CHAPTER 3

FADING & DIVERSITY IN MULTIPLE ANTENNA SYSTEM

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CHAPTER 3

FADING & DIVERSITY IN MULTIPLE ANTENNA SYSTEM

3.1 INTRODUCTION TO FADING

The path between the base station and the mobile station of terrestrial mobile communication is characterized by various obstacles and reflections. These have a large influence on received signal, when the radio wave is propagated from the base station to mobile station. The radio wave transmitted from a base station radiates in all direction these radio waves, including reflected off of various obstacles, diffracted waves, scattering waves, and the direct wave from the base station to mobile station. In this case, since the path lengths of the direct, reflected, diffracted and scattering waves are different, the time each takes to reach the mobile station will be different. In addition the phase varies because of reflections. As a result the receiver receives a superposition consisting of several waves having different phase and times of arrival. This phenomenon is called multipath fading, and the signal level of the received wave changes from moment to moment. Multipath fading raises the error rate of the received signal, when a digital radio signal is in the mobile communication environment.

In built-up urban areas, the transmitted signal is reflected and refracted by a variety of terrestrial objects, so that it is replicated at the receiver with many different time delays. Each version of the transmitted signal arrives with its own amplitude and carrier phase. The fading channel model arises from the combination at the receiver of many versions of the transmitted signal. In addition, the channel is usually corrupted by AWGN.

Fading encountered over a mobile radio channel can be of two types: short duration rapid fading over time spans of less than a few seconds and long-duration slow fading over spans of several minutes to several hours. Here, only a brief description of simple models for fading channels is given. The propagation loss of mobile radio channels is generally modeled as the product of the $m^{th}$ power of the distance and a log-normal component representing shadowing losses. This model represents slowly varying losses, even for users in motion, and applies to both reverse and forward links. The description
of the rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance uses another model than that considered for the description of slowly varying losses. Several models for the rapid varying amplitude of the received signal have been considered in the literature. In this thesis Rayleigh fading is used.

3.2 FADING IN A WIRELESS ENVIRONMENT

Radio waves propagate from a transmitting antenna, and travel through free space undergoing absorption, reflection, refraction, diffraction, and scattering. They are greatly affected by the ground terrain, the atmosphere, and the objects in their path, like buildings, bridges, hills, trees, etc. These multiple physical phenomena are responsible for most of the characteristic features of the received signal.

In most of the mobile or cellular systems, the height of the mobile antenna may be smaller than the surrounding structures. Thus, the existence of a direct or line-of-sight path between the transmitter and the receiver is highly unlikely. In such a case, propagation is mainly due to reflection and scattering from the buildings and by diffraction over and/or around them. So, in practice, the transmitted signal arrives at the receiver via several paths with different time delays creating a multipath situation.

At the receiver, these multipath waves with randomly distributed amplitudes and phases combine to give a resultant signal that fluctuates in time and space. Therefore, a receiver at one location may have a signal that is much different from the signal at another location, only a short distance away, because of the change in the phase relationship among the incoming radio waves. This causes significant fluctuations in the signal amplitude. This phenomenon of random fluctuations in the received signal level is termed as fading.

The short-term fluctuation in the signal amplitude caused by the local multipath is called small-scale fading, and is observed over distances of about half a wavelength. On the other hand, long-term variation in the mean signal level is called large-scale fading. The latter effect is a result of movement over distances large enough to cause gross variations in the overall path between the transmitter and the receiver. Large-scale fading is also known as shadowing, because these variations in the mean signal level are caused by the mobile unit moving into the shadow of surrounding objects like buildings and hills. Due
to the effect of multipath, a moving receiver can experience several fades in a very short
duration, or in a more serious case, the vehicle may stop at a location where the signal is
in deep fade. In such a situation, maintaining good communication becomes an issue of
great concern.
Small-scale fading can be further classified as flat or frequency selective, and slow or fast
[73]. A received signal is said to undergo flat fading, if the mobile radio channel has a
constant gain and a linear phase response over a bandwidth larger than the bandwidth of
the transmitted signal. Under these conditions, the received signal has amplitude
fluctuations due to the variations in the channel gain over time caused by multipath.
However, the spectral characteristics of the transmitted signal remain intact at the
receiver. On the other hand, if the mobile radio channel has a constant gain and linear
phase response over a bandwidth smaller than that of the transmitted signal, the
transmitted signal is said to undergo frequency selective fading. In this case, the received
signal is distorted and dispersed, because it consists of multiple versions of the
transmitted signal, attenuated and delayed in time. This leads to time dispersion of the
transmitted symbols within the channel arising from these different time delays resulting
in inter symbol interference (ISI).
When there is relative motion between the transmitter and the receiver, Doppler spread is
introduced in the received signal spectrum, causing frequency dispersion. If the Doppler
spread is significant relative to the bandwidth of the transmitted signal, the received
signal is said to undergo fast fading. This form of fading typically occurs for very low
data rates. On the other hand, if the Doppler spread of the channel is much less than the
bandwidth of the baseband signal, the signal is said to undergo slow fading.

3.3 RAYLEIGH FADING MODEL

When the waves of multipath signals are out of phase, a reduction of the signal strength
at the receiver can occur. This may result in deep fading. The basic model of Rayleigh
fading assumes a received multipath signal to consist of a large number of reflected
waves with independent and identically distributed in-phase and Quadrature amplitudes.
This model has played a major role in our understanding of mobile propagation. The
model was first proposed in a common paper written by Lord Rayleigh in 1889 [75].
The Rayleigh distribution is a good model for channel propagation, where there is no strong line of sight path from the transmitter to the receiver. This can be used to represent the channel conditions seen on a busy street in a city, where the base station is hidden behind a building several blocks away and the arriving signal is bouncing off many scattering objects in local area. By definition, the Rayleigh random variable is a nonnegative continuous random variable having the one-parameter probability density function. [75]

\[ f_\alpha(\alpha) = \begin{cases} \frac{\alpha}{\alpha^2} \exp \left(-\frac{\alpha^2}{2\alpha^2}\right), & \alpha \geq 0, \\ 0, & \alpha < 0 \end{cases} \]

(3.1)

where \( \alpha \) is the parameter. It arises as the root-sum square of independent Gaussian variables; that is, \( \alpha = \sqrt{x_1^2 + x_2^2} \), where \( x_1 \) and \( x_2 \) are independent zero-mean Gaussian random variables having the variance \( \alpha^2 \). It is interesting to note that if \( \alpha \) is a Rayleigh random variable with probability density function (3.1) and the random variable \( \phi \) is uniformly distributed on the interval \([0, 2\pi]\), the random variables \( x_1 = \alpha \cos \phi \) and \( x_2 = \alpha \sin \phi \) are independent zero-mean Gaussian variables with variances \( \alpha^2 \).

Let us give the definition of the Rayleigh fading channel if the carrier transmission is involved. We will use complex envelope notation for the signal, that is, [4]

\[ s(t) = \Re\{\hat{s}(t) \exp[j(2\pi f_c t + \phi)]\} \]

(3.2)

where \( \hat{s}(t) \) is defined as the complex envelope of the signal relative to the adopted carrier frequency \( f_c \). Without loss of generality, we can assume here that the relative phase \( \phi \) is 0. The received signal waveform is

\[ r(t) = \Re\{\hat{\beta}(t - \delta)\hat{s}(t - \delta) \exp(2\pi j f_c (t - \delta))\} + \xi(t) \]

(3.3)
where $\beta(t) = \alpha(t) \exp(j\phi(t))$ is a complex-valued coefficient, $\alpha = \alpha(t)$ is the *fade amplitude*, $\phi = \phi(t)$ is the *phase shift*, and $\xi(t)$ is AWGN with two-sided spectral density $N_0/2$. We suppose that $\phi$ is uniformly distributed on $[0, 2\pi)$ and that the attenuation factor $\alpha$ is a Rayleigh random variable having probability density function (3.1). If the power of the transmitted signal equals 1, the instantaneous power of the received signal is $\alpha^2$ and the average power of the received signal is [76]

$$E(\alpha^2) = \int_0^{\infty} \alpha^2 \frac{\alpha}{\alpha^2} \exp(-\alpha^2/2\alpha^2) \, d\alpha$$

$$= \int_0^{\infty} \frac{\beta}{2\beta^2} \exp(-\beta/2\beta^2) \, d\beta = 2\alpha^2$$

(3.4)

where we have used the substitution $\beta = \alpha^2$. In the case of *non-carrier modulation formats*, which are used, for example, in PPH CDMA, we have $r(t) = \alpha s(t - \delta) + \xi(t)$.

The Rayleigh model arises from the combination of many randomly phased point scatters at the receiver, each scattering a small fraction of the total received power. In the general case, $\beta(t)$ is a time-varying transmission coefficient due to the scattering medium. The rate of change in $\beta$ is clearly controlled by the rate of change in the relative delays of the scatters.

### 3.4 DIVERSITY USING MIMO CONCEPT

There are three basic link performance parameters that completely describe the quality and usefulness of any wireless link: speed (or spectrum), range (or coverage) and reliability (or security) [75]. The use of multiple waveforms transmission in parallel constitutes a new type of radio communication – communication using multi-dimensional signals – which is the way to improve all three basic link performance parameters using multiple antenna system. The multi input – multiple outputs (MIMO), multiantenna system, answers the question of how to achieve higher data rates, wider coverage and increased reliability- all without using additional frequency spectrum. The combination of multiantenna system with multicarrier system gives an excellent performance.
MIMO is of greatest importance in today’s scenario, especially for 4G. The reason for the great interest is that multiple antennas offer an efficient way to increase the spectral efficiency of mobile radio system by exploiting the resource ‘space’.

The multipath propagation is a well known phenomenon of all mobile communication environments. The multipath is typically perceived as interference, degrading a receiver’s ability to recover the intelligent information. The MIMO, in contrast, takes advantage of multipath propagation to increase throughput, range/coverage and reliability. This is accomplished by sending and receiving more than one data signal in the same radio channel at the same time.

3.5 SPACE DIVERSITY & SYSTEMS BASED ON SPACE DIVERSITY

The capacity of a wireless link is generally measured in bits per second per Hertz (b/s/Hz). The methods available to increase this capacity in a traditional Single Input, Single Output (SISO) wireless system are fairly limited: increase the bandwidth, allowing a corresponding increase in the bits per second, or increase the transmit power, allowing a higher level modulation scheme to be utilized for a given bit error rate, effectively increasing the bits per second within the same bandwidth. The problem with both of these techniques is that any increase in power or bandwidth can negatively impact other communications systems operating in adjacent spectral channels or within a given geographic area. As such, bandwidth and power for a given communications system are generally well regulated, limiting the ability of the system to support any increase in capacity or performance.

MIMO technologies overcome the deficiencies of these traditional methods through the use of spatial diversity. Data in a MIMO system is transmitted over T transmit antennas through what is referred to as a “MIMO channel” to R receive antennas supported by the receiver terminal. If the antennas within the transmit array and the antennas within the receive array are spaced sufficiently far apart, the signals traveling between the various transmit and receive antennas through the MIMO channel will fluctuate or fade in an independent manner [77]. The transmitted data can therefore be encoded, using a so-called space-time code, to make use of this spatial diversity and allow processing at the receiver to extract the underlying data.
Four types of wireless systems are listed below, which are necessary to be categorized to study the space diversity. The space diversity again has two categories. If the antennas are at a far distance, for example, at different cellular base stations sites or WLAN access points, the diversity is called macro-diversity. If the antennas are at a distance in the order of one wavelength, this is called micro-diversity.

Presently, four types of systems can be categorized as far as diversity is concerned. (input and output refers to the number of antennas.) [82]

- Single input – single output (SISO): No diversity
- Single input – multiple outputs (SIMO): Receive diversity
- Multiple input – single output (MISO): Transmit diversity
- Multiple input – multiple output (MIMO): Transmit Receive diversity

3.5.1 Single Input Single Output

The SISO system is very simple and deals with communication with communication between a transmitter and a receiver. In SISO, error probability is critically damaged by fading [82].

![SISO SYSTEM](image)

Figure 3.1: Single Input Single Output System

3.5.2 Single Input Multi Output

In SIMO channel, the concept of Maximal Ratio combiner, as a way to exploit the receive diversity is offered. The error probability achieved by the MRC is to be much smaller than the one corresponding to the SISO channel. To perform MRC, the receiver has to know the fading, or, in other words, the receiver has to have access to the channel state information (CSI). Full CSI means the knowledge of the complete channel transfer function. Partial CSI provides limited channel information. This is usually done by sending some known signal through the channel.
3.5.3 Multi Input Single Output
When there are \( l \) antenna elements in a mobile terminal and one base station element, it makes an MISO channel. In this case, the channel impulse response is an \( l \times 1 \) matrix. In MISO specifically a beam forming technique is analyzed. Beam forming is nothing but directional reception of waves. By beam forming, one can increase the average SNR through focusing the energy into desired directions. Transmit beam forming achieves a diversity order of \( k \) and an antenna gain of \( k \) same as MRC with \( k \) receive antennas.

3.5.4 Multi input Multi output
Multiple Input, Multiple Output (MIMO) technology offers the potential for a significant increase in capacity and performance within a given bandwidth and power budget. However, these benefits must be weighed against the cost of the multiple RF front ends and additional processing necessary in supporting MIMO systems. The creation of a cost effective MIMO system can be facilitated through the use of software defined radio technology. This technology allows systems to be fielded today supporting contemporary waveforms/air interface standards, with MIMO technology added as a future upgrade as the technology matures.

3.6 COMPARISON OF CHANNEL CAPACITIES OF SISO, SIMO, MISO, MIMO

According to Shannon, the limit on the channel capacity

\[ C = B \log_2 (1 + \text{SNR}) \]

Where, \( C \) is capacity, \( B \) is bandwidth, \( \text{SNR} \) is signal to noise ratio. This is the SISO system.

For the SIMO system, we have \( M \) antennas at the receiver end. Suppose the signal received on these antennas have the same amplitude on average. Then they can be added coherently to produce \( M^2 \) times increase in the signal power. Hence, the increase in \( \text{SNR} \) is equivalent to

\[ \text{SNR} = M \cdot \text{SNR} \]

So, the channel capacity becomes

\[ C = B \log_2 (1 + M \cdot \text{SNR}) \]

For the MISO system, we have \( N \) transmitting antennas. The total transmitted power is divided into \( N \) branches. There is only one receiving antenna and the noise level is the same as in the SISO case. Thus, the overall increase in \( \text{SNR} \) is approximately

\[ \text{SNR} = N \cdot \text{SNR} \]

Thus, the channel capacity for this case is

\[ C = B \log_2 (1 + N \cdot \text{SNR}) \]
The MIMO can be viewed, in effect, as a combination of MISO and SIMO systems. In this case, it is responsible to get approximately an MN-fold increase in the SNR yielding a channel capacity equal to [82]

\[ C = B \log_2 (1 + M \cdot N \cdot \text{SNR}) \]

By analyzing the above equations, it can be concluded that the channel capacity for the MIMO system is higher.

### 3.7 MULTIPLE ANTENNA SYSTEM

There exist a multitude of reasons for using multiple antenna systems. There are three basic link performance parameters that completely describe the quality and usefulness of any wireless link: speed (or spectrum), range (or coverage), and reliability (security). The use of multiple waveforms transmission in parallel constitutes new type of radio communication – communication using multidimensional signals – which is the way to improve all three basic link performance parameters using multiple antenna system the multiple input – multiple output (MIMO), a multiantenna system, answers the question of how to achieve higher data rates, wider coverage, and increased reliability – all without using additional frequency spectrum [79]. The combination of multiantenna system with multicarrier system gives an excellent performance. This section gives a brief overview of different strategies without claiming to be comprehensive. Principally, two different categories can be distinguished. The first objective is to improve the link reliability, that is, the ergodic error probability or the outage probability are reduced. This can be accomplished by enhancing the instantaneous signal-to-noise ratio (SNR) (beam-forming) or by decreasing the variations of the SNR (diversity). If multiple access or co-channel interference in cellular networks disturbs the transmission, interferers that are separable in space can be suppressed with multiple antennas, resulting in an improved signal to interference plus noise ratio (SINR).

The manner in which multiple antennas should be used depends on the properties of the channel, especially on the rank \( r \) of \( \mathbf{H} \). As an example, we know that correlation among the sub-channels reduces the diversity gain. In the case of a strong line-of-sight component (Rice fading), diversity is also not an appropriate means because fading is not a severe problem. If we can exploit other sources of diversity, for example, frequency
diversity with the Rake receiver or time diversity due to coding over time-varying channels, we are probably already close to the additive white Gaussian Noise (AWGN) performance and little can be gained by a further increase of the diversity degree. In each of these cases, multiple antennas should be used in a different way.

3.8 DIVERSITY CONCEPT

As mentioned above, diversity combining consists of receiving redundantly the same information-bearing signal over two or more fading channels, then combining these multiple replicas at the receiver to increase the overall received SNR. The intuition behind this concept is to exploit the low probability of concurrence of deep fades in all the diversity channels to lower the probability of error and of outage. These multiple replicas can be obtained by extracting the signals via different radio paths:

In space by using multiple receiver antennas (antenna or site diversity)

In frequency by using multiple frequency channels which are separated by at least the coherence bandwidth of the channel (frequency hopping or multicarrier systems)

In time by using multiple time slots which are separated by at least the coherence time of the channel (coded systems)

Via multipath by resolving multipath components at different delays (direct sequence spread-spectrum systems with RAKE reception)

3.8.1 Brief Survey of Diversity Combining Techniques

Diversity techniques can first be classified according to the nature of the fading they are intended to mitigate. For instance, micro-diversity schemes are designed to combat short-term multipath fading, whereas macro-diversity techniques mitigate the effect of long-term shadowing caused by obstructions such as buildings, trees, and hills. Diversity schemes can also be classified according to the type of combining employed at the receiver. At this point we should distinguish the classical pure combining schemes [80] from the more recently proposed hybrid techniques.
3.8.1.1 Pure Combining Techniques. There are four principal types of combining techniques, which depend essentially on the (1) complexity restrictions put on the communication system, and (2) amount of channel state information (CSI) available at the receiver.

**Maximal Ratio Combining (MRC):** In the absence of interference, MRC is the optimal combining scheme (regardless of fading statistics) but comes at the expense of complexity since MRC requires knowledge of all channel fading parameters. Since knowledge of channel fading amplitudes is needed for MRC, this scheme can be used in conjunction with unequal energy signals (e.g., M-QAM or any other amplitude or phase modulations). Furthermore, since knowledge of channel phases is also needed for MRC, this scheme is not practical for differentially coherent and non-coherent detection. Indeed, if channel phase estimates are obtained, the designer might as well go for coherent detection, thus achieving better performance.

**Equal-Gain Combining (EGC):** Although suboptimal, EGC with coherent detection is often an attractive solution since it does not require estimation of the fading amplitudes and hence results in reduced complexity relative to the optimum MRC scheme. However, EGC is often limited in practice to coherent modulations with equal-energy symbols (M-ary PSK signals). Indeed, for signals with unequal energy symbols such as M-QAM, estimation of the path amplitudes is needed anyway for automatic gain control (AGC) purposes, and thus for these modulations, MRC should be used to achieve better performance [81]. In many applications the phase of the received signal cannot be tracked accurately, and it is therefore not possible to perform coherent detection. In such scenarios, communication systems must rely on non-coherent detection techniques such as envelope or square-law detection of frequency shift-keying (FSK) signals or on differentially coherent detection techniques such as differential phase-shift-keying (DPSK). As explained above, MRC is not practical for such detection schemes, which are used, rather, in conjunction with post detection EGC.

**Selection Combining (SC):** The two former combining techniques (MRC and EGC) require all or some of the CSI (fading amplitude, phase, and delay) from all the received signals. In addition, a separate receiver chain is needed for each diversity branch, which adds to the overall receiver complexity. On the other hand, SC-type systems process only
one of the diversity branches. Specifically, in its conventional form, the SC combiner chooses the branch with the highest SNR. In addition, since the output of the SC combiner is equal to the signal on only one of the branches, the coherent sum of the individual branch signals is not required. Therefore, the SC scheme can be used in conjunction with differentially coherent and non-coherent modulation techniques since it does not require knowledge of the signal phases on each branch as would be needed to implement MRC or EGC in a coherent system.

**Switch and Stay Combining (SSC):** For systems that use uninterrupted transmission, such as frequency-division multiple-access systems, SC in its conventional form may still be impractical since it requires simultaneous and continuous monitoring of all the diversity branches. Hence SC is often implemented in the form of switched or scanning diversity, in which rather than continually picking the best branch, the receiver selects a particular branch until its SNR drops below a predetermined threshold. When this happens the receiver switches to another branch. There are different variants of switched diversity [82], but in its simplest form the SSC receiver switches to, and stays with, the other branch, regardless of whether the SNR of that branch is above or below the predetermined threshold [83,84]. SSC diversity is obviously the least complex diversity scheme to implement and can be used in conjunction with coherent modulations as well as non-coherent and differentially coherent ones.

**3.8.1.2 Hybrid Combining Techniques:** Because of additional complexity constraints or because of the potential of a higher diversity gain with more sophisticated diversity schemes, newly proposed hybrid techniques have been receiving a great deal of attention in view of their promising offer to meet the specifications of emerging wideband communication systems. These schemes can be categorized into two groups: (1) generalized diversity schemes and (2) multidimensional diversity techniques.

**Generalized Diversity Techniques:** The complexity of MRC and EGC receivers depends on the number of diversity paths available, which can be quite high, especially for multipath diversity of wideband CDMA signals. In addition, MRC is sensitive to channel estimation errors, and these errors tend to be more important when the instantaneous SNR is low. On the other hand, SC uses only one path out of the L available multi paths and
hence does not fully exploit the amount of diversity offered by the channel. Recently, a wave of papers have been published bridging the gap between these two extremes (MRC/EGC and SC) by proposing GSC, which adaptively combines (following the rules of MRC or EGC) the $L_c$ strongest (highest SNR) paths among the $L$ available ones. We denote such hybrid schemes as SC/MRC or SC/EGC-$L_c/L$. In the context of coherent wideband CDMA systems, these schemes offer less complex receivers than the conventional MRC RAKE receivers since they have a fixed number of fingers independent of the number of multi paths. More important, SC/MRC was shown to approach the performance of MRC, while SC/EGC was shown to outperform in certain cases conventional post detection EGC since it is less sensitive to the “combining loss” of the very noisy (low-SNR) paths [85].

**Multidimensional Diversity Techniques:** Multidimensional diversity schemes involving the combination of two or more conventional means of realizing diversity (e.g., space and multipath) to provide better performance have recently received a great deal of attention. For example, in the context of wideband CDMA they are implemented in the form of two-dimensional RAKE receivers, consisting of an array of antennas, each followed by a conventional RAKE receiver. Furthermore, these schemes can take advantage of diversity from frequency and multipath, as is the case in multicarrier-RAKE CDMA systems [86] or from Doppler and multipath as proposed.

### 3.9 SPATIAL DIVERSITY CONCEPTS

This section addresses the application of multiple antennas at the receiver and/or the transmitter for the purpose of increasing the diversity degree. As already mentioned only frequency non-selective channels are considered for notational as well as conceptual simplicity. Another reason is that spatial diversity concepts achieve the highest gains for channels that do not provide diversity in other dimensions such as frequency or time. Moreover, only Rayleigh fading channels without a line-of-sight component are considered. Since we know that correlations among the contributing channels reduce the diversity gain we further assume that the channels are totally uncorrelated. Uncorrelated channels can be achieved by an appropriate antenna spacing depending on the spatial
channel characteristics, for example, the angle spread. Assuming a uniform linear array with equidistantly arranged antennas and an isotropic scattering environment where signals impinge from all directions with the same probability, a small distance \( d = \frac{\lambda}{2} \) between neighboring elements may be sufficient. The parameter \( \lambda \) denotes the wavelength and is related to the carrier frequency \( f_0 \) by \( \lambda = \frac{c}{f_0} \) where \( c \) describes the speed of light. On the contrary, \( d \gg \frac{\lambda}{2} \) must hold in scenarios with small angle spread and \( d \) can take values up to \( 10\lambda \). This obviously requires a device large enough to host several antennas with appropriate distances.

This section is divided into three parts: First, receive diversity is shortly explained. Next, orthogonal space–time block codes (STBCs) are addressed. Non-orthogonal block codes are not considered here. Space–time trellis codes providing an additional coding gain are introduced.

\[
\text{Figure 3.6 Structure of MIMO Channel}
\]

### 3.10.1 Receive Diversity

The simplest method to achieve spatial diversity is to use multiple antennas at the receiver. The structure of the system is depicted in Figure 3.7. It can be mathematically described with

\[
y[l] = h[l].x[l] + n[l]
\]

Where \( h[l] = h_1[l], \ldots, h_{NR}[l]^T \) comprises all contributing channel coefficients. Since there is no interference, a simple matched filter performing maximum ratio combining represents the optimum receiver and we obtain
\[ r[l] = \frac{h[l]H}{\|h[l]\|^2} \cdot \gamma[l] = x[l] + n[l] \]

\[ \bar{n}[l] = h[l]H \cdot \frac{n[l]}{\|h[l]\|^2} \]

Where \( \|h[l]\|^2 \) denotes the noise at the matched filter output.

Figure 3.7 Structure of Receive diversity System

The full diversity degree \( D = N_R \) is achieved as long as the channel coefficients remain uncorrelated. The single-input multiple-output (SIMO) channel is transformed by matched filtering into an equivalent single-input single-output system (SISO) channel with smaller variations of the SNR.

The application of multiple receive antennas yields not only a diversity gain but also an array gain because the \( N_R \)-fold power is collected, leading to a gain of \( 10 \log_{10}(N_R) \) dB. This gain is independent of diversity considerations and is also available for totally correlated channels.
3.11 Performance of SISO, Channel Capacities

Figure 3.8 Performance with Single Input - Multiple Output

Table 3.1: Performance with N=1, M=2 for SIMO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=1, M=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1500</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>2400</td>
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<tr>
<td>3</td>
<td>6</td>
<td>2800</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>3200</td>
</tr>
</tbody>
</table>
Table : 3.2 Performance with N=1, M=3 for SIMO

<table>
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<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=1, M=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2300</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3200</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>3800</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>4100</td>
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</tbody>
</table>

Table 3.3 : Performance with N=1, M=4 for SIMO

<table>
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<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=1, M=4</th>
</tr>
</thead>
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<td>1</td>
<td>2</td>
<td>2800</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
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<td>4200</td>
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<td>4</td>
<td>8</td>
<td>5100</td>
</tr>
</tbody>
</table>

Table : 3.4 Performance with N=1, M=5 for SIMO

<table>
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<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=1, M=2</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>2</td>
<td>3500</td>
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<td>2</td>
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<td>8</td>
<td>5400</td>
</tr>
</tbody>
</table>
Figure 3.9 Performance with Multi Input - Single Output

Table 3.5 : Performance with N=2, M=1 for MISO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=2, M=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2300</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3100</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>3700</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>4100</td>
</tr>
</tbody>
</table>
Table 3.6: Performance with N=3, M=1 for MISO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=3, M=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2800</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3700</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>4200</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>4600</td>
</tr>
</tbody>
</table>

Table 3.7: Performance with N=4, M=1 for MISO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=4, M=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3200</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4100</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>4700</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>5100</td>
</tr>
</tbody>
</table>

Table 3.8: Performance with N=5, M=1 for MISO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=5, M=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3500</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4400</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>5000</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>5300</td>
</tr>
</tbody>
</table>
The red curve shows the capacity with single input and the green curve indicates the capacity with multiple inputs. From the above curve it is clear that by increasing the number of inputs capacity is also increased.

![Figure 3.10 Performance with Multiple Input - Multiple Output](image)

**Table 3.9 : Performance with N=2, M=2 for MIMO**

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=2, M=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3100</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4100</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>4700</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>5000</td>
</tr>
</tbody>
</table>
Table : 3.10 : Performance with N=3, M=3 for MIMO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=3, M=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>4200</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>5200</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>5800</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>6100</td>
</tr>
</tbody>
</table>

Table : 3.11 Performance with N=4, M=4 for MIMO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=4, M=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5000</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>6000</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>6600</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>7000</td>
</tr>
</tbody>
</table>

Table : 3.12 : Performance with N=5, M=5 for MIMO

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Signal to Noise Ratio</th>
<th>Capacity in kbps (simulated) For N=5, M=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5800</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>6700</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>7200</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>7700</td>
</tr>
</tbody>
</table>
Conclusion: The performance with Multi Input – Multi Output (MIMO) is better than Single Input – Single output (SISO) Multi Input – Single output (MISO), and Single Input – Multi output (SIMO) as from the above graphs and tables.

3.12 RECEIVE DIVERSITY

3.12.1 Selection Diversity

BER Simulation Model

The MATLAB performs the following
(a) Generate random binary sequence of +1’s and -1’s.
(b) Multiply the symbols with the channel and then add white Gaussian noise.
(c) At the receiver, find the receive path with maximum power
(d) Chose that receive path, equalize (divide) the received symbols with the known channel
(d) Perform hard decision decoding and count the bit errors
\[ \frac{E_b}{N_0} \]
(e) Repeat for multiple values of \( \frac{E_b}{N_0} \) and plot the simulation and theoretical results.
Figure 3.11: BER plot for BPSK in Rayleigh channel with Selection Diversity

Observations
Around 16dB improvement at $10^{-4}$ BER points with two receive antenna selection diversity.

3.12.2 Equal Gain Combining
MATLAB model for simulating BER with Equal Gain Combining
The MATLAB script performs the following:
(a) Generate random binary sequence of +1’s and -1’s.
(b) Multiply the symbols with the channel and then add white Gaussian noise.
(c) At the receiver, for each receive path, equalize by compensating with the known channel phase
(d) Accumulate the equalized symbols from all the receive paths
(d) Perform hard decision decoding and count the bit errors $rac{E_b}{N_0}$
(e) Repeat for multiple values of $\frac{E_b}{N_0}$ and plot the simulation and theoretical results.
3.12.3 Maximal Ratio Combining

BER Simulation Model for MRC

The MATLAB script performs the following:
(a) Generate random binary sequence of $+1$’s and $-1$’s.
(b) Multiply the symbols with the channel and then add white Gaussian noise.
(c) Chose that receive path, equalize the received symbols per maximal ratio combining
(d) Perform hard decision decoding and count the bit errors
\[
\frac{E_b}{N_0}
\]
(e) Repeat for multiple values of $\frac{E_b}{N_0}$ and plot the simulation and theoretical results.
Figure 3.13: BER plot for BPSK in Rayleigh channel with Maximal Ratio Combining

3.13 Transmit Diversity

3.13.1 Alamouti STBC with 2 Transmit Antennas and 1 Receive Antenna

Fig. 3.14 2-Transmitter and 1-Receiver Alamouti STBC coding
Simulation Model
The MATLAB script performs the following:
Generate random binary sequence of +1’s and -1’s.
Group them into pair of two symbols.
Code it as per the Alamouti Space Time Code, multiply the symbols with the channel and then add white Gaussian noise.
Equalize the received symbols.
Perform hard decision decoding and count the bit errors.

\[
\frac{E_b}{N_0}
\]
Repeat for multiple values of \( \frac{E_b}{N_0} \) and plot the simulation and theoretical results.

Figure 3.15 BER plot for BPSK in Rayleigh channel with 2 transmitters and 1 receiver Alamouti STBC
Observations
Compared to the BER plot for nTx=1, nRx=2 Maximal ratio combining, we can see the Alamouti Space Time Block coding has around 3dB poorer performance.

3.13.2 Alamouti STBC with two transmit and two receive antennas
The principle of space time block coding with two receive antenna’s the system can be modeled as shown in the figure 3.16.

![Figure: 3.16 Transmit 2 Receive Alamouti STBC](image)

Simulation Model
The MATLAB script performs the following
(a) Generate random binary sequence of +1’s and -1’s.
(b) Group them into pair of two symbols
(c) Code it per the Alamouti Space Time code, multiply the symbols with the channel and then add white Gaussian noise.
(d) Equalize the received symbols
(e) Perform hard decision decoding and count the bit errors
\[ \frac{E_b}{N_0} \]
(f) Repeat for multiple values of \( \frac{E_b}{N_0} \) and plot the simulation and theoretical results.
Observations:
1. Can observe that the BER performance is much better than 1 transmits 2 receive MRC case. This is because the effective channels concatenating the information from 2 receive antennas over two symbols results in a diversity order of 4.
2. In general, with $m$ receive antennas, the diversity order for 2 transmit antenna Alamouti STBC is $2m$.
3. As with the case of 2 transmit, 1 receive Alamouti STBC, the fact that $H^H H$ is a diagonal matrix ensured that there is no cross talk between $x_1$, $x_2$ after the equalizer and the noise term is still white.
3.14 Results & Discussion

This chapter of fading & diversity in multiple antenna systems various models are explained. The various types of diversity specific concepts are explained. Comparison of channel capacities of single input single output, single input multiple output, multiple input single output, multiple input multiple output are discussed in section 3.6.

The simulation of performance of SIMO channel capacity vs. SNR is done in MATLAB and results shown in fig 3.8 and explained in tabular form in tables 3.1,3.2,3.3, 3.4 for N=1 & M=2,3,4,5. These tables explained that the if value of M increased then capacity of channel increases. The figure 3.9 performance simulation for MISO channel is done & explains with the help of tables 3.5, 3.6, 3.7, 3.8 for N=2,3,4,5, M=1 respectively. In figure 3.10 performance simulation for MIMO is done by taking multiple input value N=2, 3, 4, 5 and multiple output value M=2, 3, 4, 5.

We can see for the same capacity vs. SNR graph and tables the capacity is higher for the MIMO will Better compare to SIMO and MISO.

Multiple antenna system different diversity types effects are simulated by MATLAB.

The BER analysis for BPSK modulation in Rayleigh channel with selection diversity is shown in fig. 3.11 using MATLAB. Result is drawn that 16 dB improvement over $10^{-4}$ BER points.

Fig 3.12 explains BER Vs. SNR simulation by taking equal gain combining diversity channel for BPSK modulation. The result shows that 16 dB improvement over $10^{-4}$ BER points is achieved.

Fig 3.13 explains the BER Vs. SNR for maximal ratio combining diversity channel for BPSK modulation. The result shows 18 dB improvement over $10^{-4}$ BER points.

Fig 3.15 explain the simulation for BER and $E_b/No$ of one transmitter and two receiver with maximal ratio combining with STBC and it show that later one has 3dB poorer performance.
Fig. 3.17 explains the simulation and comparison of 2 transmitters and 2 receiver antenna system with maximal ratio combining with STBC.

By comparing simulations result drawn that BER performance is much better in MIMO STBC then one transmitter and 2 receiver MRC case.