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Characterization of Reconfigurable MIMO Antennas for Channel Capacity in an Indoor Environment

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Abstract—In this paper, three different frequency reconfigurable multiple-input-multiple output (MIMO) antennas are characterized in terms of their channel capacity performance in an indoor environment. Two 2×2 and one 4×4 MIMO antenna configurations are investigated. A complete MIMO system is implemented using software defined radio (SDR) platform. The antenna under test can be used at either transmitter or receiver ends. The channel capacity of the system is evaluated by computing the channel coefficient matrix. The measurements are performed at 2.45 GHz for line of sight (LOS) and non-line of sight (NLOS) scenarios. A comparison of the antennas is performed with an ideal system scenario with totally uncorrelated channels as well as an array of standard monopoles which are half-wavelength apart. The effects of antenna element efficiencies, radiation patterns and spacings on the channel capacity are discussed.

1. INTRODUCTION

Multiple-input-multiple-output (MIMO) systems are utilized in wireless communication systems to provide better system performance with enhanced throughput. The multiplexing gain of an MIMO system can be utilized to provide better data rate in multi-path environments than a single-input-single-output (SISO) system. A linear relationship exists between the channel capacity and the number of independent channels [1]. However, the linear relationship is limited because of the correlation between the channels. This correlation depends on the propagation environment as well as on the radiation characteristic of the antennas within a MIMO system. Hence, it is necessary to evaluate and characterize antennas of the MIMO system. The correlation coefficient is one of the important MIMO antenna parameters which indicates the level of correlation between channels due to the antenna radiation behavior. Highly correlated channels degrade system performance, and hence the real channel capacity gets lower than the uncorrelated ideal MIMO system.

The usage of MIMO antenna systems is on the rise in small wireless handheld devices, tablet PC's and mobile terminals [2–4]. These devices are compact and require low profile antennas. Very few antennas can be accommodated in a small area and hence critical to address. The channel capacity of these devices greatly depends on the design of MIMO antenna system and is greatly affected by correlated channel. Hence, it is desirable to characterize the MIMO antenna systems for channel capacity in an actual environment to analyze the system performance.

Various works appear in literature in which MIMO antenna systems are analyzed in terms of their effect on the multiplexing gain in different environments [5–12]. Some of them used theoretical models to emulate the channel and used the antenna elements radiation patterns to analyze the performance of the MIMO antenna system [8, 11, 12]. Others relied on measurements in an actual environment of

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interest [5, 6, 9, 10]. In [5] and [6], channel measurement systems were used in actual environment to evaluate the MIMO antenna system performance by computing channel capacity. In [7], a reverberation chamber was used to measure channel capacity for 2-element MIMO antenna system suitable for mobile phone applications. In [8–10], MIMO antenna systems for mobile handset application were investigated for channel capacity to evaluate to system performance.

In [8], a patch based MIMO was evaluated in terms of its multiplexing gain in an urban environment. Theoretical models were used to compute the average channel capacity of the system. In [9], the same antenna was analyzed for indoor environment for channel capacity using measurements utilizing a software defined radio platform (SDR). In [10], the effect of isolation enhancement was studied for two similar antennas using measurements in an indoor environment. In this work, the measurement method is updated, and three different kind of antennas (reconfigurable antennas) are analyzed for channel capacity and compared in terms of the multiplexing gain that they can offer.

The antennas were printed ones and consisted of 2-element and 4-element systems. The measurements were performed in real indoor environment using SDR platform. The channel coefficient matrix, H, was computed in both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios to get the ergodic channel capacity. LOS radio transmission is the characteristic of electromagnetic radiation traveling in a straight line while NLOS propagation is across a partially obstructed physical object.

In this paper, three frequency reconfigurable MIMO antenna systems are analyzed for system performance based on the channel capacity. The measurements are performed in a real indoor environment using SDR platform. The rest of the paper is divided into five sections. The measurement setup and scenario are given in Section 2. Sections 3, 4 and 5 describe the three MIMO antennas and analyze the channel capacity measurement results for each antenna. Conclusions are given in Section 6.

2. CHANNEL CAPACITY MEASUREMENT SYSTEM

In this section, MIMO channel capacity and the measurement setup used in this work are discussed in details.

2.1. Channel Capacity of MIMO System

A linear increase in the channel capacity of a MIMO system is achieved by increasing the number of channels. For an N channel MIMO system, the ideal channel capacity is given by:

$$C = N * \log_2\left(1 + \frac{\text{SNR}}{N}\right) \tag{1}$$

where C is the channel capacity and SNR the signal-to-noise ratio.

However, due to the correlation between channels, the maximum channel capacity that a system can achieve is much less than the ideal one. In a real environment, the capacity of a $N \times N$ MIMO system is given by [1]:

$$C = \log_2\left(\det\left[I + \frac{\text{SNR}}{N} H H^*\right]\right) \tag{2}$$

where N is the number of channels, I the $N \times N$ identity matrix, H the channel coefficient matrix and H^* the conjugate transpose of H. The channel matrix H properly characterizes the performance of a MIMO system as it contains the information about the phase and gain of the channel between transmitting and receiving antennas. The matrix relates the correlation induced between channels due to the propagation path as well as the receiving and transmitting antennas. Thus, by computing the H matrix, the channel capacity of an MIMO system with a particular set of antennas in a specific propagation environment can be computed and analyzed. Various methods exist in literature to find the H matrix. Theoretical models computes the H matrix by relying on the radiation patterns of receiving and transmitting antennas and using the standard models of the propagation environment [11]. Such models make assumptions and approximations of the propagation channel, and hence, their validity is limited to only a particular environment.

In many other works, measurements are performed to find the H matrix in the environment of interest. In such measurements, a known signal is sent on each channel from the transmitting side, and it is sensed on every channel at the receiving side. After removing the path loss effect, the channel coefficient matrix, H, is obtained [9, 10].

2.2. Measurement Setup

In this work, the experimental approach as those in [9] and [10] was followed to compute the performance of different MIMO antenna systems in terms of channel capacity. As known, the correlation among channels is induced due to the antenna patterns and propagation environment. To specifically ascertain the performance of the antennas, the propagation environment is fixed to an indoor scenario using SDR platform. SDR platform is a radio communication system that is implemented using softwares on embedded system and computers. The basic concept of the SDR platform is its ability to configure/define the system or change the configuration of the radio communication system for the function required at a particular instant. SDR platforms have the ability to reconfigure or upgrade to new standards or if the scope is changed as per any updated requirements.

A complete 4×4 MIMO system was implemented using a Lyrtech Software Defined Radio (SDR) platform. The SDR platform was equipped with a set of 4-monopole antennas on both transmitter and receiver sides working at 2.4 GHz/5 GHz bands. Each channel was embedded with RF modules and 8-channel ADC/DAC. The digital processing on each side was performed using Xilinx FPGAs. To test the performance of some given antennas, they were mounted on both receiver and transmitter by removing the monopoles. The measurement setup using the SDR platform with one MIMO antenna system is shown in Fig. 1.

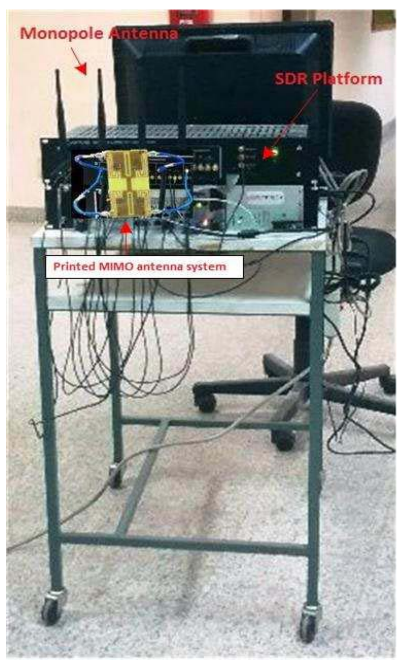


Figure 1. SDR measurement setup for channel capacity.

In this channel capacity measurement setup, a single carrier BPSK burst modem communication system was implemented on the SDR platform. The bursts were transmitted at the rate of 97.7 kBursts/s. The format of each transmitted burst consisted of a start bit followed by 2 or 4 channel estimation pulses of equal magnitude transmitted depending on whether 2-element or 4-element MIMO antenna system was under test. The pulses were transmitted from one of the transmitters at a time while all other transmitters remained silent. Each burst of data was received at the receiver with a start bit, that was used for transceiver synchronization. It allowed enough time to each receiver to adjust its parameters for proper detection of channel estimation pulses. For 2-element and 4-element

MIMO antennas, channel estimation pulses resulted in 2×2 and 4×4 complex-valued channel matrix, respectively. Each complex value was associated with magnitude and phase of the measured channel. For accurate channel measurement, the process was repeated for 1000 such measurements, thus yielding an averaged H matrix.

The channel capacity curves given for SISO and for ideal MIMO system are for the ideal conditions. The measurements gave the practical ergodic channel capacity of the system that can be attained by using the antenna under test and for the particular propagation environment. Hence, at low SNR, these values may fall below that of an ideal SISO system.

2.3. Measurement Scenario

The measurements of the H matrix, which is essential for channel capacity estimation, was conducted in an indoor environment. The measurements were performed in the corridors of the Electrical Engineering Department at King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia. The corridor was 10 feet wide and 10 feet high with concrete walls. The ceiling was covered with ceiling tiles. The measurements were performed for line of sight (LOS) and non-line of sight (NLOS) cases. The transmitter and receiver were 15 feet and 25 feet apart for LOS and NLOS cases, respectively. The layout of the measuring setup is shown in Fig. 2. Fig. 2(a) shows transceiver setting for LOS case with an average distance of 15 feet between the two SDR platforms serving as transmitter and receiver. For NLOS case, as shown in Fig. 2(b), the transmitter was 10 feet away from the corner while the receiver was located 15 feet away from the corner. As the measurements were performed in time varying environment, 20 measurements were performed for each case by slightly changing the position of either transmitter or receiver. The normalized channel matrix H is obtained using procedure given in [13].

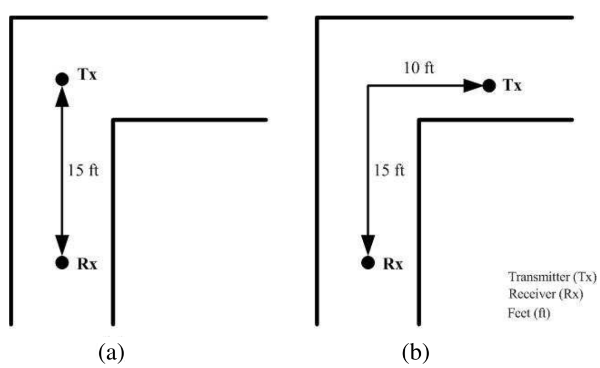


Figure 2. Layout of measurement scenarios, (a) LOS, (b) NLOS.

3. CHANNEL CAPACITY OF TWO ELEMENT PIFA BASED RECONFIGURABLE MIMO ANTENNA SYSTEM

3.1. Antenna Details

The first antenna investigated for channel capacity measurement was a 2-element reconfigurable printed inverted F-shape antenna (PIFA) based MIMO system that was first appeared in [2]. Figs. 3(a) and (b) show the simulated and fabricated antenna designs while detailed views of a single antenna element are shown in Figs. 3(c), (d), (e) and (f). The given antenna structure was a frequency reconfigurable design covering several well-known frequency bands in the frequency range between 0.7 GHz and 3 GHz. Design details and S-parameters of the antenna were described completely in [2]. For the channel capacity measurements, the antenna was tested in LOS and NLOS scenarios at 2.45 GHz. The radiation efficiency of each antenna element at 2.45 GHz was 55%. The 3D radiation patterns of the antenna elements obtained from simulations are shown in Fig. 4.

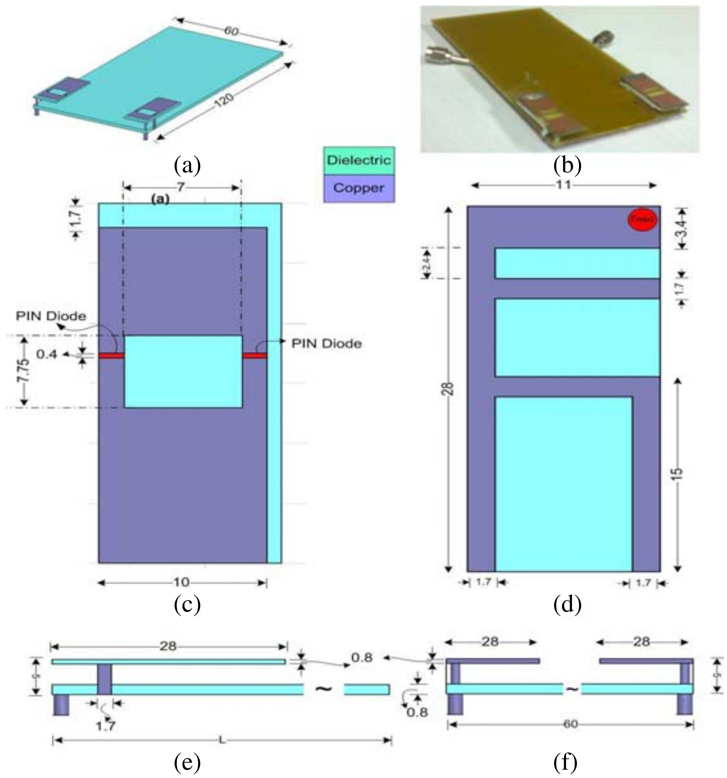


Figure 3. MIMO antenna. (a) HFSS model. (b) Fabricated model. (c) Single antenna top side. (d) Single antenna bottom side. (e) Side view. (f) Front view [2].

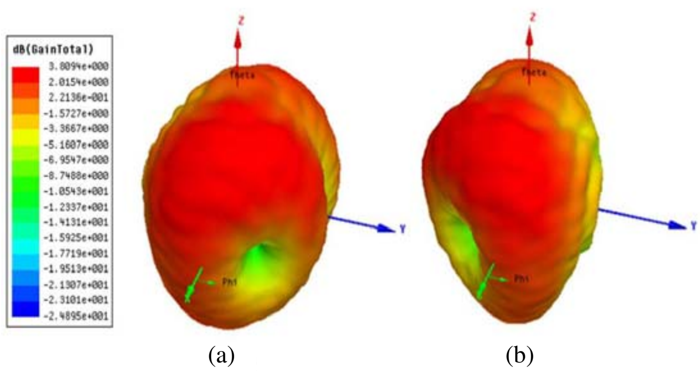


Figure 4. Simulated 3D gain pattern at 2.45 GHz. (a) Antenna element-1. (b) Antenna element-2 [2].

3.2. Measurements Results

The measurements were started by first using the monopole antennas attached to the SDR platform. There were four monopole antennas on each side of transceiver with $\lambda/2$ distance between adjacent elements. Out of them, two monopoles were used. The measurements were performed for both LOS and NLOS scenarios to compute matrix H. This was followed by finding the H matrix for 2-element PIFA for both LOS and NLOS cases. The 2-element PIFA was mounted on the transmitter and receiver sides, and measurements were performed. Fig. 5 shows the channel capacity curves for the 2-element monopole array, 2-element elevated PIFA, 2-element ideal MIMO antenna and SISO system in the LOS environment. As evident from this figure, channel capacity of the 2-element monopole array and

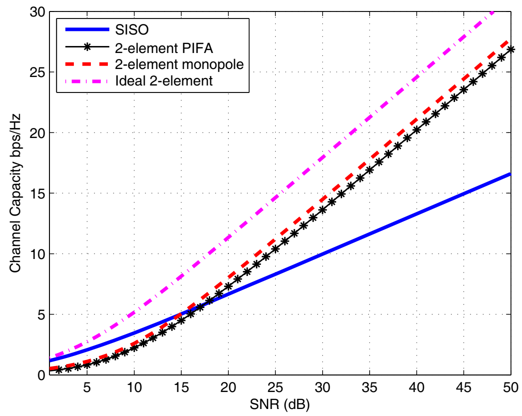


Figure 5. Average channel capacity of 2-element PIFA based MIMO antenna in LOS indoor environment.

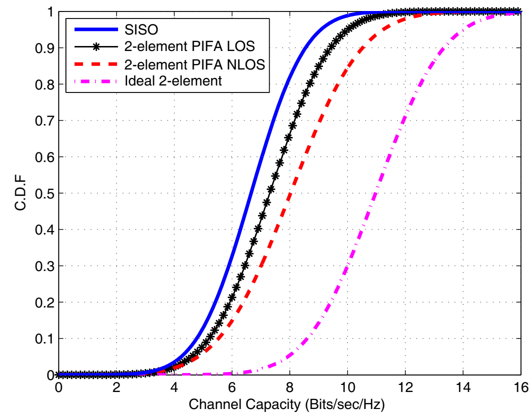


Figure 6. CDF of the channel capacity of 2-element PIFA based MIMO antenna in indoor environment.

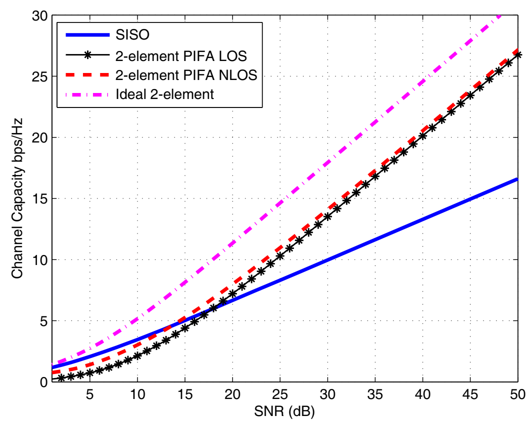
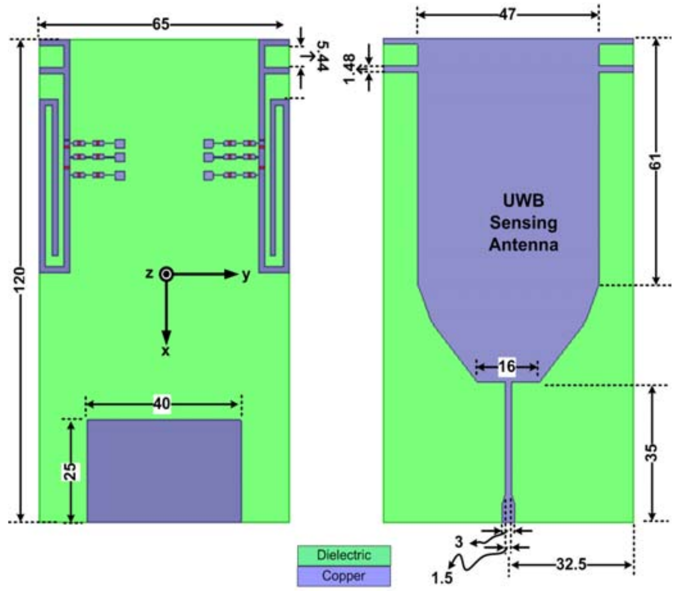


Figure 7. Comparison of the average channel capacity of the 2-element PIFA based MIMO antenna in LOS and NLOS scenario.

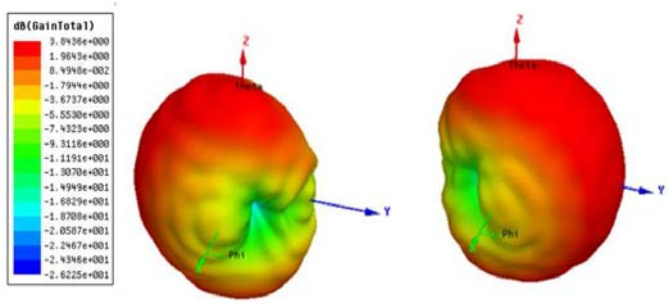
PIFA MIMO antenna systems is less than the ideal 2-element antenna system. This is because of the high correlation between the channels which degrades the MIMO system performance. The channel capacity of 2-element PIFA is less than 2-element monopole because the closely spaced PIFA elements on a standard size smart phone backplane have poor isolation and lower efficiencies than $\lambda/2$ apart monopole antenna array. Similar results are obtained for NLOS scenario as well.

The cumulative distribution function (CDF) describes the probability of variable X takes on a value x that is less than or equal to it. In the manuscript, CDF is defined as the integration of channel capacity (X in this case) at specified SNR (x in this case). CDF is plotted against channel capacity (bps/Hz) as given in all CDF figures. CDF curves of the channel capacity of given PIFA are shown in Fig. 6 for LOS and NLOS environment at an SNR of 20 dB. It is evident form the given curves that the performance of the given MIMO system is worse than the ideal capacity but much better than the SISO systems. It is also evident that the performance of the NLOS case is better than the LOS case because of the low correlation between various channels. The channel capacity curves are compared for LOS and NLOS cases and shown in Fig. 7. For the given PIFA, NLOS performs better than LOS case as the channel induced correlation was less in NLOS scenario. The average channel capacities at 20 dB SNR are 7.1 bits/sec/Hz and 8.0 bits/sec/Hz for LOS and NLOS cases, respectively. The curves for SISO system were used for the comparison with MIMO antenna system in all cases.



(a) (b)

Figure 8. MIMO antennas system. (a) Top view. (b) Bottom view — All dimensions are in millimeters (mm) [3].



(a) (b)

Figure 9. Simulated 3D gain pattern at 2.45 GHz. (a) Antenna element-1. (b) Antenna element-2 [3].

4. CHANNEL CAPACITY FOR 2-ELEMENT PLANAR MONOPOLE BASED RECONFIGURABLE MIMO ANTENNA

4.1. Antenna Details

The second antenna under test was a 2-element meandered line reconfigurable inverted F-antenna (IFA) MIMO antenna [3]. The given antenna was planar in structure and fabricated on an FR4 substrate. Each antenna element was short-circuited to GND plane to increase the electrical length. In the given design, the GND plane was used as sensing antenna for cognitive radio applications. Figs. 8(a) and (b) show the top and bottom sides of the MIMO antenna. The given antenna structure was also a frequency reconfigurable design based on PIN and varactor diodes. For this work, the H matrix was computed in both LOS and NLOS scenarios at 2.45 GHz. The radiation efficiency of each antenna element at 2.45 GHz is 86%. The 3D radiation patterns of the antenna elements obtained from simulations at 2.45 GHz are shown in Fig. 9. Design details and S-parameters of the antenna are described completely in [3].

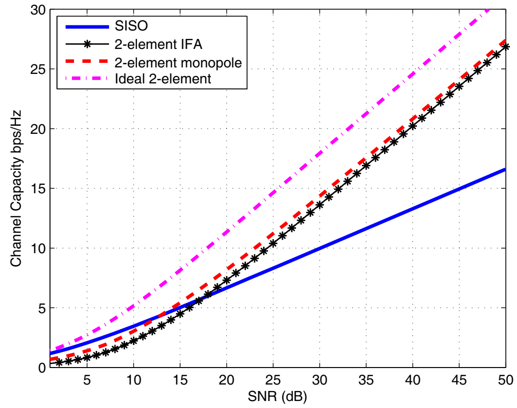


Figure 10. Average channel capacity of 2-element planar monopole based MIMO antenna in LOS indoor environment.

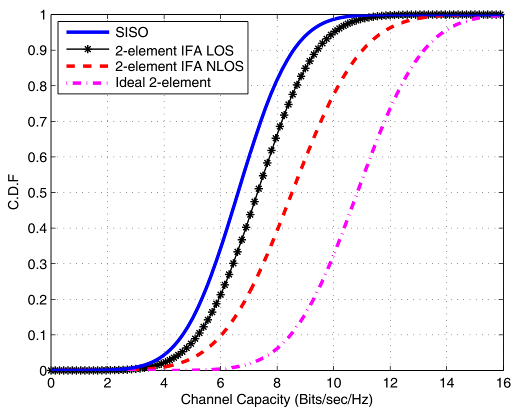


Figure 11. CDF of the channel capacity of 2-element planar monopole based MIMO antenna in environment.

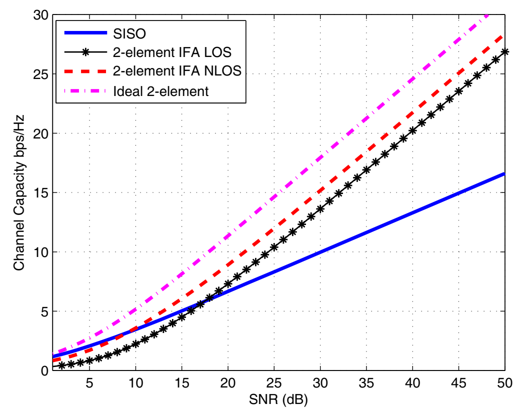


Figure 12. Comparison of the average channel capacity of the 2-element planar monopole based MIMO antenna in LOS and NLOS scenarios.

4.2. Measurements Results

The same procedure was repeated for channel coefficient matrix calculations described in Section 3.2. The H matrix measurements were performed for both LOS and NLOS scenarios using 2-element planar MIMO antenna. Fig. 10 shows the channel capacity curves for 2-element monopole and 2-element planar monopole based MIMO along with SISO and 2-element ideal MIMO antenna system, for comparison, in LOS environment. From channel capacity curves, it is evident that 2-element monopole and planar MIMO antenna systems were worse than the ideal 2-element antenna system, because high correlation between the channels degraded the MIMO system performance. On the other hand, monopole array performed better than the closely spaced planar MIMO antenna system. This is because of high correlated planar MIMO antenna system compared to $\lambda/2$ apart monopole antenna array. Similar results were obtained for NLOS scenario as well.

Cumulative distribution function (CDF) curves of the channel capacity of given 2-element planar antenna are shown in Fig. 11 for LOS and NLOS environment at an SNR of 20 dB. It is clear from CDF curves that the given antenna performed better in NLOS than LOS environment. Similarly, a channel capacity comparison is provided for LOS and NLOS cases and shown in Fig. 12. For the given planar antenna, NLOS performs better than LOS case as the channel induced correlation was less in NLOS scenario. The average channel capacities at 20 dB SNR are 7.3 bits/sec/Hz and 8.9 bits/sec/Hz for LOS and NLOS cases, respectively.

5. CHANNEL CAPACITY FOR 4-ELEMENT PLANAR RECONFIGURABLE MIMO ANTENNA

5.1. Antenna Details

The third antenna investigated for channel capacity measurement was a 4-element meandered line reconfigurable IFA MIMO antenna [4]. Each antenna element was embedded with a unique combination of PIN and varactor diodes to tune it across various frequency bands. Figs. 13(a) and (b) show the top and bottom sides of the MIMO antenna. For the given design, channel coefficient matrix was computed in both LOS and NLOS scenarios at 2.45 GHz. The 3D radiation pattern of each antenna element at 2.45 GHz is shown in Fig. 14. Each antenna element had a radiation efficiency of 78% at an operating frequency of 2.45 GHz. Design details and S-parameters of the antenna are given in [4].

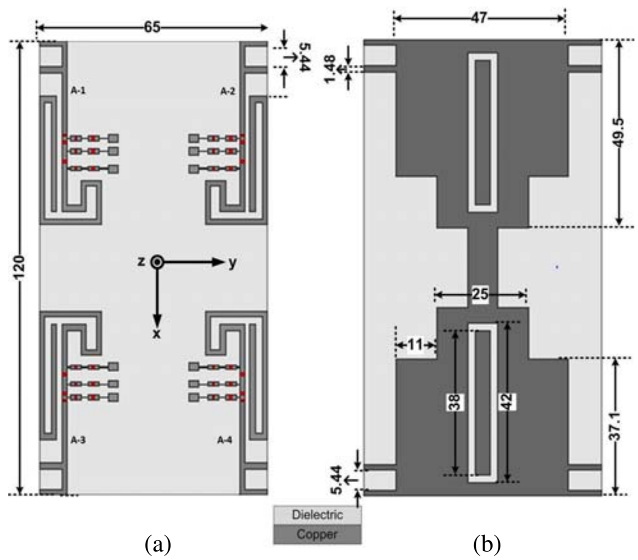


Figure 13. 4-elements MIMO antennas system. (a) Top view. (b) Bottom view — All dimensions are in millimeters (mm) [4].

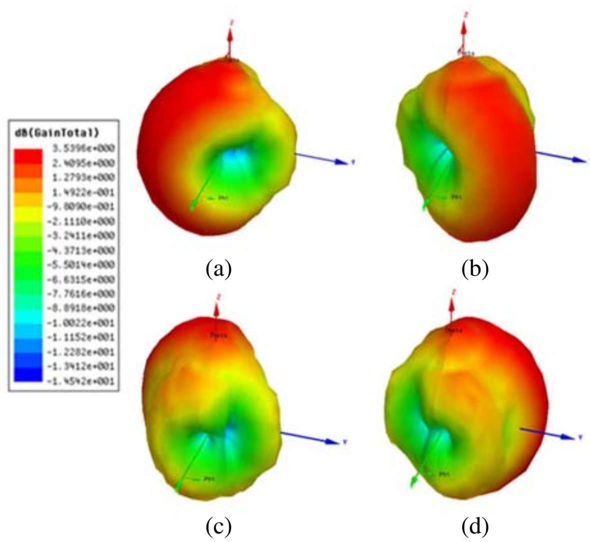


Figure 14. Simulated 3D gain pattern Mode-1 (a) Antenna element-1 excited at 2445 MHz. (b) Antenna element-2 excited at 2445 MHz. (c) Antenna element-3 excited at 2445 MHz. (d) Antenna element-4 excited at 2445 MHz [4].

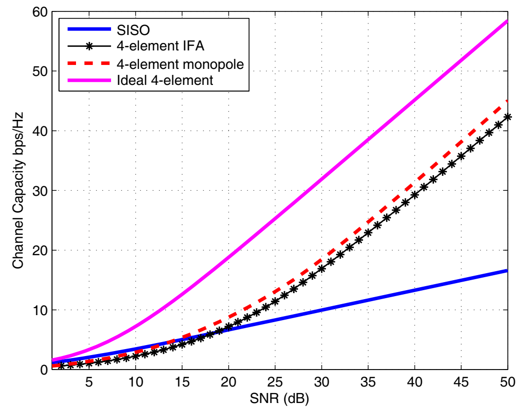


Figure 15. Average channel capacity of 4-element planar MIMO antenna in indoor LOS indoor.

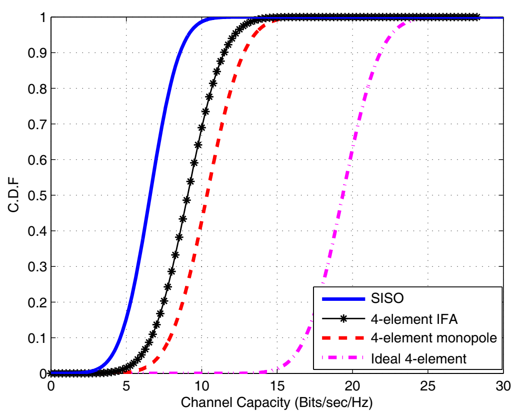


Figure 16. CDF of the channel capacity of 4-element planar MIMO antenna in indoor LOS indoor.

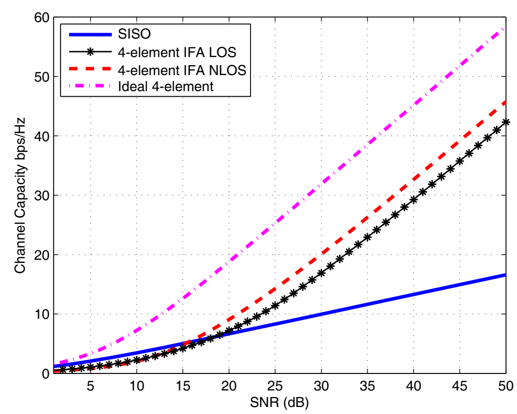


Figure 17. Comparison of the average channel capacity of the 4-element planar MIMO antenna in LOS and NLOS scenario.

5.2. Measurements Results

Figure 15 shows the channel capacity curves for 4-element monopole and 4-element planar MIMO along with SISO and 4-element ideal MIMO antenna system. The cumulative distribution function (CDF) curves of the channel capacity of given 4-element planar antenna are shown in Fig. 16 for LOS and NLOS environment at an SNR of 20 dB. Similarly, a channel capacity comparison is provided for LOS and NLOS cases and shown in Fig. 17. The results for 4-elements are close to those of the 2-element MIMO.

6. CONCLUSIONS

In this paper, three frequency reconfigurable MIMO antenna systems were investigated for channel capacity measurements. The measurements were conducted in an indoor environment for WLAN and Wimax bands of 2.45 GHz. The average channel coefficient matrix, H, was measured for LOS and NLOS scenarios for the given 3-set of MIMO antennas. The closely spaced electrically small antennas with compact size perform well yielding comparable performance to $\lambda/2$ apart monopole antenna arrays and far better than the SISO system. The MIMO antenna characterization for channel capacity measurements is an important factor in real applications for actual wireless environment.

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