ABSTRACT

ZHOU, JUNCHENG. Effects of Near-Field Loading to Compact MIMO Antennas. (Under the direction of Dr. Jacob J. Adams).

MIMO (Multiple-Input Multiple-Output) technology promises a linear increase in channel capacity without the cost of additional power and bandwidth. Thus, there will be a significant increase in the number of transmit and receive antennas. This capacity gain by MIMO is possible only if the antennas are decoupled or the signal-to-ratio (SNR) is in high regime. However, especially when antenna devices with compact form factors are desired, it introduces significant coupling between the antenna elements that limits the capacity gain by MIMO. Furthermore, near field loading is known to severely impact the antenna coupling.

This work develops a systematic method to evaluate the sensitivity of MIMO antennas to near field loading. This method allows us to examine the performance of the reflection coefficient, envelope correlation coefficient, and channel capacity for loaded MIMO antennas. The three MIMO antennas are simulated with a near field load for S parameters in a commercially available electromagnetic simulation software - FEKO. This helps to verify the simulations, the three MIMO antennas are also fabricated and tested with a near field load. Both simulated and measured results are analyzed. A narrow bandwidth MIMO antenna tends to be susceptible to near field loading. However, wideband MIMO antennas are more robust to near field loading. This research examines how near field loading impacts the compact MIMO antenna, and is gained knowledge of the impact of bandwidth and polarization on the loaded compact MIMO antenna.
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Effects of Near-Field Loading to Compact MIMO Antennas

by

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DEDICATION

To my parents, Fu Lixian and Zhou Qiaowei, for their sacrificed love, and faith in me,
even when I was a failure.
BIOGRAPHY

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During my time at North Carolina State University, not only I have gained the knowledge of Electrical Engineering, but also I have became a leader, independent researcher, and better human being.

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Chapter 1

Introduction

The Ericsson 2018 mobility report shows that the total number of mobile subscriptions such as smartphones, mobile PCs, tablets and mobile routers were around 7.9 billion in the first quarter of 2018. Moreover, mobile data traffic grew by 52 % year-over-year in 2018 [14]. Current cellular bands project higher data demands, but the current cellular bands are limited between 700 MHz to 3.6 GHz by the Federal Communications Commission (FCC) [40]. Multiple-input multiple-output (MIMO) is referred to as MIMO, which improves data rates without the cost of additional bandwidth and power. Thus, MIMO, as an established technology, has been widely employed from the third generation (3G) to the fourth generation (4G) of wireless communication, and provides a potential solution for the fifth generation (5G) to satisfy the increased data traffic [50]. As the number of antennas in MIMO increased, there is a continuous demand for developing and making the MIMO antenna size as compact as possible. By making the MIMO antenna size as small as possible, MIMO technology will then provide effective performance.
1.1 MIMO System

MIMO technology improves the performance of a radio frequency (RF) system in terms of channel capacity and reliability of signals [16, 39]. Figure 1.1 demonstrates the transmitted signals reaching to the receiver from two or more paths. After this process occurs, it results in constructive and destructive interference. As a result of buildings in a scattering environment, a phenomenon that can severely affect radio communications channels, known as multipath fading, takes place. Typically, multipath fading is a principle problem when it destructively degrades the signal quality and integrity of the RF system. However, constructive multipath in MIMO can be used to carry more information [39].

![Figure 1.1 A MIMO system in a scattering environment.](image-url)
### 1.1.1 MIMO Techniques

There are two main techniques in a MIMO system: spatial multiplexing and spatial diversity. Further, two transmit antennas and two receive antennas with digital signal processing (DSP) in fading channels are shown in Figure 1.2.

**Figure 1.2** A $2 \times 2$ MIMO antenna system: (a) the configuration of spatial multiplexing, (b) the configuration of spatial diversity.

Spatial multiplexing is used to improve data capabilities throughout a MIMO system [15]. This technique is referred to as multiplexing gain. Figure 1.2a shows how independent carrier data streams are transmitted from multiple transmit antennas at the same frequency through fading channels. A MIMO channel in Figure 1.2a is decomposed into a
number of 2 parallel independent channels. By multiplexing two independent data streams onto two independent fading channels, this MIMO system has gained a 2-fold increase in data rate as compared to a single-input single-output (SISO). In a rich scattering environment, multiplexing gain is obtained from multiple paths and time delay without the cost of additional power and bandwidth [19]. In the next section, we describe how to achieve the multiplexing gain of the increased data rate in a rich scattering environment for a MIMO system.

Spatial diversity is used to improve the reliability of MIMO system, and it also helps reduce co-channel interference significantly. Figure 1.2b represents that same carried data streams are transmitted from multiple transmit antennas at the same frequency through fading channels [19]. Coherent combining of transmitted signals increases the signal-to-noise ratio (SNR) at the receive antennas compared to the SNR obtained with just a single receive antenna [19]. The fundamental scheme of trade-off between spatial multiplexing and diversity gain is used to achieve a balanced performance instead of its maximal diversity gain or its maximal multiplexing gain alone [19, 33].

In the next section, we describe how to achieve the multiplexing gain of an increased data rate and an increase of SNR. This is achieved by the coherent combining of diversity signals in a rich scattering environment for a MIMO system.

1.1.2 Simple Model of a MIMO System

In Figure 1.2, as we consider M transmitting antennas and N receiving antennas in the MIMO system where $N \geq M$, transmitted signals and received signals can be related in Equation 1.1,
\[ [R_n] = [H] \cdot [T_m] + [N_o] \] 

where \([T_m]\) is the M-dimensional transmitted signal, \([H]\) is a channel gain matrix in fading channels, \([N_o]\) is the N-dimensional noise vector, and \([R_n]\) is the N-dimensional received signal [19, 24]. This narrowband MIMO system assumes that the information of the channel gain matrix is known at the receiver as channel side information at the receiver (CSIR) [19]. The channel matrix will be full, indicating that each transmit antenna produces some voltage at each receive antenna. As a result, these will cause an interference because each transmit antenna is sending an independent data stream. However, in the CSIR cases, the known channel matrix can be inverted and applied to the transmitted signal to improve the SNR [19, 45]. Additionally, we make an assumption for a rich scattering environment if \([H]\) is full rank and independent of one another.

We studied and analyzed channel capacity in the following two cases, SISO and MIMO [17]. SISO consists of a transmit antenna (M=1) and a receive antenna (N=1). According to the Shannon-Hartley theorem, in a high SNR regime, the channel capacity equation can be written as,

\[ C = B \log_2(1 + \frac{S_o}{N_o}) \]  

where \(C\) is the channel capacity in bits per second, \(B\) is the bandwidth of channel in Hertz, \(S_o\) is the average received signal power over the bandwidth, \(N_o\) is the average power of noise over the bandwidth at the receiver, and \(\frac{S_o}{N_o}\) is the signal-to-noise ratio (SNR).

For the MIMO system, there are N receive antennas and M transmit antennas when \(N \geq M\), different data streams using the same bandwidth are transmitted to N receive antennas. Thus, each one of transmit antennas has its own channel and the total channel...
capacity of MIMO system is

$$C = MB \log_2 \left( 1 + \frac{N}{M} \times \frac{S_o}{N_o} \right)$$  \hspace{1cm} (1.3)$$

As a result of the increased number of transmit and receive antennas, the channel throughput capacity would be linearly increased by M as compared to SISO, while assuming M = N. Table 1.1 compares channel capacity for different channel types when assuming SNR = 10 dB, M=4, and N=5. It is evident that the MIMO technology promisingly improves the channel capacity. Mentioned that, MIMO (with same data) and MIMO (with different data) are MIMO techniques that Section 1.1.1 discussed as spatial diversity and spatial multiplexing.

**Table 1.1** Comparison of channel capacity for different channel types[17].

<table>
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<th>Channel type</th>
<th>Capacity (Mbps)</th>
<th>Normalized capacity with respect to SISO</th>
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<tr>
<td>SISO</td>
<td>3.45 B</td>
<td>1.0</td>
</tr>
<tr>
<td>MIMO (with same data)</td>
<td>7.64 B</td>
<td>2.21</td>
</tr>
<tr>
<td>MIMO (with different data)</td>
<td>15 B</td>
<td>4.35</td>
</tr>
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</table>

Without fading, there is an N-fold increase in the received SNR. This N-fold increase emerges due to the combining of the M received signals from different receive antennas. With fading, the multiple independent fading paths are combined. Combining the independent fading paths reduces the probability of symbol error for demodulation in AWGN. Additionally, it lowers the probability of error and leads to a better channel capacity, which is referred to as spatial diversity [19]. For the spatial multiplexing, the MIMO channel can be seen as the parallel SISO independent channels, where the m-th
channel has input $T_m$, output $R_m$, noise $N_m$, and channel gain $H_m$ if $M = N$. Independent
data streams are transmitted across each of the parallel channels, and the total channel
capacity would have an $m$-times increase with just one transmit and receive antenna [19].

## 1.2 Multiple Port Antenna (MPA)

MIMO transmission schemes require two or more antenna ports at each end of the link.
There are two strategies to achieve this: physically separated MIMO antennas or a com-
pact, single-aperture MIMO antenna. In this thesis, we define physically separated an-
tennas and compact, single-aperture antennas.

### 1.2.1 Physically Separated MIMO Antenna

A physically separated MIMO antenna is in Figure 1.3 (b), which consists of several
radiating elements. There is a distance between ports in the physically separated MIMO
antenna. A physically separated MIMO antenna is used in base stations where the space
and size is less constrained in design specifications. It is imperative to have low mutual
coupling in a physically separated MIMO antenna. The rule of thumb is that the distance
between antenna elements is greater than half-wavelength. As a result, there is high
mutual coupling impacts on both the spatial correlation and the received signal-to-noise
ratio [18, 23, 48].

### 1.2.2 Compact MIMO Antenna

In Figure 1.3 (a), a multi-port antenna consists of a single radiating element, referred to
as the compact MIMO antenna. The fact for the compact MIMO antenna is that ports
have DC contact between each other. In other words, there is an only single-aperture the compact MIMO antenna. Compact MIMO antennas are used in handsets, portable devices, and other applications. One of designing challenges for compact MIMO antennas is to have low intrinsic mutual coupling, meanwhile, fit it into a compact size.

![Diagram of MPAs](image)

**Figure 1.3** Various forms of an MPAs: (a) MPA consisting of a single radiating element, (b) MPA consisting of several radiating elements [11].

### 1.3 Hypothesis of Sensitivity for MIMO Antennas to Near Field Loading

The compact MIMO antennas tend to have close spacing ports. Because of this, any near field propagation changes causes mismatches and introduce significant coupling for the compact MIMO antennas. Thus, this limits the capacity gain offered by MIMO. We propose a hypothesis that compact MIMO antennas are more sensitive to near field loading as compared to physically separated MIMO antennas. This hypothesis is motivated by the facts that the compact MIMO antennas may have correlated and overlapped radi-
ation patterns from close spacing ports, and the antenna aperture and bandwidth are proportional. As the size of MIMO antenna becomes more compact, the bandwidth of MIMO antenna will be narrower. This research highlights the development of a systematic method to evaluate sensitivity of MIMO antennas to near field loading.

1.4 Overview of the Thesis

In Chapter 2, a probe-fed microstrip antenna will be discussed as well as the MIMO antenna parameters. We will review mutual coupling and study the relationship between separation distance and mutual coupling for a two-port physically separated MIMO antenna. The literature review of compact MIMO antennas will be conducted, and a systematic design for a compact MIMO antenna [55] will be introduced. Overall, the aim of Chapter 2 is to select three different MIMO antenna for the sensitivity test with a near field load in Chapter 3.

Chapter 3 will explain the sensitivity test and evaluation metric. We will conduct a full-wave simulation for all three different MIMO antennas with a near field load in FEKO. All three antennas and a near field load will be fabricated and measured. We also will setup measurements on near field loaded MIMO antennas. A metric using S parameters will be employed to evaluate the performance of channel capacity for near field loaded MIMO antennas. We will discuss the impact of bandwidth and polarization in loaded MIMO antennas.

Chapter 4 will conclude our work on near field loaded MIMO antennas, and recommended directions of the future work.
Chapter 2

MIMO Antenna

In this chapter, we will first introduce MIMO antenna parameters as the evaluation parameters. The evaluation parameters are parameters that used to evaluate the sensitivity of MIMO antennas to a near field load. Then, we will review other works related to the effects of near field loading on MIMO antennas. We will briefly describe the design of a probe-fed single patch, study, and review mutual coupling in physically separated MIMO antennas. Some examples of MIMO antennas will be demonstrated in the literature review. We will introduce a compact MIMO antenna based on a systematic design methodology and explore how its design achieves good input matching and low mutual coupling [55]. The goal of this chapter is to select three different MIMO antennas to evaluate the sensitivity to near field loading.

2.1 MIMO Antenna Parameters

Antenna parameters are essential when describing both circuit properties and radiation properties of antennas. Antenna parameters constitute radiation patterns, directivity,
radiation efficiency, envelope correlation coefficient (ECC), mutual coupling, reflection coefficient, bandwidth, gain and polarization in both transmitting and receiving modes. In a two-port system, the scattering parameters included reflection coefficient and mutual coupling.

2.1.1 Scattering Parameters

Voltage reflection coefficient ($\Gamma$) is defined as the ratio of the reflected voltage amplitude ($V^-$) to the forward voltage amplitude ($V^+$) at the antenna load ($Z_L$) to the characteristic impedance ($Z_o$):

$$\Gamma = \frac{V^-}{V^+} = \frac{Z_L - Z_o}{Z_L + Z_o}$$

(2.1)

In a one-port system, the scattering parameter is equal to the reflection coefficient measured at the port.

$$\Gamma = S_{11}$$

(2.2)

In a two-port MIMO system, the scattering parameter is represented by a square matrix at the receiver or the transmitter, $S_{RR} = S_{TT} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$. The reflection coefficient represents how much the power is reflected at the antenna port. If a two-port network is symmetrical, and then

$$S_{11} = S_{22}$$

(2.3)

The off-diagonal terms in the S parameter matrix are referred to as mutual coupling. This represents how much undesired transmitted power is absorbed by an adjacent antenna when another nearby antenna operates in transmit mode. Likewise, mutual coupling is
also referred to as isolation. If the two-port network is reciprocal, then

\[ S_{12} = S_{21} \]  \hspace{1cm} (2.4)

Ideally, low reflection coefficients and low mutual coupling are desirable for antenna designs. In other words, low mutual coupling means that less incident energy should be reflected back at the antenna port in the transmitting mode, and less radiated energy should be coupled into the nearby antenna port. The reflection coefficient and mutual coupling are important antenna parameters to characterize MIMO antennas.

### 2.1.2 Envelope Correlation Coefficient

Mutual coupling is not the only factor that determines MIMO antenna's performance. Envelope correlation coefficient (\( \rho_e \), ECC) is an important parameter in the MIMO system. ECC represents how signals are correlated with each other from a communication stance. From an electromagnetic perspective, it is a measure of how radiation patterns, the relative phase of far-field between antennas and polarization are correlated to one another. The envelope correlation coefficient for a two-port MIMO antenna based on far-field radiation patterns is [47]:

\[
\rho_e = \frac{\left| \int_{\Omega} F_1(\theta, \phi) \cdot F_2^*(\theta, \phi) d\Omega \right|^2}{\int_{\Omega} |F_1(\theta, \phi)|^2 d\Omega \int_{\Omega} |F_2(\theta, \phi)|^2 d\Omega}
\]  \hspace{1cm} (2.5)

where \( F_n(\theta, \phi) \) is the 3-D far-field radiation pattern for a \( n \) port antenna in the transmitting mode and \( \Omega \) is the differential angle. We assume an isotropic scattering environment for Equation (2.5). Typically, the value of ECC ranges from 0 to 1. If \( F_1(\theta, \phi) \) and \( F_2(\theta, \phi) \) are completely independent, then the value of ECE is 0. In contrast, the value ECC of 1
means that $F_1(\theta, \phi)$ and $F_2(\theta, \phi)$ are totally correlated.

Equation (2.5) is complicated because it require the measurement of 3-D far field radiation patterns for each antenna independently in the MIMO chain. The simplified equation for envelope correlation coefficient of two-port antennas based on S parameters has been modified as [6]:

$$
\rho_e = \frac{|S_{11}^*S_{12} + S_{21}^*S_{22}|^2}{(1-(|S_{11}|^2 + |S_{21}|^2))(1-(|S_{22}|^2 + |S_{12}|^2))} \quad (2.6)
$$

where S parameters can be easily obtained by a Vector Network Analyzer (VNA). We assume a rich scattering environment with the 3-D uniform scattering and the cross-polarization ratio (XPR) of 0 dB for Equation (2.6) [52]. Equation (2.6), based on S parameters, is accurate as long as the assumption of a lossless RF system with an isotropic source is valid [3, 35].

Two half-wavelength dipoles antenna in Figure 2.1a is simulated in FEKO to validate both Equation (2.5) and (2.6). The results of envelope correlation coefficient from Equation 2.5 and Equation 2.6 is identical from 0.8 to 1.2 GHz as shown in Figure 2.1b. The S parameters approach for ECC calculation provides enough accuracy and S parameters simulation takes less time as compared to far-field simulation. Thus, Equation 2.6 will be used to evaluate the sensitivity of MIMO antennas to near field loading.

### 2.2 Effects of Near Field Loading

Near field regions are the reactive field regions and the radiating near-field regions. The reactive field region is the space immediately surrounding the antenna. For the most antennas, the distance between the reactive field region and the antenna is from 0 to $\frac{\lambda}{2\pi}$,
Figure 2.1 (a) The geometry of a two half-wavelength dipoles antenna, (b) the result of ECC based on S parameters and field radiation pattern for the two half-wavelength dipoles antenna.

where $\lambda$ is the wavelength of the antenna operating frequency. The radiating near field is the region between the reactive near field region and the far field region. The extent of this radiating near field region is from $\frac{\lambda}{2\pi}$ to $\frac{2D^2}{\lambda}$, where $\lambda$ is the wavelength of the antenna operating frequency and $D$ is the largest dimension of the antenna aperture [5].

It still remains very challenging to analyze how the near field loading impacts MIMO antennas such as handset devices. Arai [2] stated that the handset devices’ size is becoming small, thus the effect of human head and hands to MIMO antennas can’t be neglected. Therefore, human head and hands are considered as near field loads to compact handset devices. Moreover, the rigorous work [36] of mobile-phone grip styles was investigated on more than 100 samples. More specifically, the human hand causes absorption and mismatch losses while the truck of the human head adds a smaller loss. This study identified two main grip styles in the talk mode. Most of the participants used both hands while the phone was in the data mode. Moreover, the different grip styles of hands impacted the performance of mobile phones in both talk and data modes.
Plicanic, Lau, Derneryd & Ying [37] continually investigated the effects of the human hand and head in actual diversity performance of compact mobile terminals using the evaluation metric. This evaluation metric included S parameters, mean effective gain (MEG), envelope correlation and diversity performance. Figure 2.2 also illustrates four different scenarios such as no user interaction, the compact terminal in handheld position, the compact terminal in head only position, and the compact terminal in hand and head position. The compact mobile antenna in all user interaction cases decreased the performance of envelope correlation at the low band. Table 2.1 shows that it measured and simulated envelope correlation with the four different user interaction scenarios.

![Figure 2.2](image.png)

**Figure 2.2** Four different scenarios for diversity performance evaluation with user interactions, (a) free space (no user interaction), (b) handheld position (data mode), (c) head only position (side of head), and (d) hand and head position [37].

The performance of MIMO antennas can be affected by impedance mismatch and coupling loss. This is due to the user effects because external matching and decoupling networks have been integrated into handset antenna terminals [22, 29, 36, 37, 41]. In [46], MIMO Prototype A and B in three user interaction scenarios, free space (FS), one hand data mode (OH), and two hands data mode (TH), had been evaluated using the metrics
of channel capacity, multiplexing efficiency and the adaptive impedance matching (AIM) performance. The 6 dB impedance bandwidth is 85 MHz for Prototype A, and 200 MHz for Prototype B at LTE Band 18 (815-875 MHz). Figure 2.3 shows that Prototype A and B in no user interaction, one hand position, and double hands positions. Table 2.2 presents that the results of capacity, efficiency, correlation and ME for both prototypes in all three scenarios (FS, OH, TH), and averaged three frequencies in LTE 18 downlink (860, 867 and 875 MHz) with the optimized AIM at the center frequency (867 MHz) while the SNR is assumed to be 20 dB.

**Table 2.1** Measured (MEAS) and simulated (SIM) envelope correlation for four different user interaction cases: free space, handheld position, head only position, and hand and head position [37].

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Free space</th>
<th>Hand</th>
<th>Head</th>
<th>Hand &amp; Head</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.87</td>
<td>0.57</td>
<td>0.65</td>
<td>0.31</td>
<td>0.03</td>
</tr>
<tr>
<td>0.88</td>
<td>0.51</td>
<td>0.56</td>
<td>0.34</td>
<td>0.06</td>
</tr>
<tr>
<td>0.89</td>
<td>0.47</td>
<td>0.52</td>
<td>0.33</td>
<td>0.12</td>
</tr>
<tr>
<td>1.81</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>1.84</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>1.88</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.09</td>
</tr>
<tr>
<td>2.11</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.05</td>
</tr>
<tr>
<td>2.14</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.05</td>
</tr>
<tr>
<td>2.17</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Authors concluded from the results that AIM has a potential to significantly improve the performance of compact handset devices in the presence of the users. The capacity for prototypes A and B in FS were 8.4 and 7.6 bits/s/Hz, respectively. In the OH and TH scenarios, the capacity for prototype B was only decreased to 6.8 and 7.4 bits/s/Hz. However, the capacity for prototype A had several decreases in OH and TH, 7.6 and 5.7 bits/s/Hz. An interesting observation from this work was that Prototype A, which was
Figure 2.3 Prototypes A and B: Illustrations of hand position with respect to the antenna elements in all three scenarios based on 3-D models of the terminal [46].

more sensitive to user interactions, had narrower bandwidth. Whereas, the user interactions had a little impact on Prototype B. From our definition of compact MIMO antennas in section 1.2.2, Prototype A and B were defined as the physically separated MIMO antennas because both of Prototype A and B had two radiating elements. However, Prototype A and B had different quality factors (Q factor). In other words, Prototype A had a high Q factor, which was more susceptible to near field loadings. On the contrary, Prototype B was more robust in user interaction and the cost losses of AIM is lower because of a low Q factor for Prototype B [46].

2.3 MIMO Antenna

In this thesis, the compact two-port MIMO antenna Yang, Zhou & Adams [55] is the basis for all of near field loading analysis. For comparison purposes, we compare this compact two-port MIMO antenna with physically separated two-port MIMO antennas in the near-field loading analysis. One of constraints to design a physically two-port MIMO antenna
Table 2.2 Total efficiency ($n$), Envelop Correlation ($\rho_e$), Capacity, and ME results for prototypes A and B averaged over LTE BAND 18 downlink (860-875 MHZ) for FS, OH, and TH scenarios [46].

<table>
<thead>
<tr>
<th>User case/metric</th>
<th>Prototype A</th>
<th>Prototype B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 Ω</td>
<td>AIM</td>
</tr>
<tr>
<td>$\eta_1$ (dB)</td>
<td>-4.16</td>
<td>-4.42</td>
</tr>
<tr>
<td>$\eta_2$ (dB)</td>
<td>-3.64</td>
<td>-3.72</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>0.38</td>
<td>0.26</td>
</tr>
<tr>
<td>Capacity (bits/s/Hz)</td>
<td>8.4</td>
<td>8.5</td>
</tr>
<tr>
<td>Capacity gain (%)</td>
<td>1.3</td>
<td>4</td>
</tr>
<tr>
<td>ME gain (dB)</td>
<td>0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>OH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_1$ (dB)</td>
<td>-8.49</td>
<td>-7.49</td>
</tr>
<tr>
<td>$\eta_2$ (dB)</td>
<td>-3.80</td>
<td>-3.51</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Capacity (bits/s/Hz)</td>
<td>7.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Capacity gain (%)</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>ME gain (dB)</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>TH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_1$ (dB)</td>
<td>-7.81</td>
<td>-3.98</td>
</tr>
<tr>
<td>$\eta_2$ (dB)</td>
<td>-9.79</td>
<td>-5.28</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>0.43</td>
<td>0.18</td>
</tr>
<tr>
<td>Capacity (bits/s/Hz)</td>
<td>5.7</td>
<td>8.2</td>
</tr>
<tr>
<td>Capacity gain (%)</td>
<td>44</td>
<td>8</td>
</tr>
<tr>
<td>ME gain (dB)</td>
<td>5.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

is choosing the substrate based on the compact two-port MIMO antenna. The chosen substrate is the RT/duroid 5880 with a dielectric constant of 2.2 ($\epsilon_r = 2.2$), a thickness of 3.175 mm (h=3.175 mm). This section presents the design of a 2.4 GHz square microstrip antenna and mutual coupling in physically separated MIMO antennas.

### 2.3.1 Design of a Square Patch Antenna

The microstrip antenna is usually referred to as a patch antenna. The advantages of the microstrip antenna are that it is very low profile, has easy fabrication and has multiple-mode operation. Nevertheless, the disadvantages of the microstrip antennas are that the bandwidth is narrow due to a thin substrate and it has low RF power handling [4]. The common shape of patch elements are square, rectangular, dipole, and circular due to the ease of analysis, fabrication and good antenna property. The square shape is a special case of rectangular shape. For easy implementation, this thesis chooses a square...
shape for a single patch design. The resonant frequency of the design \( f_r \) is 2.4 GHz. According to [5], the width (W) and length (L) of a patch antenna can be calculated from the following:

\[
W = L = \frac{1}{2f_r \sqrt{\epsilon_{reff}} \sqrt{\mu_0 \epsilon_0}} - 2\Delta L
\]  

(2.7)

where the extension of \( \Delta L \) due to fringing effects is

\[
\Delta L = 0.412h \frac{(\epsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\epsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)}
\]

(2.8)

and the effective dielectric constant (\( \epsilon_{reff} \)) can be found as following:

\[
\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r + 1}{2} [1 + 12 \frac{h}{w}]^{-1/2}
\]

(2.9)

For feed techniques, the design applies the coaxial probe-feed because of the advantages of easy fabrication, good matching and less spurious radiation. Figure 2.4a shows that the top view of a coaxial-fed square patch antenna and the dimension of the single square patch antenna are 40 mm × 40 mm with the port 1 at \((x,y) = (8 \text{ mm},0 \text{ mm})\). The single square patch antenna is simulated in FEKO EM software and the simulated result of \( S_{11} \) for the 2.4 GHz square patch antenna is shown in Figure 2.4b. The reflection coefficient of the 2.4 GHz square patch antenna is -18.8 dB at 2.4 GHz and a 10 dB impedance bandwidth is 66 MHz on which the center frequency is at 2.404 GHz.

### 2.3.2 Mutual Coupling

For transmitting modes, some of the radiated energy from a transmitting antenna is received in a nearby transmitting antenna. This unwanted interchange of radiation energy is called mutual coupling. For the receiving mode, some of received energy from a receiving
antenna is scattered into an adjacent receiving antenna. This unwanted interchange of scattered energy is also called mutual coupling. Conventionally, the rule of thumb on a minimum distance between adjacent antennas is $\lambda/2$ in order to have low mutual coupling in MIMO antennas or antenna arrays.

A two-port physically separated MIMO antenna consists of two 2.4 GHz patch antennas in E-plane and H-plane are shown in Figure 2.5a and 2.5b, receptively. We seek to understand mutual coupling and separation distance between antenna elements. Therefore, we run a parametric sweep of separation distance for a two-port physically separated MIMO antenna at 2.4 GHz in E-plane and H-plane.

Pozar [38] had also studied the relationship between mutual coupling and antenna element distance in microstrip antenna elements. Figure 2.6a shows the calculated and measured mutual coupling between two coax-fed microstrip antennas in both E plane and H plane. Figure 2.6b shows the simulated mutual coupling at 2.4 GHz versus the edge to edge distance for the two-port physically separated MIMO antenna in both E plane and H plane, noted as $\lambda_o$ in terms of the wavelength in free space. In both Figure 2.6a and
Figure 2.5 The top view of a physically separated MIMO antenna, $W = L = 40\text{mm}$: (a) in E-plane; (b) in H-plane.

2.6b, mutual coupling are much larger in E-plane when antenna elements are far apart because of the stronger surface wave excitation between the adjacent antenna elements. Mutual coupling is also monotonically increasing as antennas become more compact. In our work, a good agreement is found with Pozar [38]’s study. In fact, mutual coupling is a concern when antenna elements move closer to each other.

Chen, Zhang & Li [9] and Wu, Linnartz, Bergmans & Attallah [51] present how mutual coupling impacts correlation, diversity gain, channel capacity, and bit error rate in MIMO antennas. The mutual coupling degrades the channel capacity of MIMO system. However, the results in [9] state that mutual coupling below -17 dB has negligible impact on the MIMO capacity. To reduce mutual coupling in MIMO antennas, decoupling techniques have been studied and investigated such as adding parasitic elements [31], multi-port decoupling network [8], using discrete metamaterial mushroom as loading [56], employing characteristic mode theory [7, 28–30], and modifying the ground plane. To conclude, the mentioned literature are on all of effects to reduce mutual coupling. The cost of multi-
port decoupling networks are extremely expensive in terms of the immense combinations for the decoupling. In other words, it is only feasible to employ decoupling networks for the narrowband scenario. Ideally, compact multi-port antennas have low intrinsic mutual coupling which is desired.

### 2.3.3 Compact MIMO Antenna

As the trend of antenna design in the 4G and 5G communication, the size of cellular handsets become more compact with the increased numbers of antennas. Low mutual coupling is a design challenge for a compact MIMO antenna when the size constraint is restricted. Efforts have been made to improve the performance of compact MIMO antennas. In [25, 32], two antenna elements are placed in orthogonal with a modified ground plane as shown in 2.7a and 2.7b. In a 10 dB impedance bandwidth of 3.1-10.6 GHz, the mutual coupling is less than -15 dB for both [25, 32]'s design. A four-port
wideband MIMO antenna loaded with a split ring resonator is shown in Figure 2.8. The antenna occupies a total area of $0.109 \lambda_d^2$. While on a 10 dB impedance bandwidth between 2.2-6.28 GHz, the isolation is higher than 14 dB and ECC is greater than 0.25. However, these three designs are only established for ultrawideband (UWB) antennas, and the designs purely rely on manipulating the antenna and ground shapes as well as the positions of the antenna elements.

**Figure 2.7** Photograph of prototype antennas: (a) [32], and (b) [25].

**Figure 2.8** (a) Configuration of four-port wideband MIMO antenna: (b) Prototype front view, (c) Prototype back view [1].
In 1971, Harrington [20] established the theory of characteristic modes (CMT), and discovered the orthogonality property of the characteristic modes. Recently, there are numerous studies on the synthesis and optimization of antenna design employed the characteristic mode theory [12, 29, 34, 57]. However, design approaches are only limited to pre-defined antenna apertures from these literature. Manipulating the chassis of antennas is to introduce more characteristic modes as inherent decoupled modes. For example, CMT is employed in [26] as the implementation of the decoupling networks. Figure 2.9 shows the configuration of the bug-like MIMO antenna with the mode decoupling network (MDN) [26]. However, the complexity of the MDN becomes large, and making design difficult. The proposed bug-like MIMO antenna has the complicated MDNs and four matching networks. This design has a wide input matching bandwidth from 2.4 to 2.58 GHz, a low mutual coupling (≤ -20 dB) as well as a low envelope correlation coefficient (≤ 0.04).

![Figure 2.9](image.png)

Figure 2.9 Configuration of the proposed bug-like MIMO antenna including the feeding network: (a) top view, (b) bottom view, (c) systematic view [26].
2.3.4 Systematic Design of a Two-Port Compact MIMO antenna

Yang, Zhou & Adams [55] developed a shape-first feed next design methodology that facilitates the optimization of a planar MIMO antenna design. First, a binary genetic algorithm is used in the optimal antenna shape with multiple self-resonant modes [54]. Second, the characteristic mode theory with a virtual probe modeling technique is employed in optimal feed positions [53]. Figure 2.10a shows the optimized antenna top metal geometry with the electrical size $0.45\lambda_d \times 0.297\lambda_d$ at 2.4 GHz. In the optimal feed specification step, port 1 at (4.76 mm, 0) and port 2 were found at (0, 3.108 mm) for good input matching and high isolation. Figure 2.10b shows the result of S parameters from full-wave simulation in FEKO for the optimized two-port 2.4 GHz compact MIMO antenna. Both of results shows that the reflection coefficient and mutual coupling from the circuit model and the full-wave simulation both have a good agreement to each other.

![Figure 2.10](image)

**Figure 2.10** (a) The optimized antenna top metal geometry with the port 1 at (4.76 mm, 0) and the port 2(0, 3.108 mm), (b) comparison of the antenna input S parameters from circuit model (solid lines) and full wave simulation (marked lines) [55].
The compact MIMO antenna was also fabricated to validate this systematic antenna design methodology. The prototypes of the compact MIMO antenna was able to achieve good input matching from 2.442 to 2.467 GHz, low mutual coupling ($S_{12} \leq -35$ dB) at the center frequency as well as extremely low envelop correlation ($\rho_e \leq 10^{-5}$). In the Table 2.3, we compare Yang, Zhou & Adams [55] work with other compact MIMO designs from the literature. The 10 dB bandwidth of [55] is the smallest among this literature due to the more compact size. Even though [26] design has the wider 10 dB bandwidth, but also the electrical size of [26] design is the largest. Despite the two close ports, this two-port compact MIMO antenna has good input matching and low mutual coupling without an external decoupling network.

Table 2.3 Comparison of the existing compact antenna designs.

<table>
<thead>
<tr>
<th>Designs</th>
<th>Metrics</th>
<th>10 dB Bandwidth</th>
<th>Isolation (dB)</th>
<th>ECC</th>
<th>Electrical Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>[44] (with parasitic elements)</td>
<td>3.8% (2.52-2.62 GHz)</td>
<td>$\geq 20$</td>
<td>NA</td>
<td>0</td>
<td>$0.30 \lambda_d^2$</td>
</tr>
<tr>
<td>[43] (consider first two ports)</td>
<td>2% (2.425-2.475 GHz)</td>
<td>$\geq 12$</td>
<td>$\geq 0.3$</td>
<td>0</td>
<td>$0.27 \lambda_d^2$</td>
</tr>
<tr>
<td>[26] (CMT with MDN)</td>
<td>7.2% (2.4-2.58 GHz)</td>
<td>$\geq 20$</td>
<td>$\leq 0.04$</td>
<td>0</td>
<td>$0.846 \lambda_d^2$</td>
</tr>
<tr>
<td>[55] (CMT)</td>
<td>1% (2.442-2.467 GHz)</td>
<td>$\geq 33$</td>
<td>$\leq 0.001$</td>
<td>0</td>
<td>$0.13 \lambda_d^2$</td>
</tr>
</tbody>
</table>

$\lambda_d$ is the wavelength in the dielectric substrate.

2.4 Testing Cases

The aim of this chapter is to select three different MIMO antennas as testing cases. From this Section 2.3, we selected two two-port physically separated MIMO antennas, for distance between edge to edge of 0.048 $\lambda_o$ ($D = 6$ mm) in H plane, this antenna is referred to as a D6 MIMO antenna. Distance between edge to edge is 0.224 $\lambda_o$ ($D = 28$
mm) for another two-port physically separated MIMO antenna, we called this antenna as a D28 MIMO antenna. The third testing antenna is the compact MIMO antenna from [55]. The top views of three testing MIMO antennas are shown in Figure 2.11.

![Figure 2.11](image)

**Figure 2.11** The top views of MIMO antennas: (a) D6 MIMO antenna, (b) D28 MIMO antenna, (c) compact MIMO antenna.

In Figure 2.12, the mutual coupling is -8 dB for the D6 MIMO antenna, -18 dB for the D28 MIMO antenna, and -35 dB for the compact MIMO antenna at the center frequency, respectively. In the next chapter, we will compare the sensitivity performance among all three testing cases with near field loading.
Figure 2.12 Comparison of S parameters from the D6 MIMO antenna, the D28 MIMO antenna, the compact MIMO antenna.
Chapter 3

Sensitivity Evaluation of MIMO Antennas to Near Field Loading

The D6 MIMO antenna, the D28 MIMO antenna, and the compact MIMO antenna were selected to perform the sensitivity test. The sensitivity test is to evaluate the sensitivity of MIMO antennas in a near field load. In this chapter, the full aperture sampling of three MIMO antennas in a near field load will be simulated in FEKO, and the results of tests will be analyzed by the evaluation metric. We will also fabricate all three MIMO antennas and a near field load. S parameters will be measured for unloaded MIMO antennas and loaded MIMO antennas. The channel capacity metric using S parameters will be employed to evaluate the channel capacity performance of loaded MIMO antennas.

3.1 Full Aperture Sampling

Full aperture sampling is a process that is sampling a near field load with a MIMO antenna within the antenna aperture at a certain height. First of all, we select the geometry
of a flare as a near field load that is shown in Figure 3.1. The dimension of the near field load is arbitrarily chosen where bottom width (Wb): 40 mm, bottom depth (Db): 20 mm, Height (H): 10 mm, Flare angle (Au): -20, Flare angle (Av): -30. The material of the near field load in FEKO simulation is assigned a perfect electric conductor (PEC). By using PEC as the material of the near field load, the simulation results are expected to comply with the calculation results from Equation (2.6). Other studies on effects of near field loading consider biological materials as near field loads (e.g. hands and head). However, the scope of this research is to investigate how near field loading impacts compact MIMO antennas in general. Therefore, a PEC object will still allow us to make conclusions about our hypothesis.

![Figure 3.1](image)

**Figure 3.1** Geometry of a flare for the near field load.

Figure 3.2 shows that the PEC near field load is 10 mm above the MIMO antennas. The sweeping positions are based on the size of the MIMO antenna aperture and the number of 36 loading positions on which shown in Table 3.1. In each position, a testing MIMO antenna with the PEC near field load is simulated and the result of S parameters is recorded into a SnP file in FEKO. FEKO is a computational electromagnetic simulation
software that employs Method of Moments (MoM). FEKO is well-suited for the test of a electrically small MIMO antenna with near field loading because of efficient simulation and high accuracy. FEKO has its own function of parametric sweep, which enables sweep the position of the PEC near field load on the top of MIMO antennas.

Figure 3.2 An illustration of full aperture sampling: (a) the D6 MIMO antenna with the PEC load, (b) the D28 MIMO antenna with the PEC load, (c) the compact MIMO with the PEC load.

Table 3.1 Full aperture sampling for the three testing cases.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>$L$</th>
<th>$W$</th>
<th>Loading Positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>86 mm</td>
<td>40 mm</td>
<td>36</td>
</tr>
<tr>
<td>D28</td>
<td>108 mm</td>
<td>40 mm</td>
<td>36</td>
</tr>
<tr>
<td>Compact</td>
<td>38 mm</td>
<td>25 mm</td>
<td>36</td>
</tr>
</tbody>
</table>
3.2 Evaluation Metric

In Chapter 2, two characterized parameters of MIMO antennas, S parameters and envelope correlation coefficient are defined. This section will introduce an evaluation metric with evaluation bandwidth and pass rate, to characterize the sensitivity of MIMO antennas to a near field load.

3.2.1 Evaluation Parameters

As we discussed antenna parameters in Section 2.1, we learned the importance of S parameters and envelope correlation coefficient for MIMO antennas. Even more, we consider the reflection coefficient as an evaluation parameter. However, mutual coupling and ECC are two different antenna parameters. The low mutual coupling cannot guarantee low ECC because both reflection coefficients and mutual coupling should be taken account in the calculation of ECC. Therefore, envelope correlation coefficient, instead of mutual coupling, is used in the evaluation the effect of near field loading on MIMO antennas.

3.2.2 Evaluation Bandwidth

Bandwidth is a fundamental antenna property that refers to a range of frequencies that an antenna is able to correctly transmit and receive signals. The reflection coefficient and mutual coupling are used to characterize an antenna’s bandwidth. The reflection coefficient is less than -10 dB. In the range of frequencies, is often called the 10 dB impedance bandwidth. The impedance bandwidth can demonstrate how good impedance matching is in antennas. Therefore, this thesis uses the 10 dB impedance bandwidth, which is from 2.404 to 2.4217 GHz for the compact MIMO antenna, as the evaluation
frequency in all three testing cases.

### 3.2.3 Pass Rate

Pass rates represent the percentage of samples of antenna parameters that successfully exceed a particular threshold (a acceptable value). Specifically, S parameters pass rate (\(R_s\)) at a pass threshold (PT) is defined as:

\[
R_s = \frac{N_p}{N_t}
\]  

(3.1)

where \(N_p\) is the total number of passed samples and \(N_t\) is the total number of samples.

For example, Figure 3.3 (a) shows that S parameters for the compact MIMO antenna with the PEC near field load. For the pass threshold of -10 dB, this sample would fail because \(S_{11}\) across the band are above the pass threshold, though \(S_{22}\) are below the pass threshold from 2.415 to 2.4217 GHz. Therefore, \(S_{11}\) and \(S_{22}\) pass rate provides some insights for how near field loading impacts on input impedance matching of MIMO antennas. The S parameters pass rate also helps to determine the sensitivity of MIMO antenna to a near field load in terms of input matching.

\[
R_e = \frac{N_p}{N_t}
\]  

(3.2)

Equation 3.2 is the ECC pass rate at a ECC pass threshold, where \(N_p\) is the total number of passed samples and \(N_t\) is the total number of positions. As an illustrative example shown in Figure 3.3 (b), this sample fails because the ECC are above the ECC threshold of -25 dB from 2.415 to 2.42 GHz. Both S parameters (\(S_{11}\) and \(S_{22}\)) and ECC pass rate are essential to determine the sensitivity of MIMO antennas to a near field
Figure 3.3 An illustrative example: (a) the plot of ECC, (b) the plot of S parameters, (c) the compact MIMO antenna with the PEC near field load.

load. The evaluation metric is employed for each testing case to generate the $S_{11}$ and $S_{22}$ pass rate and ECC pass rate. Additionally, we developed the MATLAB code for the evaluation metric to post process raw data from SnP files.

3.3 Results and Sensitivity Analysis

We setup the full aperture sampling and ran the parametric sweep of 36 loading positions on the x-y plane for each MIMO antenna in FEKO. In a conventional way, we plot S parameters and ECC for each testing case with the near field load, as shown in Figure
3.4, 3.5 and 3.6. With 12 plots of S parameters and ECC, it is extremely complicated to interpret the data and understand how the near field load impacts on MIMO antennas. The evaluation metric enables us to extract the information from full aperture sampling and the MATLAB code to automatically generate the plots of the $S_{11}$ and $S_{22}$ and ECC pass rate from the evaluation metric. Hopefully, only looking for the plots of $S_{11}$ and $S_{22}$ and ECC pass rate can help us draw a conclusion on the sensitivity of MIMO antennas to a near field load.

Solid lines in Figure 3.7 represent the $S_{11}$ and $S_{22}$ pass rate for the sensitivity tests of the D6 MIMO antenna, the D28 MIMO antenna and the compact MIMO antenna,
Figure 3.5 36 loading positions for the D28 MIMO antenna: (a) S11, (b) S22, (c) S12, (d) ECC.

calculated over 11 frequencies in the 10 dB impedance bandwidth of the compact MIMO antenna, with the total number of 36 positions. Dash lines in Figure 3.7 represent the $S_{11}$ and $S_{22}$ pass rate for the D6 MIMO antenna, the D28 MIMO antenna and the compact MIMO antenna in free space. As we expected, the $S_{11}$ and $S_{22}$ pass rate for the compact MIMO antenna in free space is the yellow dash line at the pass threshold of -10 dB because the 10 dB impedance bandwidth of the compact MIMO antenna. This prevents passing if the pass threshold is less than -10 dB. However, the yellow solid line is shifted from the yellow dash line to right a lot because of the presence of the PEC near field load in the reactive near field region. The blue and red dash lines are the $S_{11}$ and $S_{22}$
Figure 3.6 36 loading positions for the compact MIMO antenna (a) S11, (b) S22, (c) S12, (d) ECC.

pass rate for the D6 MIMO antenna and D28 MIMO antenna in free space, respectively. Both the blue and red solid curves show that similar characteristics in terms of slope of curves and pass rate. This also indicates that the PEC near field load has less impact on the D6 MIMO antenna and the D28 MIMO antenna as compared to the compact MIMO antenna. Interestingly, the PEC near field load even improves the input matching and ECC in some cases for the D6 MIMO antenna and the D28 MIMO antenna.

Figure 3.8 shows that the ECC pass rate for the sensitivity test of the D6 MIMO antenna, the D28 MIMO antenna and the compact MIMO antenna, calculated from S parameters using Equation 2.6. Additionally, dash lines represents the ECC pass rate of
**Figure 3.7** $S_{11}$ and $S_{22}$ pass rates for the sensitivity test in the D6 MIMO antenna, the D28 MIMO antenna, and the compact MIMO antenna.

**Figure 3.8** The ECC pass rate for the sensitivity test in the D6 MIMO antenna, the D28 MIMO antenna and the compact MIMO antenna.

three MIMO antennas in free space. In Figure 3.8, dash lines from left to right are the ECC Compact, ECC pass D6 and ECC pass D28 because the ECC value for the compact MIMO antenna is the smallest among all three MIMO antennas. Both of the solid curves for the ECC pass D6. The ECC pass D28 are close to their red dash line, which indicates that the PEC near field load has a small impact ECC for the D6 MIMO antenna and
the D28 MIMO antenna. However, the yellow solid curve has a much smaller slope than other two solid curves and is also shifted to right compared to the yellow solid line.

From the previous two analyses, we concluded that the compact MIMO antenna is more sensitive to the PEC near field load as compared to other two MIMO antennas. We also observe an interesting phenomenon, the PEC near field load improves both input matching and the performance of ECC for some cases of the D6 MIMO antenna and the D28 MIMO antenna. However, the PEC near field load degrades the input matching of the compact MIMO antenna as well as the performance of ECC.

### 3.3.1 Impact of Evaluation Bandwidth

We only discussed the 10 dB impedance bandwidth for the compact MIMO antenna in Section 3.2.2. Nevertheless, the three MIMO antennas have different 10 dB impedance bandwidth because the aperture of MIMO antennas are different. Usually, an antenna with a large aperture tends to have wide bandwidth, and low Q factor [10, 21]. Therefore, we need to investigate the impact of evaluation bandwidth in the sensitivity test. Each testing case is evaluated over its own 10 dB impedance bandwidth with the evaluation metric. This is refereed to as the independent 10 dB impedance bandwidth. Table 3.2 shows the independent 10 dB impedance bandwidth for the D6 MIMO antenna, the D28 MIMO antenna, and the compact MIMO antenna.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>10 dB Bandwidth</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>2.379-2.445 GHz</td>
<td>66 MHz</td>
</tr>
<tr>
<td>D28</td>
<td>2.3698-2.4336 GHz</td>
<td>63.8 MHz</td>
</tr>
<tr>
<td>Compact</td>
<td>2.404-2.4217 GHz</td>
<td>17.7 MHz</td>
</tr>
</tbody>
</table>

**Table 3.2** Independent 10 dB impedance bandwidth for the D6 MIMO antenna, the D28 MIMO antenna and the compact MIMO antenna.
All three dash lines are vertical at the pass threshold of -10 dB in Figure 3.9a, and it also validates that the independent 10 dB bandwidth are correctly selected from the MATLAB code. With all dash lines at the threshold of -10 dB, it makes the comparisons between solid curves easier and more fair. To compare Figure 3.9a and 3.7, the blue and red solid lines are still around the pass threshold of 10 dB, but the yellow solid line is no longer near to the pass threshold of -10 dB. Moreover, the slope of the yellow solid curve is much smaller than the slope of other two solid curves in Figure 3.9a. The input matching of the compact MIMO antennas is affected more by the presence of the PEC near field load, whereas the input matching of physically separated MIMO antennas does not change too much.

Figure 3.9 Pass rates with independent 10 dB impedance bandwidth for the D6 MIMO antenna, the D28 MIMO antenna and the compact MIMO antenna: (a) $S_{11}$ and $S_{22}$ pass rate, (b) ECC pass rate.

The red and blue dash lines in Figure 3.9b have moved to right as compared to the red and blue dash lines in Figure 3.8, but the yellow dash line does not change in both Figures because of the same evaluation bandwidth for the compact MIMO antenna. However, the
evaluation bandwidth for the D6 MIMO antenna and the D28 MIMO antenna are 66 MHz and 63.8 MHz, which are wider than the evaluation bandwidth of the compact MIMO antenna. We inspect that selective bandwidth impacts the performance of S parameters and ECC pass rate. With this easier comparison between all three testing cases, we still conclude that the compact MIMO antenna is more sensitive to the PEC near field load.

### 3.3.2 Impact of Polarization

The two-port compact MIMO [55] has the x and y linear polarization at the port 1 and port 2, respectively, due to this, both of the feeds are the x and y center lines. However, the D6 and D28 MIMO antennas only have the y linear polarization for both port 1 and port 2. The length of the PEC near field load is larger than the width of the PEC near field. Therefore, it is longer and aligned with the D6 and D28 MIMO antennas’ E plane. In other words, we suspect that this near field load has more effects on the y linear polarization. Thus, we plotted the $S_{11}$ pass rate and the $S_{22}$ rate for the compact MIMO antenna, This is shown in Figure 3.11a. The dash lines represent the $S_{11}$ pass rate and $S_{22}$ pass rate for the compact MIMO antenna in free space. The bandwidth of $S_{11}$ is wider than the bandwidth of $S_{22}$ because of the red dash line at the pass threshold (-12.5 dB) and the black dash line at the pass threshold (-10 dB). The red solid line has shifted from the the red solid line to right in 7 dB. To compare between the red and black solid lines, the $S_{22}$ pass compact has a similar curve with the $S_{11}$ pass compact, However, the $S_{11}$ pass rate for the loaded compact MIMO antenna is lower than the the $S_{11}$ pass rate for the loaded compact MIMO antenna. This indicates that the near field load has more impact for input matching of the compact MIMO antenna at the port 1 compared to the port 2. We ran an identical analysis of the compact MIMO antenna with the elongated
load rotated by 90 degrees, which is illustrated in Figure 3.10a. To compare Figure 3.11a and Figure 3.11a, changing the rotation of the near field load by 90 degrees does not have a significant effect on the \( S_{22} \) pass rate. However, the \( S_{11} \) pass rate has improved by rotating the near field load 90 degrees. As we predicted, the polarization of MIMO antennas has significant impacts on the sensitivity to the near field load.

![Figure 3.10](image.png)

**Figure 3.10** The illustration of the compact MIMO antenna with the elongated near field load rotated by: (a) 0 degree, (b) 90 degrees.

We also studied the impacts of polarization on the loaded D6 and D28 MIMO antenna and run identical analysis of the D6 and D28 MIMO antenna with the elongated load rotated by 90 degrees. The Figure 3.12 represents the \( S_{11} \) and \( S_{22} \) pass rate and ECC pass rate for the all three MIMO antenna with 10 dB impedance bandwidth when the elongated loaded rotated by 90 degrees. To compare between Figure 3.9a and 3.12a, the rotation of the near field load in 90 degrees has boosted the \( S_{11} \) and \( S_{22} \) rate for the compact MIMO antenna. However, it makes the \( S_{11} \) and \( S_{22} \) rate for the D6 and D28 MIMO antenna worse. In the ECC pass rate, the near field load in 90 degree has improved the performance of ECC for the D6 and D28 MIMO antenna. Therefore, we concluded
Figure 3.11 $S_{11}$ and $S_{22}$ pass rates with independent 10 dB impedance bandwidth for the compact MIMO antenna when the elongated near field load rotated by: (a) 0 degree, (b) 90 degrees.

that the elongated load has more affects on the $x$ polarization.

Figure 3.12 Pass rates with independent 10 dB impedance bandwidth for the D6 MIMO antenna, the D28 MIMO antenna and the compact MIMO antenna when the elongated loaded rotated by 90 degrees: (a) $S_{11}$ and $S_{22}$ pass rate, (b) ECC pass rate.
3.4 Full Aperture Measurement

To validate the simulation results, all three MIMO antennas were fabricated as well as a near field load. The measured and simulated results of the all three MIMO antennas are compared in this section. We will describe the full aperture measurement setup. The measured results will be post-processed and analyzed and we will conclude the findings from the full aperture measurement.

3.4.1 Fabrication and Results

Figure 3.13a shows that a near field load fabricated by PLA plastic in a reliable and easy-to-use 3D printer, Lulzbot Taz 6. Even the PEC near field load was used in the simulations, but the perfect electrical conductor does not exist in practice. Copper has the best electrical conductivity of any metal besides silver. Therefore, the copper foil was used to wrap the PLA plastic. The final prototype of the near field load is shown in Figure 3.13b. The top ring is used to hold the near field load during the full aperture sampling measurement. The distance between the ring and the near field load is set at 51 mm, which is in the far field region. Therefore, the ring is not in the near field load, so it would not affect the performance of the MIMO antennas.

The infinite ground, loseless materials and probe-feds were assumed for initial simulation in FEKO. The final simulation was conducted in HFSS considering a finite ground, lossy material and SMAs or small MMCX connectors. Then all three MIMO antennas were fabricated on Rogers (RT/duroid 5880) using a photolithography process. We used a Vector Network Analyzer (Agilent E5071C) to measure S parameters for the all three prototypes.
The prototype of the D6 MIMO antenna is shown in Figure 3.14a. The dimension of a single square patch is $39 \text{mm} \times 39 \text{mm}$, and the distance between edge to edge is 6 mm. The solid lines in Figure 3.14b show the measured two-port S parameters from the VNA. From the measured results, the resonant frequency is slightly shifted from the simulated results in HFSS. Similarly, the dimension of the single square is $39 \text{mm} \times 39 \text{mm}$ for the prototype of the D28 MIMO antenna, which is shown in Figure 3.15a. Both these two prototype D6 and D28 are expected to have slightly different results from the simulation and measurement because of the rough soldering techniques and loss from the SMA connectors.

The prototype compact MIMO antenna was scaled 1 % on the width and Port 1 $(4.5 \text{ mm},0)$ and Port 2 $(0,2.5 \text{ mm})$ were tuned for the feeding positions due to the close spacing (about 5 mm) between the ports. The small MMCX connectors were used as feedings. The final prototype of the compact MIMO antenna as shown in 3.16a. Both the simulation and the measurement have a good agreement with each other in Figure 3.16b.
Table 3.3 shows the measured 10 dB impedance bandwidth for the prototype D6 MIMO antenna, the prototype D28 MIMO antenna, and prototype compact MIMO antenna from solid lines in Figure 3.14b, 3.15b and 3.16b. For the prototype D6 MIMO antenna, the 10 dB bandwidth of the reflection coefficient is from 2.394 to 2.449 GHz.
where $S_{12} \leq -10$ dB. For the prototype D28 MIMO antenna, the 10 dB bandwidth of the reflection coefficient is from 2.379 to 2.431 GHz where $S_{12} \leq -20$ dB. For the prototype compact MIMO antenna, the 10 dB bandwidth of the reflection coefficient is from 2.445 to 2.467 GHz where $S_{12} \leq -33$ dB.

### Table 3.3 Measured 10 dB impedance bandwidth for the D6, D28, and compact antenna.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>10 dB Bandwidth</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>2.394-2.449 GHz</td>
<td>55 MHz</td>
</tr>
<tr>
<td>D28</td>
<td>2.379-2.431 GHz</td>
<td>52 MHz</td>
</tr>
<tr>
<td>Compact</td>
<td>2.445-2.467 GHz</td>
<td>22 MHz</td>
</tr>
</tbody>
</table>

### 3.4.2 Measurement Setup

We conducted the full aperture measurement of the prototype D6, the prototype D28 and the prototype compact with the near field load. The experimental setups for three
prototypes is the same except for the change of the MIMO antennas under test [Figure 3.17]. The near field load was hung above the prototype and the distance between the prototype and the near field load is 10 mm as shown in Figure 3.17a. The metal holder held the ring of the near field load. The near field load was in the y linear polarization, which was also aligned with the D6 and D28 MIMO antennas’ E plane. We controlled the metal holder so that the near field load was able to move around the full aperture of the MIMO antennas on the horizontal plane. Table 3.4 shows the size of the aperture of the MIMO antennas as well as the total number of loading positions. For each sample, the two-port S parameters were measured from the VNA and stored as a SnP file. Additionally, the metal ruler was not presented during the full aperture measurement.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>L</th>
<th>W</th>
<th>Loading Positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>84 mm</td>
<td>39 mm</td>
<td>18</td>
</tr>
<tr>
<td>D28</td>
<td>106 mm</td>
<td>39 mm</td>
<td>18</td>
</tr>
<tr>
<td>Compact</td>
<td>38 mm</td>
<td>25.25 mm</td>
<td>15</td>
</tr>
</tbody>
</table>

### 3.4.3 Measured Results and Analysis

As discussed in the section 3.3.1, the evaluation metric was considered for the independent 10 dB impedance bandwidth for all three prototypes. The independent 10 dB impedance bandwidth helps to make easier and fairer comparisons between three testing cases. Therefore, we use the independent 10 dB impedance bandwidth in this section as well. Figure 3.18 presents the $S_{11}$ and $S_{22}$ and the ECC pass rate for all prototypes with the full aperture sampling, calculated over each independent 10 dB impedance band-
width, and evaluated over 18 loading positions for the prototype D6 and D28, and 15 loading positions for the prototype compact.

The dash lines in Figure 3.18a show the $S_{11}$ and $S_{22}$ pass rate for all three prototypes in free space. The yellow solid curves in Figure 3.18a and 3.9a have similar behaviors. This means that the simulated and measured results are consistent. The yellow solid
curve also has shifted significantly to right as compared to the blue and red solid curves in Figure 3.18a.

As we expected, the dashed lines as shown in Figure 3.18b are arranged from left to right. This is because the value of ECC for the prototype compact is the smallest. Additionally, the value of ECC for the prototype D6 is the largest among three prototypes. Accordingly, the yellow solid curve of ECC pass Compact has changed dramatically as compared to the yellow dash line. The solid curves of ECC pass for the prototype D6 and D26 are very similar but only slightly shifted. This is due to different mutual coupling and the separation distance between antenna elements. In the measurements, the near field load degrades both performances of input matching and ECC in all three testing cases. However, we find that the prototype compact is also more sensitive to a near field load as compared to the other two MIMO antenna in the measurements. The prototype compact antenna has the narrower 10 dB impedance bandwidth. However, the prototype compact antenna has the narrower 10 dB impedance bandwidth. However, the prototype compact antenna has the narrower 10 dB impedance bandwidth. However, the prototype compact antenna has the narrower 10 dB impedance bandwidth.
D6 and D28 have relatively wider 10 dB impedance bandwidth. From the simulation and measurement, we compared the $S_{11}$ and $S_{22}$ and ECC pass rate among three testing case. We drew a similar conclusion from [46], the wideband MIMO antenna (prototype D6 and D28). We learned that it was more robust to the influence of near field loading. On the contrary, the narrowband MIMO antenna (prototype compact) was more sensitive to a near field loading in terms of input matching and ECC.

### 3.5 MIMO Channel Ergodic Capacity

Previously, we reviewed the effects of mutual coupling degrades the performance of channel capacity. In this section, we also investigate how a near field load impact the performance of channel capacity in MIMO antennas. As a simple $M \times M$ MIMO system model shown in Figure 3.19, we assume the channel ergodic capacity with the channel state information at the receiver (CSIR), and no matching network with the front-end [42, 48, 49] is

$$C = E \left[ \log_2 \det \left( I_M + \frac{\rho_T}{M} H_w R_{RR} H_w^H \right) \right] = E \left[ \log_2 \det \left( I_M + \frac{\rho_T}{M} H H^H \right) \right]$$

(3.3)

where $I_M$ is the $M \times M$ identity matrix, and the $\rho_T$ is the SNR. The SNR ($\rho_T$) is defined as $\rho_T = P_T/\sigma_n^2$, where $P_T$ is the transmitted power and $\sigma_n^2$ is the noise power at the receiver [42]. Then, the MIMO channel is given by the MIMO channel matrix:

$$H = R_{RR} H_w$$

(3.4)
where the $H_w$ is assumed as the random Raleigh fading channel matrix (i.i.d.). The correlation matrix at the receiver is

$$R_{RR} = I - S_{RR} S_{RR}^H$$  \hspace{1cm} (3.5)

Figure 3.19 A simple MIMO system connected the multiple matching circuits and individual loads in S parameters [48, 49].

For convenience, we do not consider the matching networking, so that $S_{RR}$ is S parameters at the receiver. Hence, the simple case of MIMO antennas as the receiver can be evaluated by the channel ergodic capacity for the narrowband case. In [13, 27, 52], the broadband capacity of MIMO-OFDM is calculated the sum of the sub-bands in the bandwidth as shown:

$$C = \frac{1}{K} \sum_{k=1}^{K} E[\log_2 \det(\mathbf{I}_M + \frac{\rho_T}{M} \mathbf{H} \mathbf{H}^H)]$$  \hspace{1cm} (3.6)

where K is the number of the sub-bands, in here, $K = 20$.

Based on the Equation 3.6, We obtained the broadband channel capacity from the
channel capacity of the Monte Carlo simulation. Therefore, the broadband channel capacity is calculated over the independent 10 dB bandwidth for the D6, D28, and compact MIMO antenna in free space, and with the near field load when the SNR is assumed to be 20 dB.

In Figure 3.20, the symbol of red crosses represent the broadband channel capacity for each MIMO antenna in free space (FS). The blue error bar is the maximum and minimum values of broadband channel capacity. The symbols of the blue circle are medians for each MIMO antenna with the near field load (NFL). The simulated results in Figure 3.20a are calculated from Equation 3.6 with simulated S parameters, and the measured results in Figure 3.20b is calculated from Equation 3.6 with measured S parameters.

![Figure 3.20](image)

**Figure 3.20** Comparison of channel capacity for the D6, D28, and compact MIMO antenna in free space (FS) and with the near field load (NFL): (a) simulated S parameters, (b) measured S parameters.

In free space, the broadband channel capacity for the compact MIMO antenna is the highest whereas the D6 MIMO antenna is the lowest from both Figure 3.20a and 3.20b. The effects of the near field load impact a little on the performance of channel
capacity for D6 MIMO and D28 MIMO because the blue error bars are still closed to the symbols of red crosses in both Figure 3.20a and 3.20b. However, the channel capacity of the compact MIMO antenna has decreased more in the presence of the near field load. Additionally, the range of error bars for the compact MIMO antenna is much larger than other two error bars. In other words, the compact MIMO antenna is more sensitive to the near field load in term of the performance of channel capacity as compared to physically separated MIMO antennas. This investigation has the same conclusion from the section 3.3.1 and 3.4. The near field load has more impact on the narrowband MIMO antenna (the compact MIMO antenna) in the terms of the channel capacity. Whereas, the wideband MIMO antennas (the D6 and D28 MIMO antennas) for the channel capacity is more robust to the influence of the near field load.
Chapter 4

Conclusion and Future Work

In conclusion, we will revisit some of highlights for this work and list the contributions to the antenna research. We will also discuss the prospects for future research.

4.1 Summary

We developed the systematic evaluation metric using S parameters and the envelope correlation coefficient. The metric has been used to evaluate three MIMO antennas: the D6 MIMO antenna, the D28 MIMO antenna, and the compact MIMO antennas with the near field load. We conducted both the simulation and measurement for the sensitivity tests and analyzed the results. In FEKO simulation, we considered the lossless RF system and PEC as the material for the near field load. However, the dielectric loss from the substrate as well as other loss in the near field load were included in the measurements. Surprisingly, the simulated and measured results were in a good agreement for the S parameters pass rate, ECC pass rate, and channel capacity. From the simulated and measured results of S parameters pass rate, ECC pass rate, and channel capacity, we
observed that the compact MIMO antenna was more sensitive to near field loading as compared to the physically separated MIMO antennas. To justify our original hypothesis, the wideband MIMO antennas (the D6 and D28 MIMO antennas) are more robust to the near field load. On the contrary, the narrowband MIMO antenna (the compact MIMO antenna) is more sensitive to near field loading. Therefore, the distance between ports and the compactness of antenna aperture is not the critical criterion for the sensitivity of MIMO antennas to a near field load. However, the Q factor/bandwidth is a critical criterion for the effects of near field loading to MIMO antennas.

4.2 Contributions

This work has made several important contributions to the research area of MIMO antenna and the effect of near field as following:

- This work developed the systematic evaluation metric to evaluate the sensitivity of MIMO antennas to a near field load. The evaluation metric only needs to have S parameters to formulate the S parameter pass rate, ECC pass rate. This research was effective because it helped make this sensitivity test more efficient as compared to the time-consuming, active sensitivity test with a real receiver. However, the sensitivity test in this thesis focuses more on the performance of MIMO antennas with a near field load, whereas the active sensitivity test with the real receiver focuses more on the entire RF system performance.

- This work also employed the channel metric using S parameters with valid assumptions. This channel metric can be used to evaluate the performance of channel capacity for loaded MIMO antennas. The channel metric also provided insights on
how a near field load affect to MIMO antennas in terms of channel capacity.

- Our research on the effects of near field on compact MIMO antennas have gained insights of how near field load impacts on MIMO antennas. Our full aperture sampling with the evaluation metric is the first systematical method to evaluate MIMO antennas with the effect of near field loading. Additionally, we concluded that the narrowband MIMO antennas are more susceptible to a near field load as compared to wideband MIMO antennas.

### 4.3 Future Work

In this thesis, we have only considered the perfect electrical conductor as the material for the near field load. However, in other research works on the effects of near field from the literature review, biological materials are usually used as a near field load. We think that it is worth studying how biological materials impact MIMO antennas as well. Moreover, we believe that the position and rotation of a near field load may also impact the performance of MIMO antennas. Therefore, the extended study of a near field load on compact MIMO antennas is needed. We need to consider more testing cases including various shapes of near field loading and the different positions of a near field load.

As MIMO antennas become more compact, there is a raising concern for the sensitivity of compact MIMO antennas to a near field load. Usually, external matching and decoupling networks are used in MIMO antennas to improve the system performance. For a $M \times M$ MIMO system, there are the M matching networks and the $(M-1)!$ decoupled networks. As the number of ports in MIMO antennas increased, the cost of the matching and decoupling network became extremely expensive. Particularly, it is impossible to apply all of matching and decoupling networks at the same time in MIMO system. Therefore,
the study for the cost function of matching and decoupling networks on loaded compact MIMO antennas is needed. Equally important, we can categorized four scenarios: matching only, decoupling only, matching and decoupling only, the optimized matching and decoupling. For future research, we plan to explore more areas or iterations of MIMO antennas and the effects of near field.
BIBLIOGRAPHY


