Chapter 2

MULTIPLE INPUT MULTIPLE OUTPUT ANTENNAS

2.1 Introduction

MULTIPLE INPUT MULTIPLE OUTPUT (MIMO) configuration has proved its importance in achieving diversity performance for wireless applications. In MIMO technique transmission and reception of signal is done by multiple antenna elements which leads to increased data rate, reliability, and efficiency of wireless systems. But attenuation of the signal over some bands is observed due to fading effect which reduces the quality of data transmission. Fading reduces signal power due to multi-path propagation. As errors in transmitting data increases, the effective throughput of the system decreases which deteriorates the channel capacity of a RF transmitter [1]. Use of diversity technique decreases the fading effect by discovering different signal paths for communication. Time and frequency diversity techniques play a major role in this regard. An advanced technique such as space diversity is used to reduce multi-path propagation. Multiple antennas are used at the transmitter as well as at the receiver to increase channel capacity by reducing the fading effect. Standard single input single output (SISO) operation was used to transmit diversified signal but this system has limited performance in terms of the channel capacity. Multiple antenna elements at the transmitter and the single element at the receiver form multiple input single output (MISO) system which creates transmit diversity. Single input multiple output (SIMO) antennas allows receiving diversity when multiple antenna elements are used at the receiver. MIMO system is formed when multiple antenna elements are being used at both the transmitter and receiver side for communication[2]. The channel capacity of MIMO antenna can be increased by reducing coupling between antenna elements. Also gain enhancement can be done by increasing the number of antenna elements. But this, in turn, increases the fabrication cost, size of antenna and power handling capacity of the multiple streams of data. This generates the limitation to the number of antennas. To achieve compact size, minimum correlation and high gain for a single structure with multiple radiating elements is a challenging issue and provides research opportunity in the domain of MIMO antennas.

2.2 Performance parameters of MIMO antennas

This section discusses various performance parameters of single element antenna as well as special parameters which characterizes multiple-element antenna [3].

2.2.1 Impedance Bandwidth

Bandwidth (BW)is defined as the range of frequencies over which the antenna characteristics are acceptable with respect to the center frequency. In wireless applications, bandwidth is measured for the return loss less than -10 dB. The bandwidth of an antenna can be expressed as either absolute bandwidth (ABW) as per eqn. (2.1) or fractional bandwidth (FBW)as per eqn. (2.2). The ABW is defined as the difference between the lower and higher edge frequency and the FBW is defined as the percentage of the difference in frequency over the center frequency. F_H and F_L denote the upper edge and the lower edge of the antenna bandwidth, respectively.

$$ABW = F_H - F_L \tag{2.1}$$

$$FBW = 2[\frac{F_H - F_L}{F_H + F_L}] \tag{2.2}$$

2.2.2 Radiation performance characteristics

The radiation properties of the antenna device are studied with the help of radiation pattern. Generally, in the far field region radiated power is distributed independently with respect to distance.

The radiation property of antenna is described with following three radiation patterns.

- Isotropic Antenna: An antenna having equivalent radiation in all directions is called an isotropic radiator. This property is applicable only for an ideal antenna. Usually, isotropic radiator is taken as a reference for calculating directive properties of practical antennas.

- Directional Antenna: These antennas shows directional properties where antenna radiates more effectively in particular direction compare to other directions.

- Omni-Directional Antenna: An antenna has a non-directional pattern in a given plane and a directional pattern in an orthogonal plane.

2.2.3 Directivity

Directivity describes the directional properties of an antenna. Directivity is defined as the ratio of the radiation intensity (U) in a given direction from the antenna to that of an isotropic source. Eqn.(2.3) shows directivity depends on the radiated power.

$$D = \frac{4\pi U_{max}}{P_{rad}} \tag{2.3}$$

2.2.4 Gain

The antenna gain gives relation between the intensity in a given direction to the radiation intensity obtained when the power accepted by the antenna radiated isotropically. Antenna gain (G) and the directivity are related with the radiation efficiency (e_{rad}) and is given by eqn.(2.4)

$$e_{rad} = \frac{G}{D} \tag{2.4}$$

2.2.5 VSWR and Return Loss

Voltage Standing Wave Ratio describes power reflections from the antenna. It is related with reflection coefficient (τ), then VSWR is defined by eqn.(2.5) and corresponding return loss is given by eqn.(2.6)

$$VSWR = \frac{1 + |\tau|}{1 - |\tau|} \tag{2.5}$$

$$RL = -20log\left|\tau\right| \quad (2.6)$$

The VSWR ranges from 1 to ∞. For delivering more power to the antenna i.e. better matching smaller value of VSWR is required. Hence reflection coefficient will be zero i.e. no power reflected back.

For characterizing MIMO antenna along with basic antenna characteristics such as gain, bandwidth, efficiency etc., parameters such as isolation, correlation coefficient, channel capacity are also essential. In this section, additional MIMO antenna metrics are discussed in details.

2.2.6 Total Active Reflection Coefficient (TARC)

Total Active Reflection Coefficient (TARC) (as per eqn. 2.7) is defined as the square root of the ratio of the power available at all the ports minus the radiated power to the total available power.

$$\Gamma_a^t = \sqrt{\frac{Availablepower - Radiatedpower}{Availablepower}} \quad (2.7)$$

TARC is expressed in terms of frequency. TARC is a real number between 0 and 1. If TARC=0; All delivered power is radiated. If TARC=1; All power delivered to the antenna is either reflected back to the source or goes to other port.

2.2.7 Correlation Coefficent

Correlation coefficient is the key parameter for the diversity applications. The correlation coefficient (ρ) describes isolation between communication channels. This metric can be calculated either with the scattering parameters or from the radiation pattern of the antenna system. The square of the correlation coefficient is known as the envelope correlation coefficient. In an isotropic communication channel, the envelop correlation coefficient ρ_e can be calculated as per eqn.(2.8)

$$\rho_e = \frac{\left|\int\int_{4\pi} F_1(\theta,\phi) \times F_2(\theta,\phi) d\Omega\right|^2}{\left|\int\int_{4\pi} F_1(\theta,\phi) d\Omega\right|^2 \times \left|F_2(\theta,\phi) d\Omega\right|^2} \quad (2.8)$$

where $Fi(\theta,\phi)$ is the field radiation pattern of the antenna. When the i^{th} port is excited and remaining ports are matched with 50Ω load. This expression is complicated and requires three-dimensional measurement of radiation pattern. Envelope Correlation coefficient (ECC) can be calculated using numerical integration. Another method in [3] proves that S- parameters can be used to calculate ECC. eqn. (2.9) gives general expression for calculating ECC,

$$\rho_e = \left| \frac{S_{11}^* S_{12} + S_{21}^* S_{22}}{\sqrt{1 - S_{11}^2 - S_{21}^2}\sqrt{1 - S_{22}^2 - S_{12}^2}} \right| \tag{2.9}$$

2.2.8 Diversity Gain

Diversity gain is used to measure the performance of diversity technique.

$$DG = 10\sqrt{1 - \rho_e^2} \tag{2.10}$$

From eqn. (2.10) it is clear that as correlation coefficient decreases, the diversity gain increases. Hence systems with high isolation provide good diversity gain.

2.2.9 Mutual Coupling

Ideally, in MIMO application the transmitted signals from multiple antenna elements must be independent and uncorrelated to have lower fading effect. But, in reality, mutual coupling is observed between two radiating elements due to the current induced on one antenna element produces a voltage at nearby elements. Hence, for MIMO application, very low mutual coupling is needed.

2.2.10 Isolation

Isolation is the amount of transmitted power between two input ports of the multi-port antennas under test. Isolation is characterized by S_{21} parameter and is calculated by eqn. (2.11).

$$Isolation = -10log|S_{21}|^2 \tag{2.11}$$

In MIMO systems for maximum radiations by an antenna, it is expected to have minimum energy loss into the ports of other antennas with matched impedance. Though all the ports are isolated, practically some amount of current gets induced in the nearby antenna affecting the radiation pattern of the antenna.

2.3 Antenna Diversity

Improvement in quality and reliability of the wireless system can be achieved by utilizing two or more antenna called as antenna diversity. There are many ways to realize antenna diversity. As per environment condition and the estimated interference, RF engineers can adopt different methods to improve signal quality.

In **spatial diversity**, multiple antenna elements with the same characteristics were employed which are separated with some distance from each other. This is especially advantageous for wireless communication applications such as mobile communication where many clients share a restricted communication spectrum and interference between co-channel can be avoided.

In **pattern diversity**, technique two or more antennas are placed parallel to each other with different radiation characteristics. In this type of diversity technique antennas directed in one particular direction are used and are usually placed at some short distance from one another. In pattern diversity, antennas are capable of differentiating a large portion of space in an angular pattern. The gain achieved form such antennas is higher compared to a single radiator with the omnidirectional pattern.

In **polarization diversity**, the pair of antennas gets combined with orthogonal polarizations such as horizontal as well as vertical polarization, slanting polarization, Left-hand as well as Right-hand circular polarization. Polarization diversity can be decided by reflected signals as polarization changes depend on the traveling medium. Combination of two opposite polarizations, protect a system from polarization mismatches else signal fading takes place. This kind of diversity type is more applicable to radio communication and mobile communication base stations as system is less prone to interference of the signals to the nearby randomly oriented antennas at the transmitter side.

Transmit/receive diversity, have two different antennas placed parallel at the transmitter as well as at receiver side. In such systems, the duplexer is not required. This protects receiver components from the high power.

2.4 Challenges in MIMO antenna system design

Antenna designing for the diversity applications in various wireless systems has several challenges. In this section, the key challenges that are faced by the RF designer for wireless systems are discussed.

2.4.1 Miniaturization and integration Issues

Antenna miniaturization and integration is a challenging task in applications such as mobile antennas, satellites antennas where antenna elements are placed in close proximity. Radiation efficiency and bandwidth get affected due to the compact size of the antenna. These important factors need to be carefully explored for the adequate performance of the wireless system. An appropriate study on such issues was conducted in [4]

2.4.2 Antenna coupling and isolation enhancement

If the distance between two antenna elements is less then high coupling is observed in MIMO antenna. In the devices with compact size such as mobile phones, USB dongles where multiple antenna elements are spaced adjacent to each other and hence high coupling is obvious. Efficiency, data rate and capacity of the MIMO system gets affected due to high coupling between antenna elements spaced closed to each other. Many configurations have been discussed in the literature to reduce the coupling effects on the basis of the antenna structure, its radiation and feeding mechanisms. Following methods are reported to increase the isolation in the MIMO antenna system:

1) Orientation and placement of antenna elements: Antenna elements placed closed to each other in a wireless system have high coupling. Structure of the ground plane as well as radiated fields affects the coupling characteristics. This affects efficiency and coupling between antenna radiating elements, this affects the channel capacity of the system. By placing the radiating elements apart within a wireless system is a simple way to reduce coupling effects. Change in position of antenna elements affects the nature of the coupling currents and the polarization nature of the radiated fields. Coupling in ground plane can be reduced by placing an antenna in phase quadrature with each other. Hence it is necessary to study antenna orientation and its placement to reduce mutual coupling effects. Literature and experimentation of similar work is discussed in [5] - [8].

2) Decoupling Networks: A decoupling network is used to increase the efficiency of the antenna in terms of radiations to decouple the input ports of adjacent antennas. Lumped elements as well as distributed elements used while designing a matching circuit of decoupling network so that isolation between adjacent antennas can be enhanced. This technique has been used in several designs such as those in [9] - [12].

3)Parasitic elements: Improvement in efficiency, isolation and envelope correlation coefficient among the nearby antenna elements is observed by canceling most of the coupled fields between them. Coupling current gets reduce because of the creation of opposite coupling fields on the radiating antenna. These fields are opposite in polarity that of original fields. These parasitic elements are studied in [13] -[18].

4) Defected Ground Plane Structures (DGS): The characteristics of the antenna elements have been affected by modifying the bottom plane (ground plane) of the antenna system. Ground plane provides the path of the return current and occasionally at lower frequencies becomes part of the radiating structure. The perturbations on the ground plane induce a current. The perturbations also affect the mutual coupling between adjacent multiple antenna elements. Previous work includes designs such as a group of slits [19] - [21], the use of dumble-shaped defects [22] - [23]. In literature lot of survey for these kinds of geometries for making defects has been found in [24].

5) Neutralization lines: This technique is an enhancement in isolation where the current phase at a particular location is converted by choosing a suitable length of the line. This inversion in current element is supplied to the adjacent antenna element. Thus neutralization line decreases the amount of coupled current. As the location of a point on neutralization line changes, it varies corresponding impedance which directly affects the effective bandwidth. The point at which impedance is found to be low of radiating structure is chosen as a starting point of neutralization line. This method is effectively used for mutual coupling reduction between adjacent multiple antenna elements [25] - [28].

6) Use of Metamaterials (MTM): Metamaterials can be one of the solutions for reducing coupling between nearby antenna elements of a MIMO antenna system. In literature lot of work shows the utilization of metamaterial for isolation enhancement such as those in [29] - [32].

2.4.3 Correlation coefficient calculation

Diversity behavior of MIMO antenna depends on the correlation coefficient. Ideally, MIMO antenna radiation patterns must possess zero correlation. Practically, it is difficult to achieve so. Hence, reducing the interference between fields is a challenging task when the two antennas are placed very close to each other. The correlation coefficient can be evaluated based on S- parameter method as well as from radiation patterns.

2.4.4 Measurements

Measurement of antenna radiation characteristics in the real environment is carried out by over the air testing (OTA) method. This challenging task depends on different factors such as the processing of baseband signals at the receiver, operating modes of signals, performance of the antenna system and the various conditions of channel propagation.

The three methods widely used are:

1) The Anechoic chamber testing method [33].

2) The two-stage testing method [34].

3) The Reverberant chamber method [35] - [36].

2.5 Literature Survey:Contribution towards MIMO antenna design based on challenges and techniques available

A lot of research has been made for increasing impedance bandwidth and reduce coupling between the radiating element in the MIMO antenna system. Size reduction, as well as achievement of high gain, is also a challenging task.

- Use of neutralization-line technique [23-24]

  A neutralization line technique is used for decoupling of ports in antenna for USB dongle used in wireless applications. Two monopoles are placed on the two opposite corners of the printed circuit board. A noticeable improvement is seen in isolation when a small portion from the ground is removed and a thin printed line is used to connect two antennas. Use of neutralization line improves isolation from -9 dB to -19 dB. The antenna showed a peak gain of 2.1 dBi (decibels isotropic) with radiation efficiency exceeding about 70%.

- Decoupling and Matching Network [DMN] for Diversity Application [25]

  A compact decoupling and matching network with frequency tuning capability using a single varactor diode is used for better isolation purpose. The decoupling and matching network achieves perfect matching and thus simultaneous isolation and matching of a system can be achieved by keeping the circuit size small. DMN is demonstrated by arrays of wires placed close to each other and a pair of microstrip monopoles. The proposed DMN uses one varactor diode to achieve 18.8 % of tuning range. Return loss and isolation better than -10 dB is achieved when the spacing between the antennas is $0.05\lambda_0$. λ_0 is a free space wavelength.

- Compact electromagnetic band gap (EBG)structures [26-27]

  EBG is the periodic arrangement of dielectric materials or slots embedded on metal sheet. Periodic structures reduces mutual coupling in array antennas. Cells are joined to improve the mutual coupling between patch antenna arrays.Reduction in mutual coupling level reduces coupling coefficient can be calculated by eqn.(2.11) [49].

$$|C|^2 = \frac{|S_{21}|^2}{\left(1 - |S_{11}|^2\right)\left(1 - |S_{22}|^2\right)} \tag{2.12}$$

- Fractal Shape Monopole Antenna for Multi-band Wireless MIMO Communications [28]

  Basically, antennas are narrow-band devices. Strong variation is seen in antenna parameters with respect to frequency and it's size. But for given frequency antenna cannot be made arbitrarily small. Hence fractal design and metamaterial is a perfect solution to explore multi-frequency operation and size reduction in the antenna. Self similarity in fractal geometry gives rise to multi-frequency, self-filling in fractal reduces overall dimension of the structure, boundary fractals, and mass fractal increases directivity and reduces side lobes in radiations. Use of fractal geometry in MIMO improves gain, reduces the size of structure and coupling between two radiating structures.

- Compact Printed UWB Diversity Slot Antenna With 5.5 GHz Band-Notched Characteristics [29]
  Slot and defected ground structure method are type of decoupling structures. This technique enhances isolation in MIMO antenna structure. In [29] the antenna with coplanar waveguide feeding and staircase shaped radiating element is used for orthogonal radiation patterns. Isolation is improved by using stub placed at 45 degrees. The same antenna structure can be act as a filter by rejecting some of the frequencies. This can be achieved by using split ring resonator slots on the radiating patch. In [30] slots are used on radiating plane as well as on ground plane to enhance isolation.

2.6 Design challenges in MIMO antenna systems

- Isolation: Isolation and mutual coupling are related parameters in MIMO antenna. Mutual coupling shows an effect on the antenna efficiency as well on the correlation. For better performance of MIMO antenna isolation of -15 dB or less is expected in the operating zone of the antenna system.

- Bandwidth: Bandwidth is related to return loss characteristics.Return loss (S_{11} in dB) should be less than -10 dB for particular application. For ultra wide-band applications i.e. 3.1 GHz to 10.6 GHz range covers the impedance bandwidth. Achieving high isolation and high impedance bandwidth simultaneously in a multiple antenna structure is a major challenge in the MIMO antenna system.

- Size: Recent communication technologies require high-speed data transmission and reception. Hence MIMO has been adopted in wireless applications such as WiMAX, WLAN, mobile phones. Due to less space availability in wireless devices, a compact wide-band MIMO antenna is required. Antenna miniaturization affects the radiation efficiency of the antennas as well as its operating bandwidths.

- Correlation coefficient calculation: A correlation coefficient is the measure for good diversity system. In industrial applications, an envelope correlation coefficient of 0.5 is acceptable for good diversity performance [3]. The correlation coefficient can be evaluated by using the S-parameter method as well as from the radiation pattern method. Maintaining a correlation below 0.5 between MIMO elements is a challenging task.

2.7 Proposed solution

In the present work ,design of various MIMO antenna structures with high gain and low correlation coefficient using various configurations are proposed. To achieve challenges antenna must be designed considering the following factors:

- The antennas must have some degree of directivity that can be controlled
- The antennas must have high gain and efficiency
- The antenna must possess ultra wide band characteristics
- The antenna should have differently-directed spatial radiation patterns
- Coupling between the antennas must be minimized
- The antennas must be electrically small to minimize interaction between them
- The antennas must have properly matched terminations
- The correlation coefficient between the MIMO antenna must be as low as possible

2.8 Planning to achieve proposed solution

- Designing the planar antenna
- Modification using different methods such as monopole, slot, fractal, DGS, EBG etc.

- MIMO antenna design for increase in the channel capacity and to reduce the mutual coupling using above methods
- Orientation of the antenna elements to study polarization characteristics
- Increase in the number of radiators to study gain characteristics

2.9 Research Methodology

2.9.1 Current scenario of development of MIMO antenna

In present trends, MIMO antenna focuses on high capacity wireless systems which show applications like WLAN, WiFi, bluetooth, satellite applications etc. The present research will focus on MIMO antenna design for single band applications, multi band applications, band reject characteristics, UWB applications, K band, Ku band applications. The research methodology for the same is discussed as follows:

2.9.2 Antenna parameters to be studied

The quality of any wireless system is based on characteristics of the antenna element present at the transmitter as well as receiver side.

- The parameters such as return loss (S_{11}), gain, isolation, radiation pattern as well as polarization decides performance of the antenna in wireless applications.
- VSWR should be less than or equal to 2 over the required bandwidth which indicated return loss is less than or equal to -10 dB.
- The isolation between two radiating elements which indicates how much coupling present between radiating structures.
- The gain of an antenna refers to a maximum gain of the antenna in the angular range.
- The radiation characteristics determine the directional characteristics of the antenna elements. To observe the radiation patterns completely polarized E-field and H-field needs to be defined. For each plane, both co-polarization and cross polarization need to be plotted for required frequencies.

2.9.3 Use of software tools for MIMO antenna design: Selection of IE3D software for present work

The software tool can be chosen according to the geometry of the structure and accuracy of the results. IE3D (mentor graphics) software is based on MoM solution of an integral equation and gives better results for frequency domain analysis for planar configurations. For planar structures, IE3D would be an appropriate choice.

2.9.4 Feeding technique used in designing MIMO antenna

There are many techniques that can be used to feed MIMO antennas. The feeding method in MIMO antennas can be

- Coaxial feed
- Microstrip line feed
- Coplanar waveguide feed

Method of feed decides the accuracy of input impedance and characteristics of the antenna such as bandwidth, radiation pattern etc.

Microstrip line feed

A microstrip feed line is well-known technique used to design printed antennas. Commonly, 50Ω impedance line is used to feed the radiating patch. Inset feed microstrip feeding technique can be used to achieve good impedance matching. A width of the 50Ω feed line is much smaller than that of patch hence it is easy for fabrication, simple to match, and simple to model.

2.9.5 Simulation and fabrication of MIMO antennas

For the designing single element of MIMO antenna, an empirical formula used in literature have been used. With the help of available software (IE3D) the antenna configuration is optimized to get the required bandwidth, isolation, polarization, and gain by selecting the following parameters:

- Radiating patch dimensions

- Size of ground plane
- Dimensions of the feeding line
- Distance between two radiating elements
- Number of radiating elements
- Orientation of radiating elements

After achieving satisfactory simulated results, antenna hardware is fabricated using the following steps:

- From IE3D basic schematic is imported as a .dxf file
- Negative film is to be made on a transparency sheet
- Printed circuit board can be fabricated using a photo etching process
- SMA connectors are connected at feeding line as per the requirement

MIMO antennas are fabricated using FR4 (glass epoxy) substrate as it is economical and easily available.

2.9.6 Testing of MIMO antennas

While characterizing MIMO antenna, antenna parameters such as VSWR, return loss, isolation loss, maximum gain, E and H plane radiation patterns, polarization are to be studied. The most optimized design of the antenna is to be fabricated using photo-etching process on FR4 substrate. The parameters of fabricated antennas to be tested using Vector Network Analyzer. The maximum gain and the radiation pattern can be measured using an anechoic chamber or using a signal generator and spectrum analyzer. Various MIMO antennas designed using different techniques are discussed in next chapters.