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Design Issues and Challenges in Indoor MIMO Antenna Systems

Lingaraj Duggani, Udaykumar Naik, Vijay Rayar

Abstract: ***The promising solution for next generation wireless communication system is multiple input multiple output (MIMO) system. It can transmit and receive data from different channels simultaneously without any need of additional frequency band. In this paper the design issues and challenges in MIMO antenna system for different applications have been reviewed. The major applications of MIMO systems include Wi-Fi, High Speed Packet Access, LTE, WiMAX (4G), and also MIMO has been used in power line communication. Implementation of MIMO antenna system is dependent on important parameters such as: Peak gain, Average Gain, Mutual Coupling, Envelop Correlation Coefficient (ECC), Total Active Reflection Coefficie***

nt (TARC), Signal polarization and Miniaturization of antenna system. Hence an optimal MIMO antenna design to suit for communication applications in an indoor environment is a challenging task. This paper proposes comparative study for the different MIMO antenna parameters. The different modeling techniques for MIMO antenna system are surveyed and areas for future research work in line with tradeoffs between different design parameters are suggested.

Keywords: ***Self-interference, mutual coupling, ECC, TARC, MIMO***

I. INTRODUCTION

In 21st century the applications of wireless communication technology are developing rapidly. There are 2.5 quintillion bytes (2.5 X 10^{18} bytes or 25,00,000 Terabyte) of data created each day at our current speed and as of June 2019 about 4.4 billion people use the internet daily, according to the IBM marketing data records in India per month data usage is 9.8GB and it will double at 2024 [1]. One of the dynamic requirements of these applications is antenna models. High bandwidth and high speed data rate are the major requirements for the current wireless communication systems. This can be achieved by MIMO antenna system which can support multimedia services are to be used and having high channel capacity, high data transmission speed and system reliability. The block diagram of MIMO antenna system M x N is shown in Figure 1. It has multiple antennas on both the nodes.

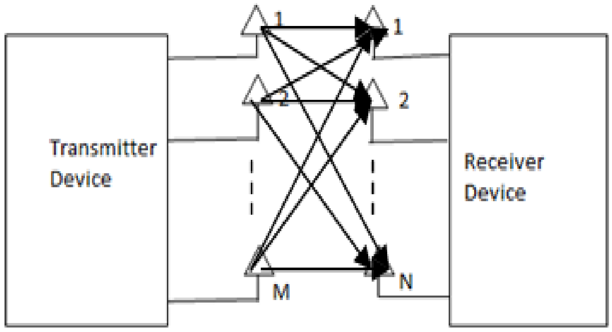

Figure 1: M x N MIMO system

One of the major advantages of MIMO antenna system is that, it can transmit and receive data from different channels simultaneously without any need of additional frequency band. The significant design issues and challenges in indoor MIMO antenna systems are signal polarization, peak gain, average gain, mutual coupling, TARC, self-interference, ECC and miniaturization of the system. The MIMO technology is the most important enhancements in the 4G wireless standards that provide large increase in channel capacity and data rate. In this system multiple antennas are installed in both transmitter and receiver terminals and operated simultaneously with different frequency channels [2]. The MIMO antennas design is one of the tricky area and developer need to focus on numerous issues.

Advancements in MIMO technologies offer promising solutions for indoor and outdoor terminal communications. MIMO systems both in indoor and outdoor environment have become a necessary element of wireless communication environment. The standards it includes are Wi-Fi, High Speed Packet Access (HSPA), LTE, WiMAX (4G) and latest MIMO technology also used in power line communication for 3-wire installations [3]. MIMO improves overall performance by mitigating the fading in multipath environment. By novel MIMO antenna system designs will increase the receiving capacity and throughput to support diversity and this attracted the researchers. In case of indoor wireless terminal communication system capacity is affected by the standard received signal power. In the line of sight (LOS) environment parallel polarized systems attain lesser capacities than their perpendicularly polarized systems [2].

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Accurate positioning of a wireless device by studying the received signal power in different positions, or geometric location algorithm (GLA) can increase the accuracy of the system in indoor terminal communication [4].

In recent years a great deal of efforts have been made to improve spectral efficiency, throughput, improvement with lower ECC, mutual coupling and high gain of the MIMO antenna for indoor terminals.

The emphasis of this paper is on review of various MIMO antenna system design parameters and performance metrics. The modeling efforts by different researchers and tradeoffs between these performance parameters are reviewed. This review paper is structured as follows: Part II presents MIMO antenna parameters and performance metrics. Part III presents recent results of researchers with respect to performance parameters. Part IV recommends future trends in MIMO antenna design. Followed by Part V presents conclusion.

II. MIMO ANTENNA PARAMETERS AND PERFORMANCE METRICS

The single antenna performance metrics parameters are also important, when we consider single antenna system. These parameters play a very important role in MIMO antenna system. A single antenna element metrics for instance efficiency, radiation patterns, signal polarization, and operating frequency are varies the performance of the MIMO antenna system. In this section only the major performance metrics of MIMO antenna systems are considered. These metrics affects the performance of MIMO antenna system and details of these are presented in this section.

A. Self Interference:

Multiple antennas are used to transmit signals in full duplex single channel MIMO systems with identical frequency which causes self interference at the transceiver node. The full duplex single channel system offers double throughput comparatively conventional systems. Because of this advantage we can save the cost of spectrum [5]. In this system single channel is used for both transmission and reception and remaining channels can be used for further services. Figure 2 shows the self interference in transmitter and receiver devices. The self interference builds between two antennas in each node which reduces the efficiency of the MIMO system.

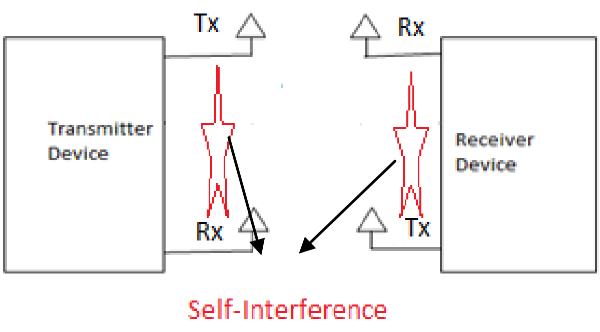

Figure 2: Single channel MIMO system with self-interference

B. Mutual Coupling:

Mutual coupling is one of the major factors, which drastically decreases the performance of MIMO antenna system. Mutual coupling loss arises between successive two antennas, or between any two antennas in the array, or from the third party object in the communication system. It can be defined as one antenna absorbs the radiated power from the other antenna element in the array system. It means that current flowing in one antenna radiator produces the radiations are absorbed by the nearest antenna element in the system. Here distance between two antenna and operating frequency plays a very important role. Because of reciprocity characteristics of antenna elements it can transmit or receive electromagnetic waves, due to this antenna element may be in active or passive state which will degrades the radiation pattern characteristics of other antenna element in the MIMO system. The mutual coupling loss basically depends on the signal propagation delay, current distribution on antenna radiators, channel coefficients, and phase difference of the signals. This effect of mutual coupling on MIMO system depends on number of antenna elements, distance between one antennas to another antenna, radiation pattern, polarization of signals from antenna elements, scan angle, phase shifters, attenuators, couplers, impedance matching point of antennas [6]. The affected above factors degrades the MIMO system performance. Figure 3 Shows the mutual coupling originated from different sources. A1, A2 and A3 are antenna elements.

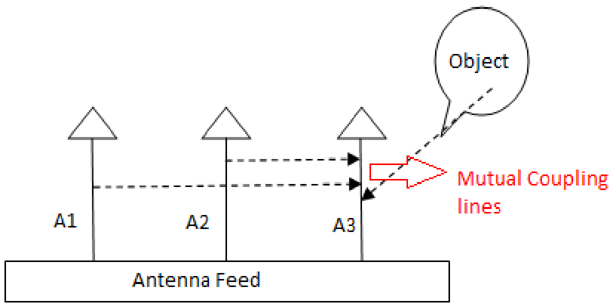

Figure 3: Mutual coupling sources

C. Envelop Correlation Coefficient:

ECC explains independency of the two antenna radiation patterns in MIMO system. It depends on the type of polarization used for radiation purpose in antenna elements. For example let consider an antenna radiations are horizontally distributed and other antenna radiations are vertically distributed, the ECC between these two antenna elements is zero. It shows that if multiple antenna elements having same type of polarization for distribution of signal in MIMO system bear the more ECC and reduces the throughput of the system. In many situation hybrid combination of signal polarization are used [7]. It can be easily calculated by using scattering parameters as shown in equation (1).

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

If the value of ρ_e is larger, the isolation is poor between two antennas.

D. Total Active Reflection Coefficient (TARC):

TARC is an important parameter measured in N-port microwave device. It is mainly used in MIMO antenna system to measure the total output radiated power to input or available power.

This can be calculated by using equation (2), where total available power considering all ports subtracted by total radiated power from all antenna elements in array system to the total available power. This ratio gives the square of the total active reflection coefficient [8].

$$\Gamma_a^t = \sqrt{\frac{available\ power - radiated\ power}{availble\ power}} \quad (2)$$

TARC depends on frequency, tapering and scan angle for active reflection coefficient. It is used to calculate the MIMO antenna system frequency bandwidth and radiation performance. From the scattering matrix it can also calculated as follows.

$$\Gamma_a^t = \frac{\sqrt{\sum_{i=1}^{N} |yi|^2}}{\sqrt{\sum_{i=1}^{N} |xi|^2}} \quad (3)$$

Where, [y] = [s][x].[s] ; scattering matrix
[x] ; excitation vector
[y] ; real number between 1 and 0, expressed in decibels.

E. Channel Capacity:

Channel capacity describes number of bits transmitted in given bandwidth. It expressed in bits per seconds. Comparatively it used to compare the performance of different antenna systems. MIMO system has enhanced channel capacity compare to single channel system, because its diversity in transmission of information. Usually channel capacity is calculated using cumulative distribution function (CDF), relative distribution function (RDF) or relative to signal to noise ratio (SNR). Channel matrix is used to measure the channel capacity and it can be calculated by using radiation patterns is explained below [9].

$$H = \psi_R^{1/2} G\, \psi_T^{1/2} \quad (4)$$

Where, ψ_{RMXM} and ψ_{RNXN} are receive r and transmitter coefficient matrices respectively, G_{MXN} is a matrix of Gaussian random numbers. Once H value is known, the capacity is given by:

$$C = log_2[\det(I_R + \frac{\rho}{N_T} HH^T)] \quad (5)$$

Where, I_R = identity matrix

N_R & N_T= Number of receive and transmit antennas and

H^T = Conjugate transpose of the H Matrix.

III. DISCUSSION ON EXISTING DESIGN AND MODELING STRATEGIES

Several researchers have studied performance parameters in deep and suggested different techniques to reduce the affect of antenna parameters on efficiency of MIMO systems in indoor and outdoor environment terminal communication. In this section we present the design and modeling strategies used in MIMO antenna system.

A. Self Interference: Jianfei Liu., et al in [10] the adaptive steepest descent algorithm is used to detect self interference channel in broadband full duplex MIMO relays. Once the channel is detected it is suppressed by estimated signal to tolerable level. Estimated results conclude this will work efficiently in deep fading scenarios and calculated mean square error is above the mitigation level of 10^{-3}. In [11] self-interference is reduced by calculating the mutual coupling signals. In this design attenuator and phase shifters are utilized to design the matrix. It is also reduces the mutual coupling between two elements in the MIMO system. Antenna system consists of four elements and distance between two antennas is assumed to λ/2 where frequency for analysis 2.45GHz is used. All the signals are passed through the matrix which includes attenuators and phase shifters to reduce the interference losses. Here mutual interference signals and negative self interference signals are placed nearer to each other and matrix will adjust the phase and voltage level. This reduces the interference level in both the signals. In reference [12] researchers calculated the self-interference signal and subtracted it from received signal. The design of this system consists of two rat race couplers, four antenna elements placed in equidistance, adders and dividers are employed in the network. With the help of above network passive suppression of self-interference signal is done, which reduces the interference loss in the designed 2x2 MIMO antenna system.

B. Mutual Coupling: The work in [13] explains the different methods used for reduction of mutual coupling between two antenna elements or in array by different authors. In first method electromagnetic band gap structures or photonic band gap structures are used with micro-strip antenna array which will reduces the mutual coupling. These structures are used in between two antenna elements in array. EBS structures suppress the surface waves and reflection coefficients which will increases the radiation efficiency and gain of the antenna system. In second method a pair of slits is used in ground plane to reduce the mutual coupling loss. These slits are in same size which blocks the current flow between two antenna elements in MIMO system. A band stop filter is created by these equal length slits for operating frequency of antenna elements. In third method consists a U shaped slot is created in radiating patches which increases the total surface current length because of this increased distance current absorption rate will reduce in turn it reduces the mutual coupling loss in MIMO antenna system. In fourth method defected ground structures are used which are in rectangular shape. These are employed in micro-strip patch antenna array which reduces the mutual coupling loss. It consists of pair of rectangular slits are absorbs the radiated current and flows it to ground therefore radiated energy not absorbed by nearest antenna element. These slits created the band reject filter for operating frequency and simulation is done for resonant frequency of 9.2GHz and achieved mutual coupling of 16.5 dB between two antennas. Figure 4 shows placement of slits in antenna array system.

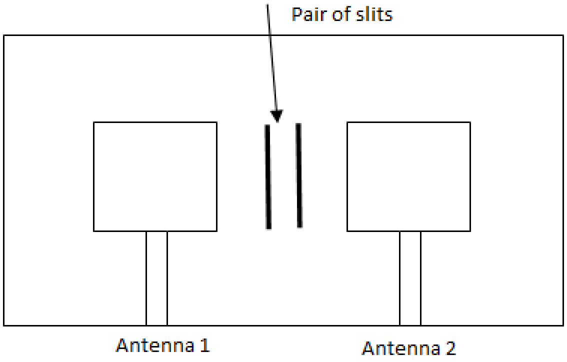

Figure 4: Pair of slits in antenna array

C. Envelop Correlation Coefficient (ECC): The work in [14] proposed the design of antenna system for wireless personal area network. In this system antenna is compact in size and has four port ultra wideband MIMO antennas. All four ultra wideband antennas are placed orthogonal to each other and each antenna has a bowel shaped patch. Each patch structure having truncated partial ground point and dome top. Radiating patch formed by two antennas with semicircle and two antenna elements with rectangular slots forms larger semicircle to obtain broad band response. From simulated results ECC obtained at port1 with respect to all three other ports is 0.05. In [15] MIMO system is designed using dielectric image lines. Two identical antennas are placed opposite to each other with minimum distance between them is λ with respect to operating frequency. From simulation results calculated ECC is 0.02 is obtained. In [16] low profile planar meander antenna is designed and current distribution from the feeding source is completely on antenna radiators. To reduce the size of the antenna designer used the meander lines. It has two sections one is straight lines in which larger amount of antenna current is flowing and second section is folded to form the meander lines. From the first section of this wire high gain vertical polarizes signals are generated because the strong current flows in vertical direction. It provides the enhanced antenna efficiency and vertical antenna gain. Performance comparison in multi-antenna system has been made. The simulation result tells the ECC value between two antenna is less than 0.002 is achieved.

D. Total Active Reflection Coefficient (TARC): In [17] design of wireless broadband (WiBro) MIMO array antenna is proposed. In this system U shaped slot is used with inverted F antenna and the size of this antenna is less than λ/2 so it is electrically small antenna. The U shaped slot avoids the reflection and reduces the reflection coefficient in the antenna system. The size of the antenna is very small it can be used in MIMO systems. It has resonance at 2.6GHz and simulation is done using CST Micro Wave Studio. Comparative study shows that TRAC value of MIMO system and single antenna is same.

E. Channel Capacity: In [18] it is proved that MIMO antenna systems can increases the channel capacity. The experiment is done using dual polarized and directional beam patterns are designed by using three different MIMO antenna systems. This system can be used in indoor environment terminal communication and improved results are observed. The EEM-RTM software is used to design indoor MIMO base station and ray launching method is used for propagation environment. By using iterative methods the trajectories of large numbers of transmitted signals are tracked and computed. The results and comparison between antenna systems is shown in Table I.

Table I: Comparative study for different systems

Antenna System	SISO	MIMO 2 x 2	MIMO 4 x 4
Capacity [bits/s/Hz]	11.38	16.77	20.64

IV. FUTURE WORK

A. Following are the issues reviewed:

- Self interference cancellation scheme the steepest descent algorithm can work well for only deep fading MIMO system. In other cases we require the knowledge of pre-know interferences to suppress or eliminate. This will increase the complexity of the system. Two rat race couplers are also used to reduce the self-interference in the system by adapting passive suppression technique. This technique increases the size of MIMO antenna system [11][12].
- To reduce mutual coupling many researchers suggested usage of slits in between two antennas. Increasing the number of slits in complex MIMO antenna system leads to high power exchange between an antenna with number slits which degrades s-parameters performance is MIMO system [13].
- To achieve lower ECC dielectric image line (DIL) based MIMO antenna and PLMA can used. The DIL antenna works well for frequency 28-32GHz but variable gains are achieved. The PLMA system design is critical for high-sensitive routers and more complex [15][16].
- In case of WiBro MIMO antenna analysis of TARC is done based on the radiation patterns and not considered the spacing between two antenna elements [17].

V. CONCLUSION

- It is well established that channel capacity enhancement using MIMO is achievable. The best optimization of the array allocation is challenging task and ECC can still be reduced which will helps to achieve better throughput and bandwidth utilization.
- It will be extremely useful to device elaborate simulation models based on empirical data to have better radiation antenna patterns for sensitive router design.
- MIMO antenna system design are still in its infancy stage and appears more promising for the Multi user antenna design for MIMO with OSDM, switched optimal beam forming for massive MIMO, and antennas for 5G scenario applications.
- The valuable tradeoff between design parameters can be used to simulate MIMO antenna in the high capacity dynamic environment with low computational complexity.

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