1

Introduction

> The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York, and it meows in Los Angeles. The wireless is the same, only without the cat.
>
> \- Einstein

Since Marconi's era, wireless communication has seen a lot of growth. Scientists have been continuously developing new technologies (vacuum tubes, transistors, ICs) and new techniques (modulation and error correcting schemes) to fuel this growth. The chronology of these inventions can be found in [1]. Among all the communication modes, the cellular mobile communication is very convenient. As a result, no other consumer electronics invention has become as popular as the mobile phone. By the end of the last century, the cellular revolution has begun and now more and more people are becoming subscribers to the cellular services. Proportionally the growth of mobile phone sales has increased. Gartner reports that 428 million mobile communication devices were sold in the first quarter of 2011, an increase of 19 percent.

Now there is a paradigm shift in the use of mobile phones. No more are the mobile phones meant to be used only for voice communication and text messaging. They are being used for web browsing, high speed data access and Global Positioning System (GPS) etc. The requirement for high data rate is ever increasing as the user of a mobile device wants many services [2]. The upper limit of the data rate of any communication system is determined by the bandwidth of the system and the signal to noise ratio (SNR). Fundamentally one can increase the bandwidth and/or power to improve the data rate. But the challenge is the scarcity of available bandwidth and highly constrained transmit powers.

One of the promising technologies to increase the data rate without consuming extra bandwidth and extra radiated power is multiple input and multiple output (MIMO) technique. This technique uses multiple antennas at the transmitter and at the receiver of a wireless system. The transmission schemes over MIMO channels fall into two classes: spatial multiplexing or diversity maximization [3]. For the spatial multiplexing, the capacity of a MIMO system linearly increases with $m = \min(M, N)$ where M and N being the number of transmit and receive antennas respectively. The basic idea behind a MIMO system operating in the spatial multiplexing is as follows. The input bit stream to be transmitted will be divided into as many independent streams as the number of transmitting antennas. Each stream will be encoded to protect it against transmission errors and radiated into the channel by a particular antenna. As the individual bit streams are radiated simultaneously, each receiver antenna receives a linear combination of all the transmitted bit streams. By knowing the channel, the receiver will recreate the bit streams and reconstruct the signal. The performance of a MIMO system in the physical layer depends on the following:

- Antenna element (pattern, polarization, gain and input impedance)
- Array configuration (antenna spacing, orientation of the elements)
- Channel (Amount of multipath richness, SNR)

This thesis investigates the influence of some of the antenna parameters on the MIMO performance. The following section gives the motivations behind the focuses of this research.

1.1 Motivations

Since the invention of MIMO technology, there has been an explosion of research in this area. This thesis work, a collection of certain investigations on the analysis and design of antennas for the MIMO systems, adds to this explosion. The following list enumerates the motivations behind the investigations. This thesis has three major parts in the context of MIMO antennas.

- Spatial correlation (Chapter 3) - It is a measure of similarity between the signals received by two spatially separated antennas. The spatial correlation for a uniform rectangular array (URA) with isotropic elements was analyzed considering both azimuth and elevation spreads in [4]. This motivated us to go a step forward and analyze the spatial correlation for a uniform rectangular array with dipole elements including the azimuth and elevation spreads. This investigation is much closer to reality as it treats the dipole elements considering mutual coupling.

- Reconfigurable antennas (Chapters 4 and 5) - There are a number of investigations showing the benefit of reconfigurable antennas in case of MIMO systems ([5, 6, 7]). The reason for this benefit is attributed to the SNR improvement due to reconfiguration of the antenna patterns[8]. This led us to investigate how the reconfigurable antennas provide multiplexing capacity with improved SNR and to design three novel reconfigurable antennas.

- 60 GHz MIMO proposals (Chapter 6) - There have been a few works regarding MIMO at 60 GHz ([9], [10]). We asked ourselves what if we employ the switched beam antennas as the elements of MIMO systems at 60 GHz. This motivated us to analyze a 2×2 MIMO system with switched beam elements. The MIMO technology is an option for fixed wireless systems [11]. The analysis of a 4×4 alternatively polarized LOS MIMO is a result of this motivation.

1.2 Organization of the thesis

This section gives the outline of the thesis. Chapter 2 gives some fundamental points about the MIMO technique. Here we discuss the MIMO capacity for the independently, identically distributed (i.i.d) channel. Furthermore, the one ring and Kronecker channel models are briefly discussed. Using the one ring model, the influence of the antenna inter element spacing on the MIMO capacity is shown. The effect of scatterers on the capacity has also been illustrated. Through ray tracing, a case has been made for a MIMO system with reconfigurable antennas. We conclude this chapter by giving some thoughts on antennas.

The MIMO capacity is affected by the correlation between the path gains of the channel matrix. The covariance matrix of the channel matrix of a MIMO system is a Kronecker product of the spatial correlation matrix at the transmitter and at the receiver. This is true when the behaviour of the scatterers around the transmitter has no relation to the behaviour of the scatterers around the receiver. This allows us to analyze the MIMO capacity of different array configurations for which the spatial correlation can be easily evaluated. Chapter 3 takes a fundamental look at the definition of correlation. We derive an analytical expression for the spatial correlation for the uniform rectangular array with dipole elements. The spatial correlation between the diagonal elements of URA with dipole elements is compared with the SC of the URA with isotropic elements.The effect of mutual coupling on the spatial correlation is analyzed for the URA case.

MIMO capacity is not only dependent on the multipath richness of the channel, which in turn depends on the distribution of scatterers in the channel, but also on the SNR of the received signal. The benefit of MIMO can be harnessed fully if the antenna elements can change their pattern and/or polarization depending upon the channel conditions. Chapter 4 introduces a three layer beam switching reconfigurable antenna. This is designed to operate in two modes. The principle of operation has been explained using the traditional Yagi antenna. But with little modification in the biasing circuit, it can be made to operate in six modes. It is interesting to see how the capacity of a MIMO system employing these antennas gets improved. In this chapter, we also provide the steps involved in the design and fabrication process of reconfigurable antennas.

In chapter 5, a pattern and polarization reconfigurable antenna is presented. A simple model in terms of dipoles is given for understanding the radiation pattern. This antenna can change its pattern in four directions and switch between orthogonal polarizations. In [12], it has been shown that polarization diversity can improve the bit error-rate (BER) of a MIMO system. Another pattern reconfigurable antenna has been presented in this chapter. Copper stripes are used to simulate the ON condition of the RF switches.

Chapter 6 proposes and analyses two situations where MIMO is used at 60 GHz. In the first situation, the benefit of using switched beam antennas as elements of MIMO is compared with the unidirectional antennas through two dimensional ray tracing simulations. In the second part of the chapter, we derive the distance criterion for a 4×4 LOS MIMO involving alternatively polarized antennas for the maximum capacity. The results for such a system will be compared with a 4x4 LOS MIMO system with single polarized antennas. Chapter 7 gives the conclusions out of the this research. Some future directions are also given in this chapter.

1.3 Contributions

This section lists the contributions of this research work.

- One of the performance degraders in the case of MIMO is spatial correlation. It, along with mutual coupling, sets the limit on how close the antennas can be in a MIMO transmitter and receiver. An analytical expression for evaluating the spatial correlation for a uniform rectangular array with dipole elements has been derived. The expression was derived considering a 3D power angle spectrum for the incoming waves. The SC for the URA with dipole elements was also compared with the URA with isotropic elements.
- A three layer beam switching reconfigurable antenna has been created. This antenna is designed to switch its pattern in three directions depending on the status of the RF switches in the antenna. We show how such an antenna can increase the capacity of a MIMO system which is used in an indoor situation through ray tracing. A ray tracing program has been developed using the image theory method. This program is designed to work for simple 2D indoor environment. It accounts for the antenna radiation patterns, the dependence of reflection coefficients on angle.
- A pattern and polarization reconfigurable antenna was created. This can switch its pattern in four directions and can switch between two orthogonal polarizations. An approximate model to understand the radiation pattern was also proposed. The antenna can be fed by a coaxial probe or a microstrip line.
- A planar dipole based reconfigurable antenna has been designed and fabricated. This antenna can switch its beam in two directions in the E - plane.
- Finally a 4 × 4 dual polarized LOS MIMO system has been studied through MATLAB® simulations. The expressions for the eignenvalues and the capacity were derived. It has also been demonstrated that a 2 × 2 MIMO at 60 GHz with switched beam antenna elements can perform well compared to unidirectional elements through capacity simulations.

2

MIMO fundamentals

> The ability to simplify means to eliminate the unnecessary so that the necessary may speak.
>
> -Hans Hofmann

It is important to have some background information about MIMO to understand the following chapters. This chapter gives the basic concepts behind a MIMO system. One of the sections is devoted to explaining the capacity of MIMO systems. A brief account of the one ring and the Kronecker channel model used in this thesis is given in this chapter. With help of the one ring model, the effect of the number of scatterers on the MIMO capacity is studied. It turns out that the number of scatterers needed to create decorrelated channel gains is not high. We discuss a single-input and single-output (SISO) system in brief in the next section so that the discussion of the MIMO system is clear.

2.1 SISO system model

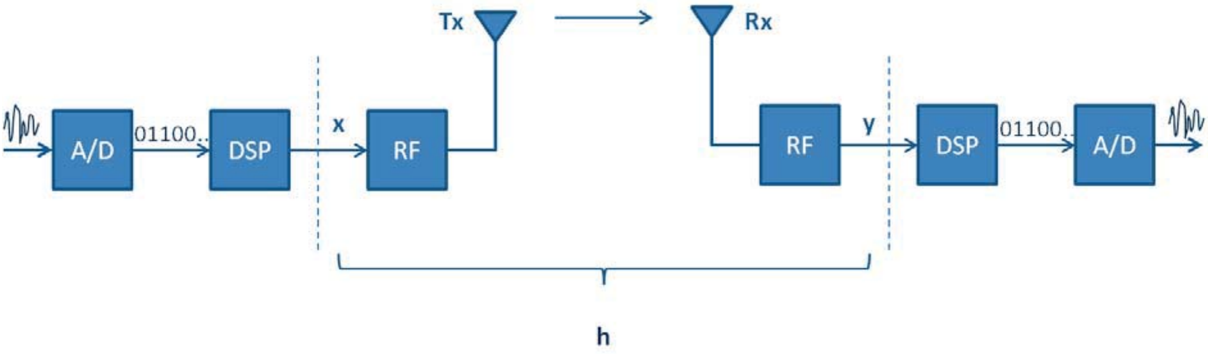

Figure 2.1: SISO block diagram.

The above figure shows a simplified block diagram of a SISO system. The input signal is discretized and digitized by the analog-to-digital converter (ADC). The digital signal processor (DSP), which follows the ADC, will do the necessary coding and modulation.

The RF part will up-convert the modulated signal so that it is radiated into the channel. The receiver does the reverse of what the transmitter has done. The input-output relationship of this system is given by

$$y(\omega) = h(\omega)x(\omega) + \eta(\omega) \tag{2.1}$$

In (2.1), $y(\omega)$ and $x(\omega)$ are the transmitted and received base band signals respectively and $h(\omega)$ is the channel gain. The channel gain is dependent on the wireless channel characteristics, antenna elements and the RF sections. $\eta(\omega)$ is additive noise due to the channel and the RF sections. When the bandwidth of the transmitted signal is much smaller than the coherence bandwidth of the channel (frequency flat channel), the input-output relationship is simply

$$y = hx + \eta \tag{2.2}$$

In this thesis, we always use the frequency flat condition for the channel. For extremely high data rates (higher bandwidth), the multipath channel becomes frequency selective. But the frequency flatness condition can still be imposed when orthogonal frequency multiplexing (OFDM) is used. In OFDM, the sub carrier bandwidth is smaller than the coherence bandwidth of the channel.

2.2 MIMO system model

A 2 × 2 MIMO system is reviewed in this section because of its simplicity. As shown in Fig. 2.2, there are two transmit antennas and two receive antennas. Here the input bit stream is divided into two individual streams. The separated streams are up-converted by the RF sections. The output of each RF section is radiated into the channel by an antenna at the transmitter. It should be noted here that the bit streams use the same bandwidth. As the bit streams are radiated simultaneously and use the same bandwidth, the signal at each receive antenna will be a linear combination of the transmitted bit streams. If we assume a frequency flat channel, the received base band signals y_1 and y_2 are written mathematically as

$$\begin{aligned} y_1 &= h_{11}x_1 + h_{12}x_2 + \eta_1 \\ y_2 &= h_{21}x_1 + h_{22}x_2 + \eta_2 \end{aligned} \tag{2.3}$$

where x_i $(i = 1, 2)$ are the transmitted bit streams and h_{ij} $(i = 1, 2$ & $j = 1, 2)$ are the channel gains (See Fig. 2.2). For instance, h_{21} is the complex channel transfer function between Rx2 and Tx1. η_i $(i = 1, 2)$ is the Additive White Gaussian Noise (AWGN).

As the receiver knows the channel (through channel estimation), it estimates the individual bit streams and combines them to reconstruct the transmitted signal. The estimation of the transmit signals can be easily explained using basic algebra.

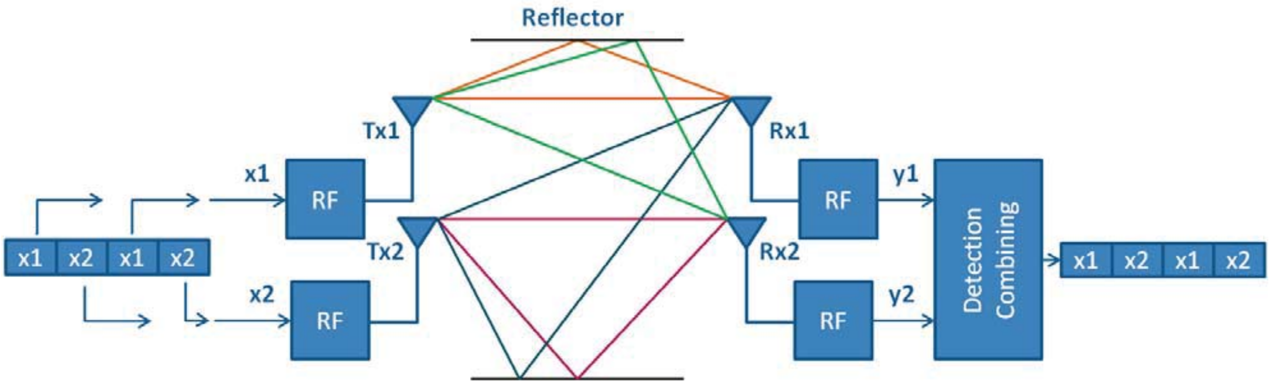

Figure 2.2: A simplified block diagram of a 2x2 MIMO system.

If the noise contribution is not considered, the received signals y_1 and y_2 are

$$\begin{aligned} y_1 &= h_{11}x_1 + h_{12}x_2 \\ y_2 &= h_{21}x_1 + h_{22}x_2 \end{aligned} \tag{2.4}$$

Now finding the transmit signals x_1 and x_2 from the received signals y_1 and y_2 is in fact finding the solution of a system of two linear equations with the channel gains as the coefficients. We know from linear algebra that when all the channel coefficients are equal or nearly equal ($h_{11} \approx h_{12} \approx h_{21} \approx h_{22}$), the channel matrix will become singular or almost singular. As this makes the inversion of the channel matrix impossible, the detection of the transmit signals is not feasible. There are also other channel configurations which make the channel matrix singular [13]. This shows that the correlated channels are not good for MIMO. In a MIMO channel, the signal from a transmitter antenna reaches a receiver antenna through multipaths. The signal transfer between another pair of transmitter antenna and receiver antenna will take place through a different set of multipaths, since the antennas in the transmitter/receiver array are not colocated, i.e., h_{11} will be different from h_{21} because the signal from transmit antenna 1 will take different routes to the receive antennas 1 and 2. Thus the multipath transmission helps create a decorrelated channel matrix. The multipath situation, which is considered to be bad in SISO, has turned out good in MIMO.

It should be noted here that the data rate has been doubled as the MIMO system sends two bit streams simultaneously.

2.3 Capacity of MIMO systems

The information theoretic capacity is defined as the upper bound on the transmission rate of a communication system with arbitrary small level of probability of error [14]. The capacity of a SISO system is given by [15]

$$C = \log_2\left(1 + \frac{P_T}{\sigma^2}|h|^2\right) \tag{2.5}$$