4

MULTIPLE INPUT MULTIPLE OUTPUT SYSTEMS

4.1 INTRODUCTION

The objective of this chapter is to describe Introduce the concept and structure of MIMO systems and describe how to derive the MIMO channel function from the SISO (Single Input Single Output) channel function. Also advantages and disadvantages of MIMO systems are listed. In wireless communication systems, frequency and time are important factors as they determine the limit for transmission quality and throughput. Generally, the concept of parallel transmission is applied to achieve high throughput and a better transmission quality. In CDMA (Code Division Multiple Access) systems, signals from different users operate (work in parallel) in time and frequency domain, but are separated in code domain. Therefore, this is a sort of "parallelism" realized by codes, which is called "software parallelism". In OFDM (Orthogonal Frequency Division Multiplexing) systems, signals work in parallel in time domain and are separated in frequency domain; it is a kind of "parallelism" realized by FFT (Fast Fourier Transform), and also calls it "semi- software parallelism".

The MIMO system uses the concept of parallel transmission in a different way. It realizes multiple outputs by multiple transmit antennas and multiple inputs by multiple receive antennas. Signals work in parallel in time and frequency domain, but are separated in space domain without frequency. Table: 4.1 compare the concept of parallelism as applied by CDMA, OFDM, and MIMO.

	Signal parallel in	**Signal separated in**	**Type of "parallel"**
OFDM	Time domain	Frequency domain	Semi-software parallelism
CDMA	Time and frequency domain	Code domain	Software parallelism
MIMO	Time and frequency domain	Space domain	Hardware parallelism

Table: 4.1 Parallelisms in CDMA, OFDM, and MIMO

In wireless communications, the capacity and SNR also important factors. Number of transmit antennas and Number of receive antennas are influences SNR and capacity of MIMO systems. However, the SNR is not enough to describe the gain of transmission quality of MIMO systems.

4.2 DIVERSITY

Diversity techniques are used to compensate for the impairments in received signal caused by a fading channel. The basic idea is to have several nearly independent versions of the transmitted signal at the receiver so that combining or selecting the received signals reduces the negative effects of a time-variant multi-path channel.

4.2.1 Diversity Techniques

If two or more antennas are spaced far enough from each other, the propagation environment affects the signals associated with different antennas dissimilarly. Thus, spatial diversity can be achieved by adding two or more antennas at the transmitter or receiver resulting in transmits or receives diversity, respectively. Polarization diversity is another space diversity scheme where a single polarization antenna can be used to send or receive two versions of a differently polarized signal. Because a reflection of a signal is polarization sensitive, the signals can be considered to be affected by distinct channels. Polarization diversity at the receiver reduces also polarization mismatch caused by random handset orientation. If the fading channel is time-varying, intuitively it can be assumed that by sending the same signal several times with a time separation greater than the channel coherence time $(\Delta t)_{coh}$, they arrive at the receiver through distinct channels. Diversity can be then achieved, for example, by using a repetition code at the transmitter. This is, however, rarely used since repetition codes are highly inefficient from the point of view of error correcting capability and capacity. A large number of better codes are known and they are used in practice to gain diversity in the time domain. The simplest way to exploit frequency diversity is to send the same signal at several frequencies that are spaced more than $(\Delta f)_{coh}$ apart from each other. However, as with time diversity, this kind of transmission is rarely used in practice as such. One example of how to take advantage of frequency diversity in real life is the wideband CDMA system (WCDMA) where the transmitted signal has a bandwidth much larger than the coherence bandwidth of the channel. As the channel is frequency selective and corresponds to, the received signal consists of L replicas of the same transmitted signal. At its simplest, the diversity is then achieved by using the rake receiver, which attempts to trace the multi-path components carrying the same information and collect all signal energy from them in the time-domain. Another approach is used in multi-carrier systems where the available signal bandwidth is sliced into multiple narrow sub-bands that are frequency non-selective and experience mutually independent fading. In general, the diversity can be achieved by coding and interleaving across the sub-bands in the same way as is done with the time diversity.

4.2.2 Transmit Diversity

In theory, probably the simplest method for achieving diversity without penalizing capacity or increasing the delay of the system is to use multiple antennas at the receiver. Combining or selecting between the multiple received signals before the detector can improve performance in a fading environment improved considerably. However, due to size, power, complexity and cost limitations of the mobile, this kind of setup is not always practical for base station to mobile link. Therefore, an interesting alternative to classical receive diversity is transmit diversity where size, cost and complexity can be moved from the mobile station to the base station. By using multiple antennas at the transmitter, the same or a somewhat decreased order of diversity can be achieved compared to the equivalent system using multiple antennas at the receiver. One simple way to artificially create time diversity in slow fading channels is to transmit the same delayed signal from uncorrelated transmit antennas. As a result, the frequency non-selective fading is turned into frequency-selective fading and equalization methods or channel coding can be used to obtain diversity.

4.3 MULTIPLE-INPUT MULTIPLE-OUTPUT CHANNEL

In a multi-antenna system, the signal at one receive antenna consists of a superposition of multiple transmissions from different TX antennas. If the environment is rich scattering and antennas are far-spaced, the propagation paths can be considered to be independent between all TX-RX antenna pairs. Thus, the channel matrix H is independent and full rank. It should be noted, however, that in theory the "keyhole effect" could make the channel matrix rank deficient even though signals between antennas are almost uncorrelated. As a result, the MIMO channel capacity can be close to that of a SISO channel.

4.3.1 Mathematical Model

An example setup of M_T transmits and M_R receives antennas with a single path MIMO channel is illustrated in Figure: 4.1. For notational simplicity the explicit presentation of time-dependence is omitted so that the complex valued channel coefficient between the *j*th transmit and *i*th receive antenna is denoted as *hi,j* .

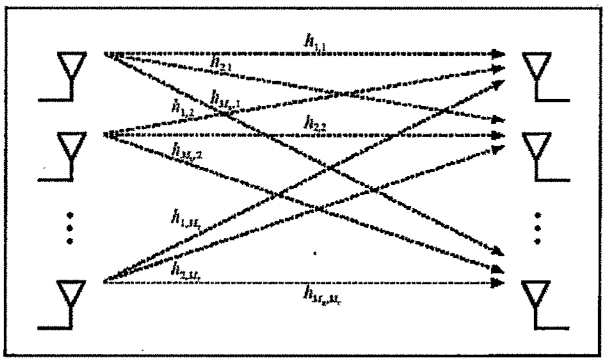

Figure: 4.1 MIMO channel

A general discrete time MIMO channel for packet transmission systems can be written as

$$H(n)=\begin{bmatrix} H_{1,1}(n) & H_{1,2}(n)\ldots & H_{1,M_T}(n) \\ H_{2,1}(n) & H_{2,2}(n)\ldots & H_{2,M_T}(n) \\ \vdots & \vdots & \vdots \\ H_{M_R,1}(n) & H_{M_R,2}(n)\ldots & H_{M_R,M_T}(n) \end{bmatrix} \in C^{M_R(L_P+L-1)X(M_TL_P)} \quad (1)$$

In practice, the MIMO channel models can be classified in different ways based on the channel features and the applications.

4.3.2 Narrowband Vs. Wideband

A radio channel is called a narrowband channel if the channel coherent bandwidth is larger than the base band signal. It is also called a flat-flat channel, because each transmitted frequency component undergoes the same fading. The frequency structure does not change. When the channel coherent bandwidth is less than the base band signal, the radio channel is called wideband channel. It is sometimes called a frequency-selective fading channel, because each transmitted frequency component undergoes different fading. The channel medium is very dispersive in a frequency-selective fading channel. The received signal contains a delayed, distorted, and attenuated version of the transmitted signal, and this produces inter symbol interference (ISI), which usually degrades communication performance. Similarly, the MIMO channel models can be divided into wideband models and narrowband models directly by considering the bandwidth of the system. The wideband models treat the propagation channel as frequency selective, which means that different frequency sub-bands have different channel response. In contrast, the narrowband models assume that the channel is flat-fading and therefore the channel has the same response over the entire system bandwidth.

4.3.3 Physical Vs. Non-Physical Models

The MIMO channel models can also be divided into physical and non-physical models. The physical models generally choose some crucial physical parameters to describe the MIMO propagation channels. The typical parameters include angle of arrival, angle of departure, and time of arrival. However, under many propagation conditions, the MIMO channels are not well described by a small set of physical parameters, and this limitation makes difficult to identify and validate the models. Another category is non-physical models, which are based on the channel statistical characteristics. In general, the non-physical models are easy to simulate under which they were identified. These models, however, give limited insight into the propagation characteristics of the MIMO channels, such as, the bandwidth, configuration, and aperture of the arrays, and the heights of the transmit and receive antennas in the measurements.

4.3.4 Measurement Based Vs. Scattering Models

To model a MIMO channel, one approach is to measure the real MIMO channel responses through field measurements. Some important characteristics of the MIMO channel can be extracted from recorded data, and the MIMO channel can be modeled to have similar statistical characteristics. An alternative approach is to postulate a model (usually involving distributed scatters) that attempts to capture the channel characteristics. Such a model can often illustrate the essential characteristics of the MIMO channel as long as the constructed scattering environment is acceptable.

4.3.5 MIMO Systems with One Modulator/Demodulator

A schematic representation of a MIMO system with one modulator is given in Figure: 4.2. The system has n transmitting antennas and m receiving antennas. The channel impulse response is given by matrix $\boldsymbol{H}$.

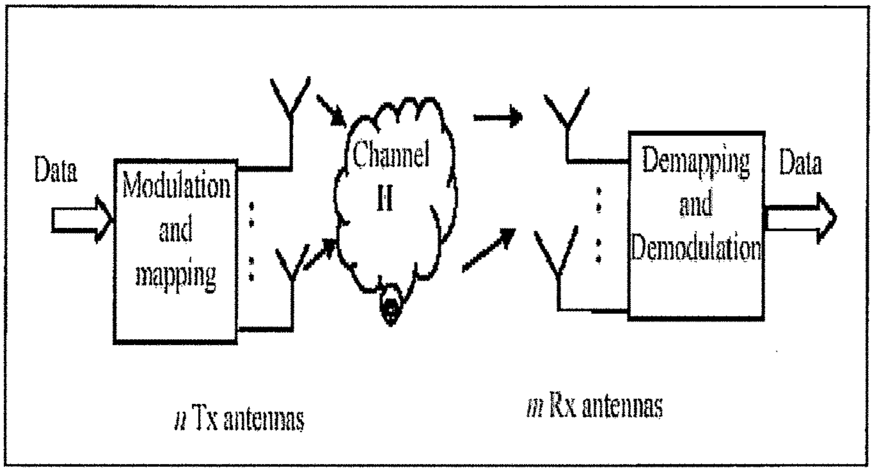

Figure: 4.2 One-Modulator/Demodulator MIMO systems with *n* transmit and *m* receive antennas

4.3.6 MIMO Systems with Multiple Modulators/Demodulators

Figure: 4.3 give another type of MIMO system with multiple modulators/demodulators. Each modulator/demodulator is connected with one antenna. At the transmit side, the data stream is converted from serial to parallel and fed to different modulators. After independent modulation, each group of data is transmitted simultaneously via its own antenna. In the receiver, each group of data received from different antennas is fed to a different demodulator. After parallel to serial conversion, the demodulated data becomes one data stream. Also refer figure: 3.4 is various transmitter and receiver structure in a multi-user MIMO scenario.

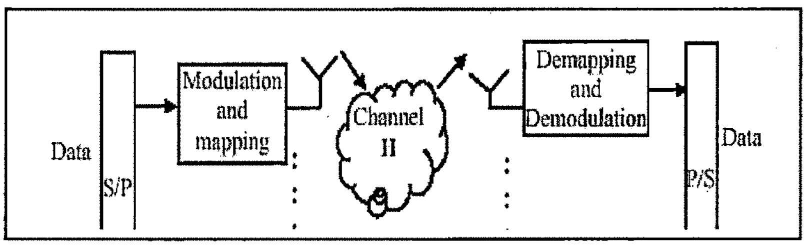

Figure: 4.3 Multiple-Modulator/Demodulator MIMO systems With *n* transmit and *m* receive antennas

4.3.7 Capacity

If the system has multiple antennas that are separated sufficiently far apart from each other, spatial diversity can provide an improvement in the reliability and spectral efficiency of the transmission. However, the information theoretical results in show that in order to achieve the full MIMO channel capacity, the user data has to be divided between different transmit antennas.

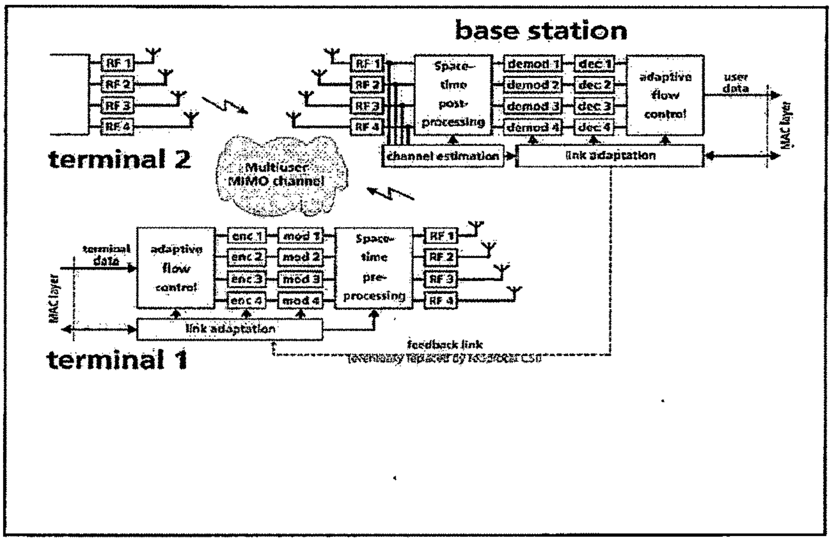

Figure: 4.4 Transmitter and receiver structure in
A multi-user MIMO scenario

4.3.8 Single-Input, Single-Output (SISO)

This is the conventional system that is used everywhere. Assume that for a given channel, whose bandwidth is *B*, and a given transmitter power of *P* the signal at the receiver has an average signal-to-noise ratio of SNR_0. Then, an estimate for the Shannon limit on channel capacity, *C*, is

$$C \approx B \bullet \log_2(1+SNR_o) \qquad (2)$$

4.3.9 Single-Input, Multiple-Output (SIMO)

For the SIMO system, we have *N* antennas at the receiver. If the signals received on these antennas have on average the same amplitude, then they can be added coherently to produce an N^2 increase in the signal power. On the other hand, there are *N* sets of noise that are added incoherently and result in an *N*-fold increase in the noise power. Hence, there is an overall increase in the SNR

$$SNR \approx \frac{N^2 \bullet (signalpower)}{N \bullet (noise)} = N \bullet SNR_o \qquad (3)$$

Thus, the channel capacity for this channel is approximately equal to

$$C \approx B \bullet \log_2(1+N \bullet SNR_o) \qquad (4)$$

4.3.10 Multiple-Input, Single-Output (MISO)

In the MISO system, *M* transmitting antennas and the total transmitted power is divided up into the *M* transmitter branches. Following a similar argument as for the

SIMO case, if the signals add coherently at the receiving antenna we get approximately an *M*-fold increase in the *SNR* as compared to the SISO case.

Note here, that because there is only one receiving antenna the noise level is the same as in the SISO case. Thus, the overall increase in *SNR* is approximately

$$SNR \approx \frac{M^2 \bullet (signalpower / M)}{noise} = M \bullet SNR_o \tag{5}$$

Thus, the channel capacity for this channel is approximately equal to

$$C \approx B \bullet \log_2(1 + M \bullet SNR_o) \tag{6}$$

4.3.11 MIMO- Same signal transmitted by each antenna

The MIMO system can be viewed in effect as a combination of the MISO and SIMO channels. In this case, it is possible to get approximately an *MN*-fold increase in the *SNR* yielding a channel capacity equal to

$$C \approx B \bullet \log_2(1 + MN \bullet SNR_o) \tag{7}$$

Thus, the channel capacity for the MIMO system is higher than that of MISO or SIMO.

However, noted here that in all four cases the relationship between the channel capacity and the *SNR* is logarithmic. This means that trying to increase the data rate by simply transmitting more power is extremely costly.

4.3.12 MIMO- Different signal transmitted by each antenna

Assume that N , M, so that all the transmitted signals can be decoded at the receiver. The big idea in MIMO is that we can send different signals using the same bandwidth and still be able to decode correctly at the receiver. Thus, it's like a creating a channel for each one of the transmitters. The capacity of each one of these channels is roughly equal to

$$C_{single} \approx B \bullet \log_2(1 + \frac{N}{M} \bullet SNR_o) \tag{8}$$

But, since we have *M* of these channels (*M* transmitting antennas), the total capacity of the system is

$$C \approx M \bullet B \bullet \log_2(1 + \frac{N}{M} \bullet SNR_o) \tag{9}$$

Thus, from (9), getting a linear increase in capacity with respect to the number of transmitting antennas, So the key principle at work here is that it is more beneficial to transmit data using many different low-powered channels than using one single, high-powered channel.

Also, the capacity for different antennas configurations becomes:

A) No diversity: $N_r = N_t = 1$

$$C = \log_2(1 + \rho \chi_2^2) bit/s/Hz \tag{10}$$

B) Receive Diversity: $N_t = 1, N_r = N$

$$C = \log_2(1 + \rho \chi_{2N}^2) bit/s/Hz \tag{11}$$

C) Transmit Diversity: $N_t = N, N_r = 1$

$$C = \log_2(1 + \frac{\rho}{N_t} \bullet \chi_{2N}^2) bit/s/Hz \tag{12}$$

D) Combined Transmit-Receive Diversity: $N_t = N_r$

$$C \succ \sum_{K = N_t - (N_r - 1)}^{N_t} \log_2(1 + \frac{\rho}{N_t} \bullet \chi_{2k}^2) bit/s/Hz \tag{13}$$

The best theoretical capacity is achieved in case D. This theoretical result confirms that the combination of transmit and receive diversity improves the data rate and the performance of wireless links.

4.4 ADVANTAGES AND DISADVANTAGES OF MIMO

4.4.1 Advantage of MIMO

In wireless communications, the objectives are to increase throughput and transmission quality. MIMO systems can take advantage of the shortcoming of a wireless channel the multi-path and turn it into an advantage. In MIMO systems, random fading and multi-path delay spread can be used to increase throughput. MIMO systems offer an increase in capacity without the need to increase bandwidth and/or power. Spatial Multiplexing (SM) is a technology that exploits this feature of MIMO systems in order to achieve the theoretical capacity limit in practice. Spatial Multiplexing uses different transmit antennas, which send different signals. The signals are multiplexed in the channel and in the receive antennas, and then de-multiplexed in the receiver.

Apart from improving throughput, MIMO systems can also improve transmission quality. Diversity is a technology used in MIMO for this purpose. Multiple antennas can be used to minimize the effect of fading caused by multi-path propagation. When the antennas at the receive side are adequately spaced, then several copies of the transmitted signal are received through different channels and with different fading. The probability, that all received copies of the transmitted signal is in deep fading, can be regarded as small, thus deduce that diversity should improve the quality of the wireless link.

4.4.2 Disadvantage and Limitation of MIMO

One obvious disadvantage of MIMO is that they contain more antennas: MIMO increases complexity, volume, and hardware costs of the system compared to SISO. MIMO systems are not always beneficial knowing that channel conditions depend on the radio environment. When there is Line of Sight (LOS), a higher LOS strength at receive will result in better performance and capacity in SISO system, while in MIMO systems capacity is reduced with higher LOS strength. This is because strong contributions from LOS lead to higher correlation among antennas, which reduces the advantage of using a MIMO system.

4.5 SUMMARY

In this chapter we discuss MIMO technology. What is diversity technique and how it's obtained by use of MIMO. We discuss how MIMO based system model is implemented. Finally we discuss advantages and disadvantages related to MIMO technology.