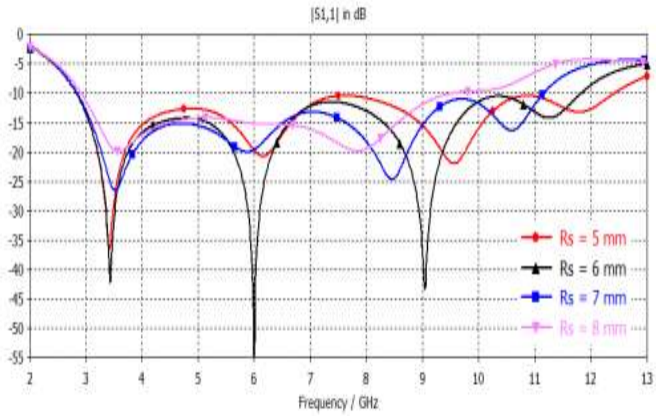


Figure 29. Simulated UWB-MIMO antenna's returns loss on 7-filters dimensions effect.

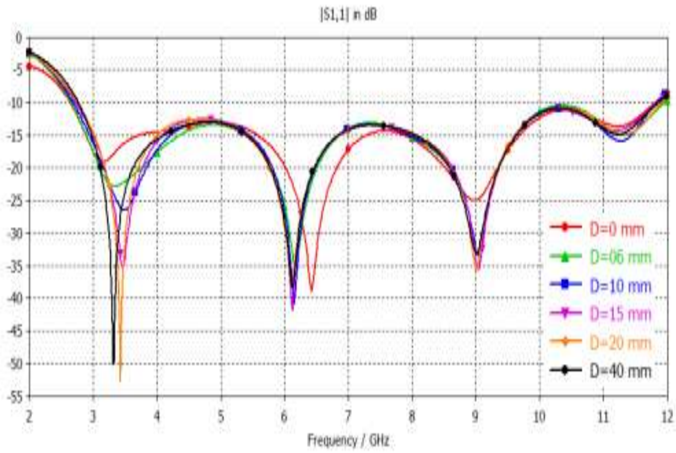


Figure 30. Simulated UWB-MIMO antenna's returns loss on IES effect.

The scattering parameters via Equation (8) are also capable of the intended correlation coefficient.

$\rho = |S_{11} * S_{12} + S_{21} * S_{22}| 2 (1 - (|S_{11}| 2 + |S_{21}| 2)) (1 - (|S_{22}| 2 + |S_{12}| 2))$ (8)

IV. Conclusion

Different isolation methods are used to improve performance parameters like ECC, Gain and isolation. In PIFA antenna, the size of antenna is reduced by applying Koch fractal geometry. It also reduces the size of radiating patch of antenna by 33%. This system offers less than equal to -10dB impedance bandwidth of about 300MHz.with an isolation of about 12dB for the lower band and 570MHz with an isolation of higher than 22dB for the upper band. E –shaped MIMO antenna provides better than -40dB mutual coupling, envelope correlation of lower then 0.002, efficiency of higher than 90% and stable omnidirectional patterns at all the three frequencies. A hybrid fractal planar monopole MIMO antenna provides measured bandwidth of 14% for the band 1 and 80% for band 2. The capacity loss remains below 0.3b/s/Hz. In high profile monopole antenna, more than 20dB reduction in mutual coupling between antenna elements is achieved. Good impedance matching can be achieved. Compact MIMO antenna, achieves good isolation between input ports.

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