ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

FACULTY OF TECHNOLOGY

ELECTRICAL AND COMPUTER ENGINEERING

DEPARTMENT

Investigation of the Performance of Different Adaptive Space-Time Transmit Diversity Schemes

By

Tadelle Simachew

A thesis submitted to the school of Graduate studies of Addis Ababa University
in partial fulfillment of the requirements for the degree of
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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Abbreviations

AM	Adaptive Modulation
ASTTD	Adaptive space-time transmit diversity
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BER_{tg}	Target bit error rate
BS	Base station
BPSK	Binary Phase Shift Keying
CDMA2000	Code division multiple access2000
CSI	Channel state information
EGC	Equal Gain Combining
FDD	Frequency division duplex
GSM	Global System for mobile
i.i.d	Identically independently distributed
MTCM	Multi trellis coded modulation
MIMO	Multiple input multiple output
MFAS	Minimum feedback allocation scheme
MQAM	M-ary Quadrature Amplitude modulation
MS	Mobile station
MRC	Maximum Ratio Combiner
OTD	Orthogonal transmit diversity
PSK	Phase shift keying
PSTD	Phase switched transmit diversity
QPSK	Quadrature Phase Shift Keying
SNR	Signal-to-noise ratio
SISO	Single input single output
STBC	Space-time block code
STTD	Space-time transmit diversity
SDC	Selective Diversity Combining
SC	Switched Combining
STC	Space-time codes

STTC	Space-time trellis codes
STS	Space-time spreading
STD	Switched transmit diversity
TDD	Time division duplex
TXAA	Transmit adaptive array
TSTD	Time switched transmit diversity
WCDMA	Wideband code division multiple access
3GPP	Third generation partnership project
3GPP2	Third generation partnership project two

Abstract

Transmit diversity techniques provide attractive solutions for increasing downlink capacity in 3G systems. Open-loop and closed-loop transmit diversity modes with two transmit antennas have already been included into 3G Partner Project WCDMA (wideband code division multiplexing access), and schemes exploiting a large number of transmit antennas are being developed. System capacity can be increased from that of open-loop modes if the transmitter is equipped with additional side information of the downlink channel. In a frequency division duplex (FDD) system this means that the receiver has to provide the information through some feedback mechanism.

In this work, a scheme which combines a closed-loop and open-loop transmit diversity (adaptive space-time transmit diversity) is investigated and the signal-to-noise ratio (SNR) to bit error rate (BER) performance of this adaptive space-time transmit diversity schemes are evaluated on a flat Rayleigh fading channel.

The performance results obtained from the simulations show that adaptive space-time transmit diversity schemes have better error rate performance than the space-time transmit diversity. Finally, this work has shown that adaptive power allocation scheme in conjunction with the Alamouti scheme has an improved error rate than the open loop transmit diversity (Alamouti scheme) and also adaptive space time modulation has an improved error rate performance than the Alamouti scheme. Moreover, this thesis showed the tradeoff between schemes combining both adaptive rate and power with different percentages and increasing the power at the same time reducing the data rate has an improved error rate performance than reducing the power at the same time increasing the data rate of the system.

Chapter 1

Introduction

1.1. Overview

The increasing demand for internet and wireless services such as voice, video and data highlights the need for an increase in the system capacity, which is aimed at in the third generation mobile communication. In particular, the 3rd generation partnership project (3GPP) [46] and 3rd generation partnership project two (3GPP2) [47] have developed the wideband code-division multiple access (WCDMA) technologies and CDMA2000, respectively. The improvement of the downlink capacity is one of the main challenges of the 3G systems, because many of the proposed services are downlink-intensive. By exploiting the available spatial diversity, multiple antenna techniques are known to enhance the capacity and quality of wireless communication especially in fading channels [3], and for downlink applications, transmit antenna diversity is typically suitable [2, 4].

In the 3G evolution, both open-loop (without channel feedback) and closed loop transmit diversity schemes (with channel feedback) have been studied. Open-loop techniques such as Orthogonal Transmit Diversity [4] and Space-Time Transmit Diversity [1, 4], and closed-loop techniques such as Switched Transmit Diversity and Beamforming (also called Transmit Adaptive Array) [4]) are considered. Alamouti Space-Time Coding [1] and Beamforming are parts of the 3GPP standard of WCDMA FDD (Frequency Division Duplex) downlink system [4, 19]. The closed-loop scheme enables the transmit array to optimally beamform the transmit signal to suit a particular channel state. Using the closed-loop communication for its high capacity achievement has been standardized in 3GPP, and is know to be effective for low-speed mobile users, whereas it is ineffective at high mobile speeds [4].

Assume that the message is intended for a single receiver. When there is little (or no) channel state information at the transmitter, the diversity schemes are the optimal, whereas when there is adequate channel state information available at the transmitter, beamforming strategy is optimal and provides much higher capacity for the system. With beamforming, the transmissions from different antenna elements at the base station add constructively at the receiver, which results in some enhancement in the received SNR. However, this improvement requires that the transmitter has a fairly accurate knowledge of the parameters of the channel to the intended receiver. This is difficult to achieve when the channel parameters are time-varying. Furthermore, in a practical communication system, feedback data is subject to imperfections such as quantization [5], feedback error [5], [6] and feedback delay [7].

1.2. Literature review

Receive diversity existed as far back as 1960. However, receive diversity is not suitable for downlink in mobile communications, hence transmit diversity has attracted attention. Alamouti presented basic two transmit diversity scheme [1] and Tarokh et al. [2, 11] extended it to the general case, called orthogonal space-time block codes (OSTBC). OSTBC have full diversity, but have little or no coding gain. To provide both diversity and coding gain, one can choose a space-time code that has an in-built channel coding mechanism, for example space-time trellis codes, or one can choose a space-time block code concatenated with an outer channel code. Borran et al. [8] discuss design issues of concatenating channel codes with OSTBC. They show that design issues in maximizing diversity gain, and maximizing coding gain can be decoupled. Due to this simplicity, this structure has been adopted in WCDMA standard.

Another class of space-time codes is trellis based space-time codes (e.g. space-time trellis codes [2], super-orthogonal space-time trellis codes [11] etc.). These codes incorporate coding and diversity into a single design. Much of the analysis of these systems concentrates on uncorrelated antennas. Tarokh et al. [11] also proposed new space-time codes which are effective in slow-fading and fast-fading (called smart and greedy space-time block codes).The Encoder of the code doesn’t have the channel state information(CSI) but it can exploit the benefits provided both by transmit and receive antennas as well as by possible rapid changes in the channel.

1.3. Thesis Objectives

The objectives of this thesis are generally the study of the development, design, and functions of the adaptive space-time transmit diversity (ASTTD). It is also to study the possibilities of performance improvement over signal fading which is inherent in wireless communication systems.

Specifically, the objectives of this work will:

- Analyze the different adaptive techniques employed in ASTTD systems, that is, STTD + adaptive modulation and STTD + adaptive power allocation schemes.
- Evaluate these two schemes in terms of bit error rate as a function of the signal-to-noise ratio (SNR).
- Comparing these two schemes with the ordinary STTD published result and selects one of the schemes for better performance achievement.

1.4. Outline of the thesis

The structure of the rest of this thesis is as follows: Chapter 2 will present the principles and characteristics of wireless channel models. Chapter 3 presents the definition and the techniques of diversity principles employed in mitigating the effect of signal fading in wireless system. Based on the concept of chapter 3, chapter 4 discusses the types of diversity scheme and mainly focuses on transmit diversity. It also discusses the classification of transmit diversity which is open loop and closed loop transmit diversity. Having the knowledge of chapter 4, we discuss in chapter 5 about the schemes used in adaptive space-time transmit diversity. Chapter 6 presents the simulation results and discusses the result of the investigation of different adaptive space-time transmit diversity schemes. Finally, in chapter 7 the conclusions drawn from the results of simulation are presented and areas for future work to extend these techniques and results are suggested.

CHAPTER 2

WIRELESS CHANNEL MODELS

2.1. Basic Principles & Characteristics of Mobile Communications

A mobile radio communication system consists of a number of fixed access ports, base stations, and of numerous mobile users. The fact that the users are mobile means that the propagation conditions and, correspondingly the channel conditions will change over time. The system usually covers large areas and supports indoor usage as well, which means that there will only be occasional line-of-sight connection between transmitter and the receiver. As a rule, the signal reaches the receiver through numerous different paths from the base station, reflected and diffracted. This is called multipath propagation. The different paths have different distances and therefore have different delays when the signals reach the receiver. All signals from the different paths will add up in the receiver, and will randomly either amplify or attenuate the total received signal. Furthermore, the mobile user is often moving while connected to the network, adding a Doppler spread to the received signal.

These characteristics make the radio channel to cause both amplitude- and phase distortion to the signal, and also modulate the frequency content of the transmitted signal. To make things worse, the channel varies in time. The basic characteristics of a mobile radio channel are illustrated in Figure 2.1 below.

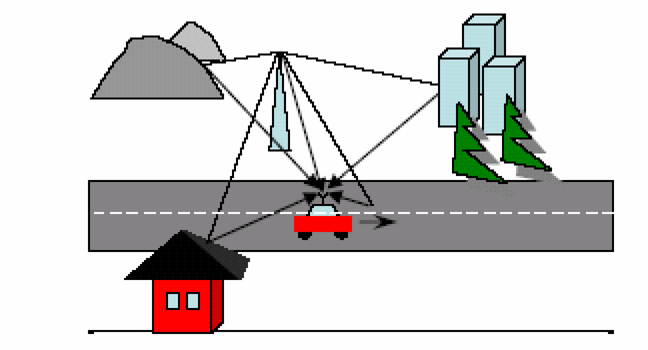


Fig.2.1. Multipath propagation

As Figure 2.1 depicts, the transmitted signal reaches the receiver (the car antenna) through one direct path and through several reflected and diffracted paths. As the signal is reflected or diffracted at an obstacle, it is attenuated and experiences a phase shift. The signals that reach the receiver will change in time as the car travels along the highway. Eventually, the base station will be shadowed by the larger buildings and there will no longer be a direct path reaching the receiver.

2.2. Fading [45]

In order to fully understand wireless communications, we need to have a basic idea on the characteristics of wireless channels. The behavior of a typical mobile wireless channel is considerably more complex than that of an additive white Gaussian noise (AWGN) channel. Besides the thermal noise at the receiver front end (which is modeled by AWGN), there are several other well-studied channel impairments in a typical wireless channel such as path loss, shadowing and Fading [42].

In a typical wireless communication environment, multiple propagation paths often exist from a transmitter to a receiver due to scattering by different objects. Signal copies following different paths can undergo different attenuation, distortions, delays and phase shifts. Constructive and destructive interference occurs and if destructive interference occurs, the signal power can be significantly diminished. The phenomenon is called fading. The performance of a system (in terms of probability of error) can be severely degraded by fading. Very often, especially in mobile communications, not only do multiple propagation paths exist, but they are also time-varying. The result is a time-varying fading channel. Communication through these channels can be difficult and special techniques may be required to achieve satisfactory performance.

2.3. Parameters of Fading Channels [45]

The general time-varying fading channel model is too complex for understanding and performance analysis for wireless channels. One approximate channel model is the wide-sense stationary uncorrelated scattering (WSSUS). In WSSUS model, the time-varying fading process is assumed to be wide-sense stationary random process and the signal copies from the scatterings by different objects are assumed to be independent. The following parameters are often used to characterize a WSSUS channel:

1) Multipath Spread T_m:

It tells us the maximum delay between paths of significant power in the channel [42, 45].

2) Coherence Bandwidth $(\Delta f)_c$:

Gives a measure of how far apart in frequency over which the signals undergo different degrees of fading [42, 45].

3) Coherence Time $(\Delta t)_c$

Gives a measure of time duration over which the channel impulse response is essentially invariant (highly correlated) [42, 45].

4) Doppler Spread B_d:

It gives the maximum range of Doppler shifts [42, 45].

2.4. A Mathematical Model for Fading Channels [42, 45]

Consider a transmitted signal $s(t) = A\cos(2\pi f_c t)$ through a fading channel. Ignoring the effects of noise, the received signal can be expressed as:

$$r(t) = A\sum_{i=1}^{N} \alpha_i \cos(2\pi f_c t + \theta_i) \tag{2.1}$$

where the variables α_i and θ_i are the attenuation and the phase-shift of the i^{th} multipath component, respectively. The above expression can be rewritten as:

$$r(t) = A\left(\left(\sum_{i=1}^{N} \alpha_i \cos(\theta_i)\right)\cos(2\pi f_c t) - \left(\sum_{i=1}^{N} \alpha_i \sin(\theta_i)\right)\sin(2\pi f_c t)\right) \tag{2.2}$$

We introduce two random processes $X_1(t)$ and $X_2(t)$, such that the above equation becomes:

$$r(t) = A\big(X_1(t)\cos(2\pi f_c t) - X_2(t)\sin(2\pi f_c t)\big) \tag{2.3}$$

When there are a large number of scatterers in the channel that contribute to the signal at the receiver, $X_1(t)$ and $X_2(t)$ become Gaussian random variables with zero mean and variance σ^2 according to the central limit theorem [45] can be rewritten as:

$$r(t) = AR(t)\cos(2\pi f_c t + \theta(t)) \tag{2.4}$$

where the amplitude $R(t)$ and the phase $\theta(t)$ of received waveform $r(t)$ are given by:

$$R(t) = \sqrt{X_1(t)^2 + X_2(t)^2} \tag{2.5}$$

$$\theta(t) = \tan^{-1}\left(\frac{X_2(t)}{X_1(t)}\right), \quad \text{respectively} \tag{2.6}$$

Since the processes $X_1(t)$ and $X_2(t)$ are Gaussian with zero mean, the envelope of the channel response at any time instant, $R(t)$, has a Rayleigh probability density function (pdf) and the phase is uniformly distributed in the interval $[0,2\pi]$.

The Rayleigh probability density function (pdf) is defined as:

$$P_{Rayleigh}(r) = \begin{cases} \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) & 0 \le r \le \infty \\ 0 & r < 0, \end{cases} \tag{2.7}$$

where $\sigma^2 = E[r^2]$. (2.8)

When there are fixed scatterers or signal reflectors in the medium in addition to randomly moving scatterers, $R(t)$ can no longer be modeled as having zero mean. In this case, the envelope $R(t)$ has a Rician distribution and the channel is said to be a Rician fading channel [42, 45]. Another distribution function that has been used to model the envelope of fading signals is the Nakagami-m distribution. [42, 45]

The distortion in the phase can be easily overcome if differential modulation is employed. The amplitude distortion $R(t)$ severely degrades the performance of digital communication systems over fading channels. It is usually reasonable to assume that the fading stays essentially constant for at least one signaling interval.

2.4.1. Time-varying Channel Impulse Response

From equation (2.7) and (2.8), we can see that the time-varying channel impulse response $C(\tau,t)$ as derived in [42] is:

$$C(\tau,t) = \sum_n \alpha_i e^{-j\theta_n(t)}\delta(\tau - \tau_n(t)) \tag{2.9}$$

where $c(\tau,t)$ represents the equivalent low pass response of the channel at time t to an impulse at time t - τ and $\theta_n(t) = 2\pi f_c \tau_n(t)$.

2.4.2 Channel Transfer Function

We can also characterize the time-varying multipath channel in the frequency domain by taking the Fourier transform of $c(\tau,t)$ with respect to τ. Then we can have the channel transfer function $C(f,t)$:

$$C(f,t)=\int_{-\infty}^{\infty} c(\tau,t)e^{-j\theta(t)}d\tau \tag{2.10}$$

Where $\theta(t)=2\pi f\tau$.

2.5. Characterizing Mobile-radio propagation [42, 45]

The intensity of radio wave in free space decays with the square of propagation distance. For most practical channels the free-space propagation model is inadequate to describe the channel and predict system performance. In a wireless mobile communication system, a signal can travel from transmitter to receiver over multiple reflective paths; this phenomenon is referred to as *multipath propagation*. The effect can cause fluctuations in the received signals amplitude, phase, and angle of arrival, giving rise to the terminology *multipath fading*. The fading in mobile communications are classified as *large-scale fading* and *small-scale fading*.

2.5.1. Large-scale fading

Large-scale fading represents the average signal power attenuation or the path loss due to motion over large areas. This phenomenon is affected by prominent terrain contours (e.g. hills, forests, billboards, clumps of building, etc) between the transmitter and receiver. The receiver is often said to be "shadowed" by such prominences. The statistics of large-scale fading provide a way of computing an estimate of path loss as a function of distance. This is often described in terms of a mean-path loss (nth-power law) and a log-normally distributed variation about the mean [45].

2.5.2. Small-scale fading

Small-scale fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes (as small as a half wavelength) in the spatial positioning between a receiver and transmitter. Small-scale fading manifests itself in two ways:

1. Time-spreading of the signal (or signal dispersion)
2. Time-variant behavior of the channel

For mobile-radio applications, the channel is time-variant because motion between the transmitter and receiver results in propagation path changes. The rate of change of these propagation conditions accounts for the fading rapidity (rate of change of the fading impairments).

2.6. Classification of fading channels [42]

Based on the parameters of the channels and the characteristics of the signal to be transmitted, time-varying fading channels can be classified as:

1) Frequency non-selective versus frequency selective

If the bandwidth of the transmitted signal is small compared with $(\Delta f)_c$, then all frequency components of the signal would roughly undergo the same degree of fading. The channel is then classified as *frequency non-selective (also called flat fading)*. We notice that because of the reciprocal relationships between $(\Delta f)_c$ and $(\Delta t)_c$ and the one between bandwidth and symbol duration, in a frequency non-selective channel, the symbol duration is large compared with $(\Delta t)_c$. In this case, delays between different paths are relatively small with respect to the symbol duration. We can assume that we would receive only one copy of the signal, whose gain and phase are actually determined by the superposition of all those copies that come within $(\Delta t)_c$.

On the other hand, if the bandwidth of the transmitted signal is large compared with $(\Delta f)_c$, then different frequency components of the signal (that differ by more than $(\Delta f)_c$) would undergo different degrees of fading. The channel is then classified as *frequency selective*. Due to the reciprocal relationships, the symbol duration is small compared with $(\Delta t)_c$. Delays between different paths can be relatively large with respect to the symbol duration. We then assume that we would receive multiple copies of the signal.

2) slow fading versus fast fading

If the symbol duration is small compared with $(\Delta t)_c$, then the channel is classified as *slow fading*. Slow fading channels are very often modeled as time invariant channels over a number of symbol intervals. Moreover, the channel parameters, which are slow varying, may be estimated with different estimation techniques.

On the other hand, if $(\Delta t)_c$ is close to or smaller than the symbol duration, the channel is considered to be *fast fading (also known as time selective fading)*. In general, it is difficult to estimate the channel parameters in a fast fading channel.

We notice that the above classification of a fading channel depends on the properties of the transmitted signal. The two ways of classification give rise to four different types of channel:

- Frequency non-selective slow fading
- Frequency selective slow fading
- Frequency non-selective fast fading
- Frequency selective fast fading

Several mitigation techniques for combating the effects of both signal distortion and loss in SNR are given in [41]. This work focuses only on the techniques for combating the effects of loss in SNR.

CHAPTER 3

DIVERSITY

3.1. Diversity Principles

One of the most powerful techniques to mitigate the effects of fading is to use diversity-combining of independently fading signal paths. Diversity-combining uses the fact that independent signal paths have a low probability of experiencing deep fades simultaneously. Thus, the idea behind diversity is to send the same data over independent fading paths. These independent paths are combined in some way such that the effect of fading on the resultant signal is reduced. There are many ways of achieving independently fading paths in wireless systems and some of the important ones are discussed below.

3.2. DIVERSITY TECHNIQUES [42, 45]

Diversity techniques can be used to improve system performance in fading channels. Instead of transmitting and receiving the desired signal through one channel, we obtain L copies of the desired signal through *M* different channels. The idea is that while some copies may undergo deep fades, others may not. We might still be able to obtain enough energy to make the correct decision on the transmitted symbol. There are several different kinds of diversity which are commonly employed in wireless communication systems. In the following subsections different diversity techniques are briefly surveyed.

3.2.1. Frequency Diversity

One approach to achieve diversity is to modulate the information signal using *M* different carriers. Each carrier should be separated from the others by at least the coherence bandwidth so that different copies of the signal undergo independent fading. At the receiver, the L independently faded copies are “optimally” combined to give a statistic for decision. The optimal combiner is the *maximum ratio combiner*, which will be introduced later. Frequency diversity can be used to combat frequency selective fading. [2, 44, 45]

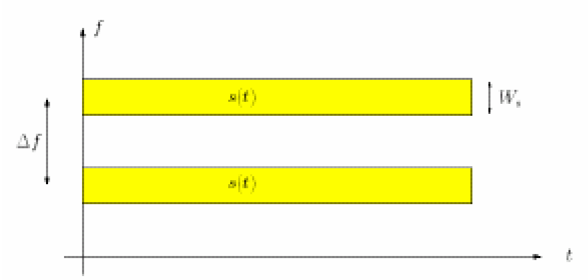


Fig.3.1. Frequency Diversity

3.2.2. Time Diversity

Another approach to achieve diversity is to transmit the desired signal in *M* different periods of time, i.e., each symbol is transmitted *M* times. The intervals between transmissions of the same symbol should be at least the coherence time so that different copies of the same symbol undergo independent fading. Optimal combining at the receiver can also be obtained with the maximum ratio combiner. We notice that sending the same symbol *M* times is applying the *(M, 1)* repetition code. Error control coding, together with interleaving, can also be an effective way to combat time selective (fast) fading [2, 44, 45].

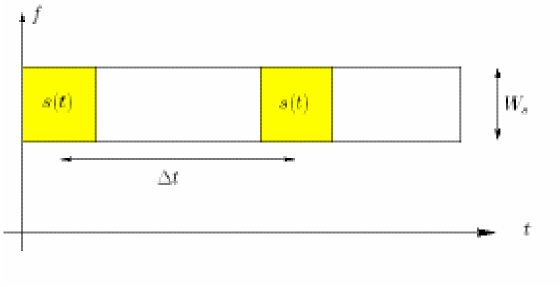


Fig.3.2. Time Diversity

3.2.3. Space Diversity

Another approach to achieve diversity is to use *M* antennas to receive *M* copies of the transmitted signal. The antennas should be spaced far enough apart so that different received copies of the signal undergo independent fading. This method is different from frequency diversity and temporal diversity as no additional work is required on the transmission end, and no additional bandwidth or transmission time is required. However, physical constraints may limit its applications. Another form of space diversity is transmit diversity where several copies of signal to be transmitted [15, 45].

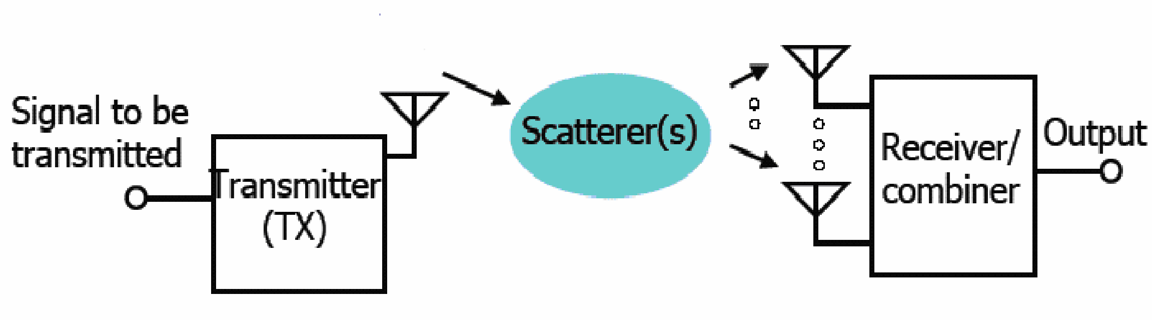


Fig.3.3.a) Receiver Diversity

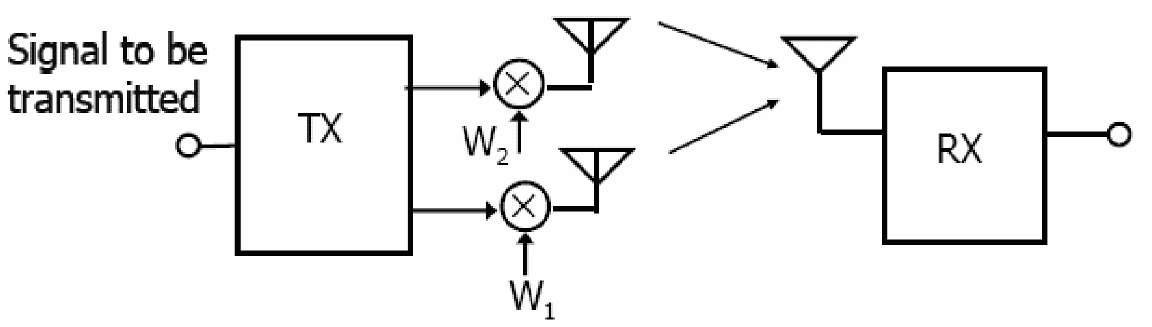


Fig.3.3. b) Transmit Diversity

3.3. Diversity Types

From the above brief explanations of diversity techniques, we note that frequency diversity needs additional energy to send the information bits & time diversity has a delay problem. These kinds of drawbacks might cause degradation of the performance of the system. A common technique to solve such drawbacks is to use antenna (space) diversity. In antenna diversity, multiple antennas with sufficient spatial separation or different polarization are used at the transmitter or/and at the receiver to provide independently fading channels. Antenna diversity increases the capacity of wireless communication systems significantly [33, 44].

Receive diversity is a topic which has been extensively studied in the literature [1, 2]. To achieve receive diversity the two ends need to be equipped with one transmit antenna and several receive antennas to achieve diversity. Transmit diversity is another form of antenna diversity which has recently been studied extensively [2, 16]. Transmit diversity offers the advantage that it can be deployed at the central station to increase the downlink performance and throughput, without requiring additional antennas at the receiving station. We can also have the combined transmit and receiver diversity in which both the basestations and the mobile stations are equipped with multiple antennas. The following subsections examine these two forms of diversity.

3.3.1. Receive Diversity

Receive diversity is a form of antenna diversity in which multiple antennas are used for reception. In receive diversity the independent fading paths associated with multiple receive antennas are combined to obtain a resultant signal that is then passed through a standard demodulator. The combining can be done in several ways which vary in complexity and overall performance [15]. The maximal ratio receiver combining (MRRC) scheme which is good example of receive diversity, is discussed below.

Example: Maximal Ratio Receiver Combining (MRRC) [1]

Fig. 3.4 shows the baseband representation of the classical two-branch MRRC. As can be seen from the figure, the MRRC scheme has one transmitting and two receiving antennas. At a given time, a signal s_0 is sent from the transmitter. The characteristics of the channel between the transmit antenna and the first receive antenna is denoted by h_0 and those between the transmit antenna and the second receive antenna is denoted by h_1 where

$$\begin{aligned} h_0 &= \alpha_0 e^{j\theta_0} \\ h_1 &= \alpha_1 e^{j\theta_1} \end{aligned} \tag{3.1}$$

Where $\alpha's$ and $\theta's$ are the magnitude and the phase of the channel between the transmitter and the receiver antenna.

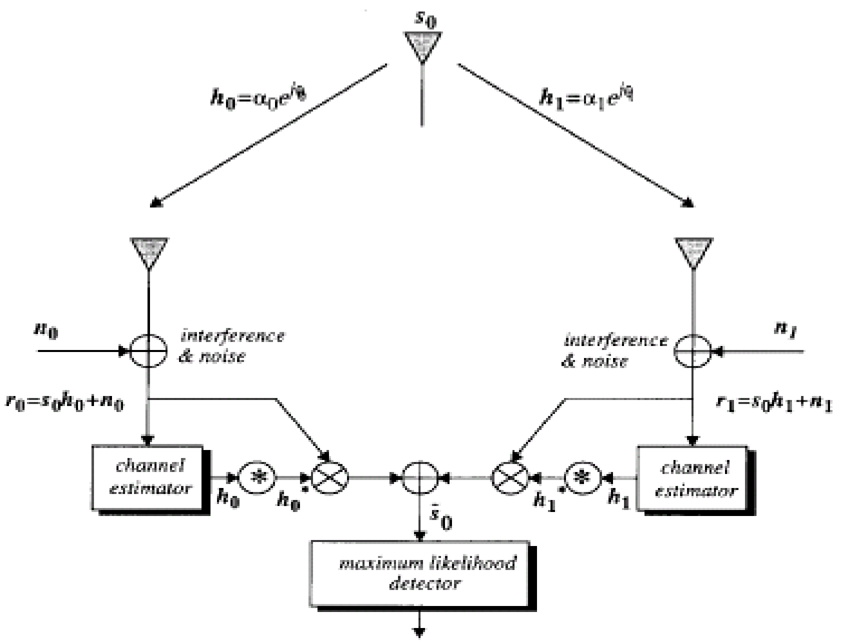


Fig.3.4. Two-branch MRRC

The resulting received baseband signals are

$$\begin{aligned} r_0 &= h_0 s_0 + n_0 \\ r_1 &= h_1 s_0 + n_1 \end{aligned} \tag{3.2}$$

where n_0 and n_1 represent complex noise and interference which are added at the two receivers. Assuming n_0 and n_1 have Gaussian distribution, the maximum likelihood decision rule at the receiver for these received signals is to choose signal s_i if and only if (iff)

$$d^2(r_0, h_0 s_i) + d^2(r_1, h_1 s_i) \le d^2(r_0, h_0 s_k) + d^2(r_1, h_1 s_k), \forall i \ne k \tag{3.3}$$

where $d^2(x, y)$ is the squared Euclidean distance between signals x and y calculated using the following expression:

$$d^2(x, y) \cong (x - y)(x^* - y^*) \tag{3.4}$$

The receiver combining scheme for the two-branch MRRC is thus as follows:

$$\begin{aligned} \tilde{s}_0 &= h_0^* r_0 + h_1^* r_1 \\ \tilde{s}_0 &= h_0^*(h_0 s_0 + n_0) + h_1^*(h_1 s_0 + n_1) \\ \tilde{s}_0 &= (\alpha_0^2 + \alpha_1^2) s_0 + h_0^* n_0 + h_1^* n_1 \end{aligned} \tag{3.5}$$

Where $\alpha_0^2 = |h_0|^2$ and $\alpha_1^2 = |h_1|^2$

Expanding (3.3) and using (3.4) and (3.5) we choose s$_i$ iff

$$\left(\alpha_0^2+\alpha_1^2\right)\left|s_i\right|^2 - \tilde{s}_0 s_i^* - \tilde{s}_0^* s_i \le \left(\alpha_0^2+\alpha_1^2\right)\left|s_k\right|^2 - \tilde{s}_0 s_k^* - \tilde{s}_0^* s_k \;, \forall i \neq k \tag{3.6}$$

Or equivalently

Choose s_i iff

$$\left(\alpha_0^2+\alpha_1^2-1\right)\left|s_i\right|^2 + d^2\left(\tilde{s}_0, s_i\right) \le \left(\alpha_0^2+\alpha_1^2-1\right)\left|s_k\right|^2 + d^2\left(\tilde{s}_0, s_k\right), \forall i \neq k \tag{3.7}$$

For PSK signals (equal energy constellations)

$$\left|s_i\right|^2 = \left|s_k\right|^2 = E_s, \forall i, k \tag{3.8}$$

where E$_s$ is the energy of the signal. Therefore, for PSK signals, the decision rule in (3.7) may be simplified to, choose s_i iff

$$d^2\left(\tilde{s}_0, s_i\right) \le d^2\left(\tilde{s}_0, s_k\right), \forall i \neq k \tag{3.9}$$

The maximal-ratio combiner may then construct the signal $\tilde{s}_0$, as shown in Fig. 3.4, so that the maximum likelihood detector may produce $\hat{s}_0$, which is a maximum likelihood estimate of s$_0$.

3.3.2. Transmit Diversity

In transmit diversity, there are multiple transmit antennas with the transmit power divided among these antennas. Transmit diversity is desirable in systems such as cellular systems where more space, power, and processing capability is available on the transmit side as opposed to the receive side.

Transmit diversity schemes [2] was classified into three broad categories which include

- Schemes with feedback [17, 20],
- Schemes with feed forward or training information but no feedback [18][19], and
- Blind schemes [31]

3.4. Diversity Combining Scheme [15]

Diversity schemes enhance reliability by minimizing the channel fluctuations due to fading. The central idea in diversity is that different antennas receive different versions of the same signal. The chances of all these copies being in a deep fade are small. These schemes therefore make most sense when the fading is independent from element to element. Our goal here is to combine these independent samples to achieve the desired goal of increasing the SNR and reducing the bit error rate.

Different techniques can be applied to combine those signals from different diversity channels. Those techniques are mainly classified as: selective combining, switched combining, maximal ratio combining and equal-gain combining.

Selective Diversity Combining

The ideal selective diversity combiner is defined as choosing as the system output, during each instant, the signal from that receiver which has the largest SNR. Selective diversity combining method can improve system performance significantly.

Switched Combining

In switched combining, a threshold is preset. A received signal is selected when it is above the threshold. The receiver stays with this signal until the signal falls below the threshold level. Then the receiver switches to another signal that is above the threshold, the switching algorithm also can handle the case where no signals are above the threshold.

Maximal-ratio combining

Maximal-ratio combining uses the signal-to-noise ratio as the criterion to combine those diversity signals. During the combination, proper weights are assigned to each branch, which can maximize the signal-to-noise ratio of the sum of the received signals. Each branch needs a receiver, and the weight computation is a very complex process [15].

Equal-gain combining

In this type of combining scheme, each branch signal is rotated by $e^{-j\theta_i}$, all branch signals are then added. The combined signal is simply the sum of the instantaneous fading envelopes of the individual branches. Compared to maximal-ratio combining, equal-gain combining only has slight degradation. Since no weight computation is required in equal-gain combining the system for equal-gain combining is relatively simple; it is usually used at the base station [15].

Diversity is used to provide the receiver with several replicas of the same signal. Diversity techniques are used to improve the performance of the radio channel without any increase in the transmitted power. Diversity Combining: MRC outperforms the Selection Combining; Equal gain combining (EGC) performs very close to the MRC. Unlike the MRC, the estimate of the channel gain is not required in EGC. Among different combining techniques MRC has the best performance and the highest complexity, SC has the lowest performance and the least complexity [44].

This chapter focused on receiver diversity and the diversity combining schemes used to combine the signals coming from the transmitter. The emphasis of this work is mainly on transmit diversity and the next chapter will discuss the concepts and the principles behind transmit diversity.

Chapter 4

Transmit Diversity

Current mobile communication systems employ multiple antennas at the base stations in order to suppress co-channel interference and mitigate multi-path fading. Two of the most popular commercial systems, GSM and IS-136, employ multiple antennas at the base stations to create receive diversity at the up-link (i.e. from the mobile to the base station). This improves signal reception at the base station, but for the down-link (from base station to mobile) it is difficult to use receive diversity. Firstly due to constrained size of the handset it is difficult to put two antennas in the unit; secondly more processing power is required, which again is limited for mobile units. On the other hand it is quite easy to incorporate multiple antennas at the base station and if necessary, provide extra transmit power for multiple transmissions. Transmit diversity thus, decreases the required processing power of the receivers, resulting in a simpler system structure, lower power consumption and lower cost. Furthermore, when required, transmit diversity can be combined with receiver diversity to further improve the system performance.

In contrast to receive diversity, transmit diversity has received little attention in cellular mobile communication systems as: (1) the transmitted signals from multiple antennas are mixed spatially before they arrive at the receiver; some additional signal processing is required at both the transmitter and receiver in order to separate the received signals and exploit diversity and (2) unlike the receiver that can usually estimate fading channels, the transmitter normally does not have access to instantaneous channel state information (CSI) unless the information is feedback from the receiver to the transmitter. The use of transmit diversity can considerably increase the channel capacity of wireless channel [14, 24]. Transmit diversity schemes proposed in the literature can be divided into two broad categories i.e. schemes with and without feedback [4].

4.1. Space-time coding [2, 11, 14]

Space-time codes (STC) were first introduced by Tarokh et.al. at AT & T research labs [2] in 1998 as a novel means of providing transmit diversity for the multiple-antenna fading channel. Previously, multipath fading in multiple antenna wireless systems was mostly dealt with by other diversity techniques, such as temporal diversity, frequency diversity and receive antenna diversity, with receive antenna diversity being the most widely applied technique. Transmit diversity schemes are growing increasingly popular as they promise high data rate transmission over wireless fading channels in both the uplink and downlink while putting the diversity burden on the base station.

The space-time coding scheme introduced by Tarokh et.al. [2],[11], is essentially a joint design of coding, modulation, transmit and receive diversity, and has shown to be a generalization of other transmit diversity schemes, such as the bandwidth efficient transmit diversity scheme by Wittneben [18] and the delay diversity scheme by Seshadri and Winters [19].

There are two main types of STC's, namely space-time block codes (STBC) and space-time trellis codes (STTC). Space-time block codes operate on a block of input symbols, producing a matrix output whose columns represent time and rows represent antennas. In contrast to single antenna block codes for the AWGN channel, space-time block codes do not generally provide coding gain, unless concatenated with an outer code [2, 9]. Their main feature is the provision of full diversity with a very simple decoding scheme. On the other hand, space-time trellis codes operate on one input symbol at a time, producing a sequence of vectors whose length represents antennas. Since they also provide full diversity gain, their key advantage over space-time block codes is the provision of coding gain. Their disadvantage is requirement for high complexity encoders and decoders.

Several methods of transmit diversity have been proposed for 3G CDMA evolution. These can be broadly categorized into *open loop* and *closed loop* techniques.

4.2. Open-loop transmit diversity

In open loop diversity methods, a predetermined form of diversity is introduced using multiple antennas. Advantages of this class of methods include:

- Signaling overhead is not required to achieve this form of diversity.
- The mobile station (MS) receiver complexity is kept relatively low.

The most obvious disadvantage is that the channel environment information is not utilized; that is, open loop techniques are a one-size-fits-all approach to achieving TD for all mobile users.

The earliest open loop diversity techniques were simple in their configuration, for example, phase-switched TD (PSTD) and time-switched TD (TSTD) [40]. But these techniques weren't adopted in favor of other techniques such as orthogonal TD (OTD) [4, 28], space-time TD (STTD) [1], and space-time spreading (STS) [4].

This work focuses on transmit diversity with space-time coding; therefore space-time transmit diversity (STTD) or the Alamouti's scheme [1] is considered.

Space-Time Transmit Diversity (STTD) or Alamouti scheme. [1]

STTD is open loop transmit diversity in which the symbols are modulated (BPSK) and space-time encoded using the technique described in [1]. This type of open loop transmit diversity has been adopted by the 3GPP because this type of transformation maximizes diversity gain. Figure 4.1 shows the baseband representation of the Alamouti two branches transmit diversity scheme [1]. The scheme uses two transmit antennas and one receive antenna and may be defined by the following three functions:

1) *The Encoding and Transmission sequence:*

During a given symbol period, two signals are simultaneously transmitted from the two antennas. The signal transmitted from antenna one is denoted by s_1 and from antenna two by s_2. During the next symbol period signal $(-s_2^*)$ is transmitted from antenna one, and signal (s_1^*) is transmitted from antenna two; where * denotes the complex conjugate operation. This sequence is shown in Table I. In Table I, the encoding is done in space and time (space-time coding) [1].

TABLE I

The encoding and transmission sequence for the Two - branch transmit diversity scheme.

	Antenna 1	Antenna 2
Time t	s_1	s_2
Time t + T	$-s_2^*$	s_1^*

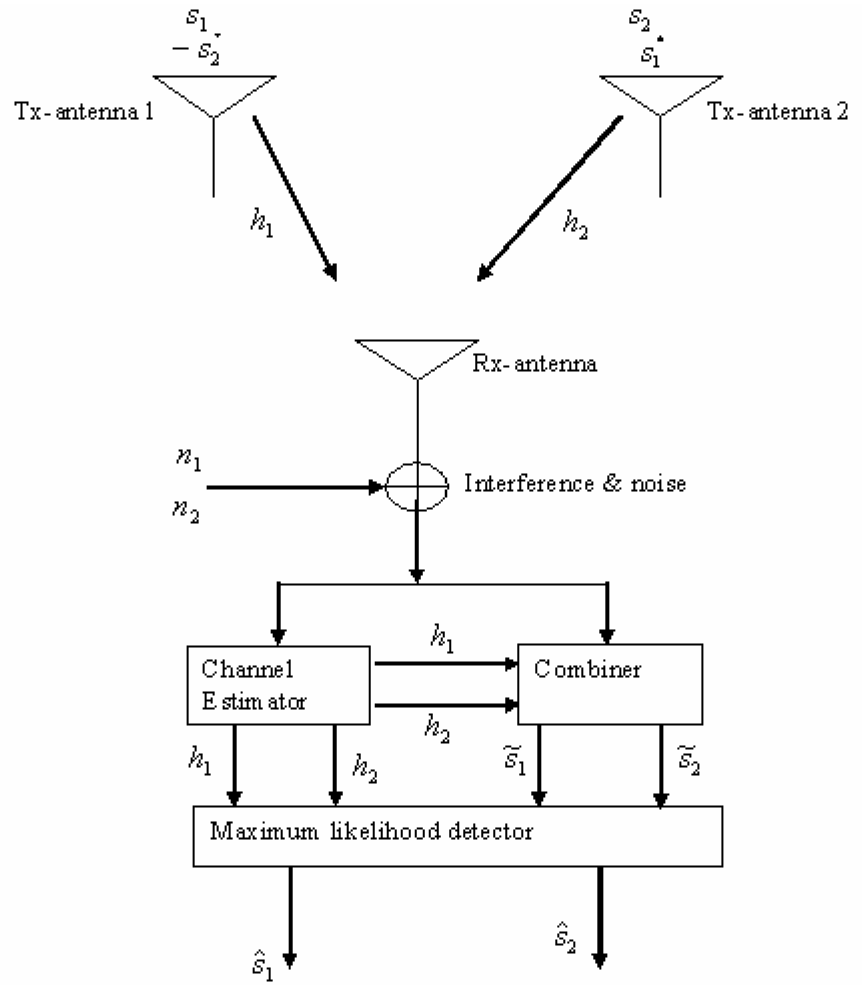


Fig.4.1. Alamouti transceiver structure

Or the 2 x 2 space-time block code may be written in matrix form as

$$S = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}$$

(4.1)

The channel at time t may be modeled by a complex multiplicative distortion $h_1(t)$ for transmit antenna zero and $h_2(t)$ for transmit antenna one. Assuming that fading is constant across two consecutive symbols, we can write

$$h_1(t) = h_1(t+T) = h_1 = \alpha_1 e^{j\theta_1}$$
$$h_2(t) = h_2(t+T) = h_2 = \alpha_2 e^{j\theta_2}$$

(4.2)

where T is the symbol duration.

The received signals can then be expressed as

$$r_1 = r(t) = h_1 s_1 + h_2 s_2 + n_1$$
$$r_2 = r(t+T) = -h_1 s_2^* + h_2 s_1^* + n_2$$

(4.3)

where r_1 and r_2 are the received signals at time t and t + T and n_1 and n_2 are complex random variables representing receiver noise and interference.

2) Channel Estimator:

The channel estimator is used to estimate the channel characteristics, h_1 and h_2. The model used for the channel estimator depends on the selected channel model. After channel estimation, the estimated channel characteristics will be used by the combiner and maximum likelihood detector.

3) Combining Scheme:

The combiner shown in Fig.4.1 builds the following two combined signals that are sent to the maximum likelihood detector:

$$\tilde{s}_1 = h_1^* r_1 + h_2 r_2^*$$
$$\tilde{s}_2 = h_2^* r_1 - h_1 r_2^* \qquad (4.4)$$

The decision statistics can be expressed as

$$\begin{aligned}\tilde{s}_1 &= \left(\alpha_1^2+\alpha_2^2\right)s_1 + h_1^* n_1 + h_2 n_2^* \\ \tilde{s}_2 &= \left(\alpha_1^2+\alpha_2^2\right)s_2 - h_1 n_2^* + h_2^* n_1\end{aligned} \tag{4.5}$$

Where $\alpha_1^2 = |h_1|^2$ and $\alpha_2^2 = |h_2|^2$

4) The Maximum Likelihood Decision Rule:

These combined signals are then sent to the maximum likelihood detector which, for each of the signals s_1 and s_2, uses the decision rule expressed in (3.7) or (3.9) for PSK signals.

The resulting combined signals in (4.4) are equivalent to that obtained from two-branch MRRC in (3.5). The only difference is phase rotations on the noise components which do not degrade the effective SNR. The resulting diversity order from the new two-branch transmit diversity scheme with one receiver is equal to that of two-branch MRRC.

Summary of Alamouti's scheme

Alamouti further extended this scheme to the case of 2 transmit antennas and m receive antennas, and showed that the scheme provided a diversity order of 2m. Characteristics of this scheme include:

- No feedback from receiver to transmitter is required.
- No bandwidth expansion (as redundancy is applied in space across multiple antennas, not in time or frequency).
- Low complexity decoders.
- Identical performance as MRC if the total radiated power is doubled from that used in MRC, else if transmit power is kept constant, this scheme suffers a 3dB penalty in performance.

4.3. Closed loop transmit diversity [27, 37]

Closed loop diversity techniques are adaptive in nature. The base station (BS) obtains knowledge of the downlink channel from the mobile station (MS) via feedback signaling, and uses this knowledge to its advantage. The use of feedback in transmit antenna arrays was first proposed by Gerlach and Paulraj [27] as transmit beamforming. They proposed that training signals be transmitted periodically on the downlink and the responses of the various MSs fed back to the BS. This information is used to calculate the optimal transmit weights for each mobile such that the received power at the desired MSs is maximized. Switched transmit diversity and transmit adaptive array (TXAA) are the two types of closed loop transmit diversity in which transmit adaptive array is more general form of switched transmit diversity. TXAA is a technique in which the mobile station periodically sends quantized estimates of the optimal transmit weights to the base station via a feedback channel. The feedback channel must have high accuracy, low bandwidth, lower delay and error free. The transmitter weights are selected to deliver maximum power to the mobile station [37]. Figure 4.2 depicts the concept of TXAA.

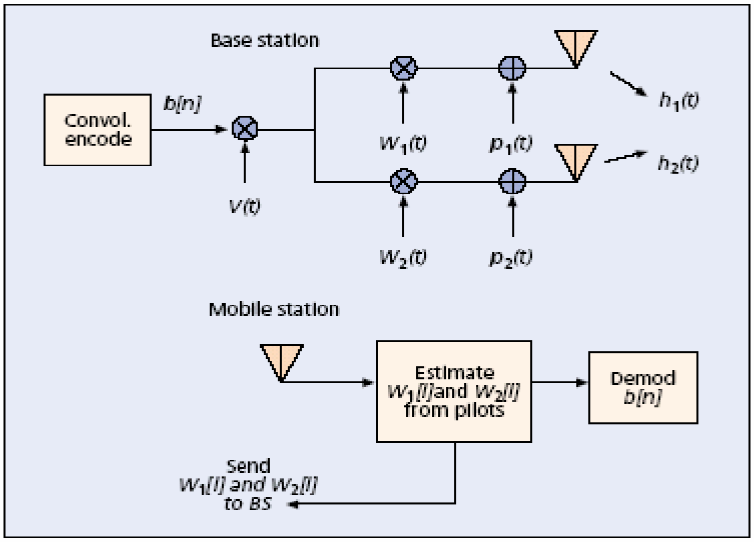


Fig.4.2. Transmit adaptive array (TXAA)

Thus, the MS calculates the weights at periodic intervals from the information h obtained through the two strong pilot signals P_1 and P_2. These weights are quantized and then fed back to the BS on the reverse link control channel.

The signal received at the MS will be

$$y = [h_1 \quad h_2] \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} b + n \text{, where } n \text{ refers to additive noise}$$

Where the weights are obtained as:

$$w_1 = \frac{|h_1|}{\sqrt{|h_1|^2 + |h_2|^2}} \quad \text{and} \quad w_2 = \frac{|h_2|}{\sqrt{|h_1|^2 + |h_2|^2}}$$

If one assumes that the feedback mechanism in TXAA perfectly tracks the channel conditions of the downlink, the signal-to-noise ratio (SNR) after demodulation and channel estimation is bounded as [4]

$$SNR \leq \left(\frac{|h_1|^2 + |h_2|^2}{\sqrt{|h_1|^2 + |h_2|^2}} \right)^2 \frac{Es}{No} = \left(|h_1|^2 + |h_2|^2 \right) \frac{Es}{No}, \tag{4.6}$$

Where $\frac{Es}{No}$ is the symbol SNR based solely on transmitted signal energy. The maximum achievable SNR of STTD on the basis of equal division of power between the two antennas is [4, 29]:

$$SNR \leq \frac{|h_1|^2 + |h_2|^2}{2} \frac{Es}{No}. \tag{4.7}$$

As it can be seen from this chapter, transmit diversity is classified into two whether the channel state information is known at the transmitter or not. We have seen Alamouti scheme which is a kind of transmit diversity without feedback, whereas transmit adaptive array (TXAA) is a type of transmit diversity with known channel state information. But TXAA used a spreading sequence to spread the signal across the two transmitter antennas rather than using the space – time coding.

The next chapter will discuss the concepts and the principles of adaptive space-time transmit diversity (ASTTD). ASTTD has the main features of the Alamouti scheme [space-time coding] and the TXAA [the transmit weights and the feedback channel].

Chapter 5

Adaptive space-time transmit diversity systems

In the previous chapters, we mentioned that transmit diversity is one of the key contributing technologies in defining 3G systems. By transmitting the downlink signal through multiple, widely spaced transmit antennas, the signals emanating from them can be assumed to undergo independent fading. Therefore, poor performance due to prolonged deep fading under low mobility conditions can be improved, which leads to an increase in the downlink capacity.

Transmit diversity methods fall into two classes: open loop and closed loop [4]. The simulation results show that the STTD is robust at higher velocities, while TXAA provides the biggest benefits at the lower velocities [4], [28]. A mixture of open and closed loop diversity technique could be, therefore, entertained to combat both fast and slow fading.

In this chapter, a scheme combining the standard STTD with adaptive power allocation and adaptive modulation is studied in order to improve the performance of the standard STTD system. The signal-to-noise ratio (SNR) performances of the two schemes are analyzed and compared with the ordinary STTD systems.

5.1. Adaptive Techniques [12]

There are many parameters that can be varied at the transmitter relative to the channel gain (h). In this section we discuss adaptive techniques associated with variation of the most common parameters: data rate, power, coding, and combinations of these.

5.1.1. Variable-Rate Techniques

In variable-rate modulation the data rate R(*h*)is varied relative to the channel gain *h*. This can be done by fixing the symbol rate $R_s = 1/T_s$ of the modulation and using multiple modulation schemes or constellation sizes, or by fixing the modulation (e.g. BPSK) and changing the symbol rate. Symbol rate variation is difficult to implement in practice since a varying signal bandwidth is impractical and complicates bandwidth sharing. In contrast, changing the constellation size or modulation type with a fixed symbol rate is fairly easy, and these techniques are used in current systems.

5.1.2. Variable – Power Techniques

Adapting the transmit power alone is generally used to compensate for SNR variation due to fading. The goal is to maintain a fixed bit error probability or, equivalently, a constant received SNR.

5.1.3. Variable – Coding Techniques

In adaptive coding different channel codes are used to provide different amounts of coding gain to the transmitted bits. For example, a stronger error correcting code may be used when the signal-to-noise ratio (SNR) is small, with a weaker code or no coding used when the signal-to-noise (SNR) is large. Adaptive coding can be implemented by multiplexing together codes with different error correction capabilities. On slowly-varying channels adaptive coding is particularly useful when the modulation must remain fixed.

The rate of channel variation will dictate how often the transmitter must adapt its transmission parameters, and will also impact the estimation error. At low speed the multipath fading is sufficiently slow so that it can be estimated and fedback to the transmitter with an estimated error and delay that doesn't significantly degrade performance. At high speed the system can no longer effectively estimate and feedback the multipath fading properties in order for the transmitter to adapt to it.

This section summarizes the different ways of adapting the channel gain in order to improve the performance of the received power (SNR) at the receiver. The rest of the section of this chapter will focus on two such schemes that are:

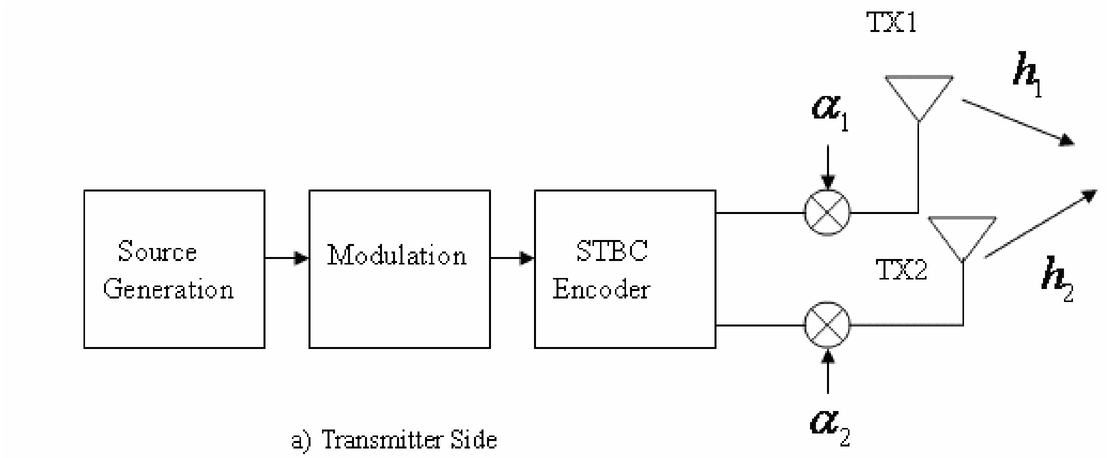
1) Adaptive Power Allocation Scheme for space – time coded systems;
2) Adaptive Space - Time Modulation

5.2. Adaptive Power Allocation Scheme [29, 30, 32]

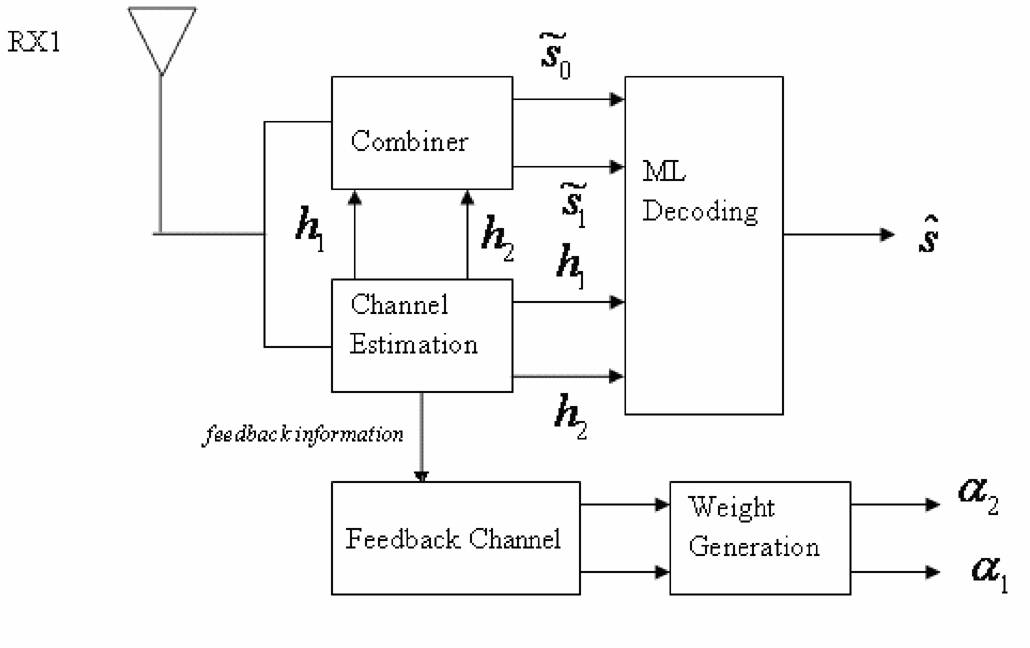
One attractive approach to achieve transmit diversity is to use space-time block code (STBC), proposed by Alamouti [1], which can achieve full diversity without bandwidth expansion. STBC system can achieve the diversity order of M for M transmit antennas and one receive antenna. The reason is that STBC maintains orthogonality between the antennas and it can avoid self – interference in flat fading channels. Furthermore, since the receiver can process the received signal using simple linear processing, the complexity is low. Finally, the transmit power is equally divided among all transmit antennas.

This work considers the transmission power adaptation in space-time block code (STBC) systems, where the transmitter is equipped with two antennas. This work also assumes that the channel gain information at each antenna are obtained at the receiver and then transported over a dedicated feedback link to the transmitter for power adaptation.

5.2.1. System Model



a) Transmitter Side



b) Receiver Side

Figure 5.1. ASTTD system with adaptive transmit weights

Consider the system shown above in Figure 5.1, in which the transmitter combines the ASTTD encoder with adaptive weights of transmitted signals. The transmit weights, α_1 & α_2 are selected based on the feedbacks from the receiver under the fixed power constraint condition of

$$|\alpha_1|^2 + |\alpha_2|^2 = 1$$

(5.1)

The ASTTD encoder uses a space-time block code which encodes two successive input data symbols $[X_1\ X_2]^T$ into a 2 x 2 output matrix [1]:

$$\begin{bmatrix} X_1 & -X_2^* \\ X_2 & X_1^* \end{bmatrix}$$

(5.2)

Where * denotes complex conjugate operation and each row of the matrix is assigned to one transmit antenna. Assume there is one antenna element at the receiver, as shown in Fig. 5.2. The received signal $r_1(n)$ and $r_2(n)$ corresponding to the two successive received symbol intervals in one space-time coded block can be expressed as

$$\begin{bmatrix} r_1(n) \\ r_2(n) \end{bmatrix} = \begin{bmatrix} \alpha_1 X_1 & \alpha_2 X_2 \\ -\alpha_1 X_2^* & \alpha_2 X_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} v_1(n) \\ v_2(n) \end{bmatrix}$$

(5.3)

Where h_j is the channel coefficient from ith transmit antenna to the receiver antenna and *v*(n) is the additive white Gaussian noise sampled at time instant n with standard deviation σ_v. The channel coefficients, h_1 and h_2, are complex - valued, i.i.d. Rayleigh fading.

And the decision variables are given as

$$\begin{aligned} \hat{s}_1 &= \alpha_1 h_1^* r_1 + \alpha_2 h_2 r_2^* = \left(\alpha_1^2 |h_1|^2 + \alpha_2^2 |h_2|^2\right) X_1 + \alpha_1 h_1^* v_1 + \alpha_2 h_2 v_2^* \\ \hat{s}_2 &= \alpha_2 h_2^* r_1 - \alpha_1 h_1 r_2^* = \left(\alpha_1^2 |h_1|^2 + \alpha_2^2 |h_2|^2\right) X_2 + \alpha_2 h_2^* v_1 - \alpha_1 h_1 v_2^* \end{aligned}$$

(5.4)

Therefore, the instantaneous SNR is obtained as

$$SNR/_{h_1 h_2} = \frac{\left(|h_1|^2 |\alpha_1|^2 + |h_2|^2 |\alpha_2|^2\right) Es}{\sigma_v^2}$$

(5.5)

Where Es is the symbol power and σ_v^2 is the noise power. From (5.5), it is straightforward to see that the ASTTD receiver is backward compatible with the ordinary STTD, in which $\alpha_1 = \alpha_2$. In fact, under the fixed power constraint, the output SNR for ordinary STTD systems can be obtained from (5.5) as

$$SNR/_{h_1 h_2} = \frac{\left(|h_1|^2 + |h_2|^2\right)Es}{2\sigma_v^2}$$

(5.6)

Since $|\alpha_1|^2 = |\alpha_2|^2 = \frac{1}{2}$.

5.2.2. Adaptive Power Allocation schemes:

This section discusses the two schemes which are employed in adaptive power allocation. The first one is the minimum feedback allocation scheme and the second one is STTD with adaptive transmit weights.

5.2.2.1. Minimum feedback Allocation Scheme (Antenna Selection):

In this scheme, the system will compare the channel fading and decides which antenna to select for transmission. If we let $\beta_1 = |h_1|^2$, $\beta_2 = |h_2|^2$ and assuming $\beta_1 \geq \beta_2$ (having a perfect feedback), thus we can write $\beta_1 = \beta_2 + \delta_1$. As derived in [34], the instantaneous SNR is expressed as:

$$\gamma = \frac{Es}{\sigma_v^2}\left[\beta_2 + \delta_1 \alpha_1^2\right]$$

(5.7)

So, we can easily see that if $\alpha_1^2 = 1$, the instantaneous SNR will be $\frac{Es}{\sigma_v^2}\beta_1$. This means that the system should allocate all its power to antenna one for better transmission. Similarly, when $\beta_2 > \beta_1$, the system should allocate all its power to antenna two for better transmission. If $\beta_2 > \beta_1$, i.e., $\beta_2 = \beta_1 + \delta_2$, substituting this into equation (5.7), we get

$\gamma = \frac{Es}{\sigma_v^2}\left[\beta_2 + \delta_1 \alpha_1^2\right]$ since $\sum_{m=1}^{M} \alpha_m^2 = 1$, $\alpha_2^2 = 1$ (since $\beta_2 > \beta_1$) and $\alpha_1^2 = 0$

$$\gamma = \frac{Es}{\sigma_v^2}\left[\beta_2\right]$$

5.2.2.2. ASTTD with adaptive transmit weights [30, 32, 34]

The above scheme uses transmit weights to enhance the performance of the ordinary STTD systems. But here the transmit weights are adaptive in the sense that at each transmission this transmit weights are adapted to the channel condition. By doing so, we can improve the system performance.

From equation (5.3), the output of the ASTTD decoder can be expressed as:

$$\begin{aligned} \tilde{s}_0 &= h_1^* r_1 + h_2 r_2^* = AX_1 - BX_2 + C_1 \\ \tilde{s}_1 &= h_1^* r_2 - h_2 r_1^* = -AX_2^* - BX_1^* + C_2 \end{aligned}$$

(5.8)

Where

$$\begin{aligned} A &= (\alpha_1 |h_1|^2 + \alpha_2^* |h_2|^2) \\ B &= (\alpha_1^* - \alpha_2) h_1^* h_2 \\ C_1 &= h_1^* v_1 + h_2 v_2^* \\ C_2 &= h_1^* v_2 - h_2 v_1^* \end{aligned}$$

(5.9)

The term B in equation (5.9) is cancelled by a cross- interference canceller which is caused by the unequal transmit weights at the transmitters. The output of the decoder is expressed as

$$\hat{s}_1 = A^* \tilde{s}_0 - B \tilde{s}_1^* = \left(|A|^2 + |B|^2\right) X_1 + \left(A^* C_1 - B C_2^*\right)$$

(5.10)

$$\hat{s}_2 = -B^* \tilde{s}_0 - A \tilde{s}_1^* = \left(|A|^2 + |B|^2\right) X_2 - \left(A C_2^* + B^* C_1\right)$$

Transmit Weight Selection: [29, 34]

Two solutions are proposed to find the optimum transmit weights in order to maximize the received SNR. The first is to maximize the SNR given in (5.5) under the fixed power constraint given in (5.1) and the second possibility is to maximize the term A in (5.9) by letting $\frac{dA}{d\alpha_1} = 0$ with respect to the constraint in (5.1), the optimum transmit weights are given as

$$\alpha_1 = \frac{1}{\sqrt{1+\left(\frac{|h_2|}{|h_1|}\right)^4}}, \qquad \text{and} \qquad \alpha_2 = \frac{1}{\sqrt{1+\left(\frac{|h_1|}{|h_2|}\right)^4}}$$

(5.11)

It shows that only the amplitude ratio of the propagation channels is needed as feedback information to calculate the transmit weights and the same as the one derived in [34]. It is clear that if $\beta_1 \geq \beta_2$, we can see that $\alpha_1 > \alpha_2$ will improve the system performance.

Applying the transmit weights in (5.11) to (5.5) the SNR of ASTTD with feedback can be obtained as:

$$SNR/_{h_1 h_2} = \frac{\left(|h_1|^6 + |h_2|^6\right)}{\left(|h_1|^4 + |h_2|^4\right)} \frac{Es}{\sigma_v^2}$$

(5.12)

Or we can use the formula proposed in [34], the power scaling coefficients α_m is given as:

$$\alpha_m = \sqrt{\frac{\beta_m^u}{\sum_{m=1}^{M} \beta_m^u}}$$

(5.13)

$$\beta_m = |h_m|^2 \ , \ m = 1,2$$

Taking u = 2 (for adaptive power allocation), we can have the same power scaling coefficients as derived before, for a (2, 1) system α_1 and α_2 are given as:

$$\alpha_1 = \sqrt{\frac{\beta_1{}^2}{\sum_{m=1}^{2}\beta_m{}^2}} = \sqrt{\frac{|h_1|^4}{|h_1|^4+|h_2|^4}} = \frac{1}{\sqrt{1+\left(\frac{|h_2|}{|h_1|}\right)^4}}$$

$$\alpha_2 = \sqrt{\frac{\beta_2^2}{\sum_{m=1}^{2}\beta_m^2}} = \sqrt{\frac{|h_2|^4}{|h_1|^4+|h_2|^4}} = \frac{1}{\sqrt{1+\left(\frac{|h_1|}{|h_2|}\right)^4}}$$

(5.14)

5.3. Adaptive Space-Time Modulation

New adaptive transmission techniques such as adaptive modulation were proposed recently to satisfy the tremendous growth in demand for wireless communications capacity [33]. Adaptive modulation is a useful approach to achieve bandwidth efficient transmission by adapting the modulation parameters (e.g. constellation size, transmitted signal power, symbol rate, etc) to current fading conditions. This thesis work investigates combined adaptive modulation and space – time transmit diversity.

Adaptive modulation and coding enables robust and spectrally efficient transmission over time – varying channels. The basic premise is to estimate the channel characteristics at the receiver and feed this estimate back to the transmitter, so that the transmission can be adapted to the channel characteristics.

This work assumes the case of two transmitter antennas and one receiver antenna and it considers modulation level controlled adaptive modulation scheme [36]. The constellation size of M-PSK is restricted to 0, 2, 4 and 8 and choosing the target BER as 10^{-3}.

The channel from the two antennas to the mobile are modeled as i.i.d. Rayleigh fading with complex coefficients h_1 and h_2. Additive white Gaussian noise is present at the receiver. Further it is assumed that accurate CSI is available at the transmitter.

In adaptive modulation, the link adaptation is either continuous adaptation or discrete adaptation. This work focuses on discrete adaptation since the constellation sizes are restricted. Specifically, a set of square constellation of M-PSK of size $M_0 = 0$, $M_1 = 2$, and $M_j = 2^{2(j-1)}$, j= 2…N – 1 for some N. Thus, at each symbol time we transmit a symbol from a constellation in the set $\{M_j: j = 0, 1,\ldots, N-1\}$; the choice of constellation size depends on the fade level *h* over that symbol time. Choosing M_0 constellation corresponds to no data transmission. For each value of *h*, we must decide which constellation size to transmit [25]. The constellation size associated with each *h* is determined by discretizing the range of the channel fade levels. The range of h is divided into N fading regions:

$$R_j = (h_{j-1}, h_j),\ j = 0,\ldots, N-1, \text{ where } h_{-1} = 0 \text{ and } h_{N-1} = \infty. \quad (5.15)$$

Therefore, M_j is transmitted when $h \in R_j$. In case of adaptive space – time modulation, *h* has to be first determined , figure 5.2 shows the operation of the two – branch adaptive space – time transmit diversity (AM + STTD) scheme.

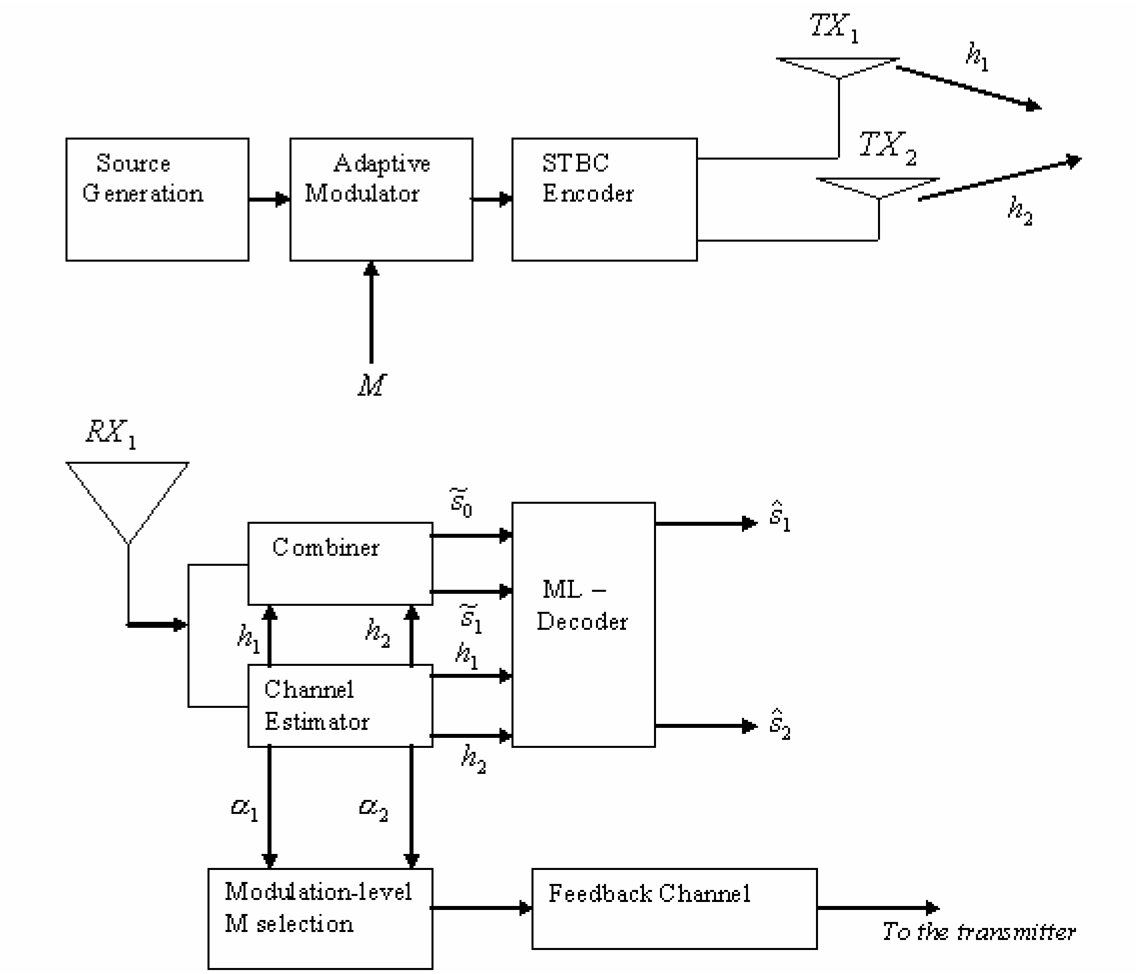


Figure. 5.2 Driving Configuration of AM + STTD.

For the system model given above, the symbols to be transmitted are generated by the source generator and modulated with adaptively selected modulation (constellation size). The constellation size is selected based on the channel fading condition. Prior to transmission, the modulated signal will be encoded using space-time block encoder. At the receiver side, the channels are estimated and the signals are combined and decoded using

ML-detector. The required channel estimates will be feedback through a dedicated feedback channel, this feedback channel must have high accuracy, low bandwidth, lower delay and error free. The channel estimates will be used to select the constellation size of the adaptive modulator.

At a given symbol period, two signals are simultaneously transmitted from the two antennas, say antenna 1 and antenna 2. The signal transmission matrix for STTD is given by

$$\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

(5.16)

Assuming that fading is constant across two consecutive symbols, we can express the received signals as:

$$\begin{aligned} r_1 &= r(t) = h_1 s_1 + h_2 s_2 + n_1 \\ r_2 &= r(t+T) = -h_1 s_2 + h_2 s_1^* + n_2 \end{aligned}$$

(5.17)

Where T is the symbol interval.

The maximum likelihood detector is based on the variables

$$\begin{aligned} \hat{s}_1 &= \left(\alpha_1^2 + \alpha_2^2\right) s_1 + h_1^* n_1 + h_2 n_2 \\ \hat{s}_2 &= \left(\alpha_1^2 + \alpha_2^2\right) s_2 - h_1 n_2^* + h_2^* n_1 \end{aligned}$$

(5.18)

Now let us calculate the instantaneous SNR for the AM + STTD scheme. If we denote the noise term $n^{'} = h_1^* n_1 + h_2 n_2$ for s_1, and $n^{''} = h_1 n_2^* + h_2^* n_1$ for s_2, then the variances of $n^{'}$ and $n^{''}$ are given by:

$$Var\left(n^{'}\right) = Var(n^{''}) = \left(\alpha_1^2 + \alpha_2^2\right) \frac{No}{2}$$

(5.19)

Here we assume $Var(n_1) = Var(n_2) = \frac{No}{2}$. Each antenna radiates half of the total power, i.e., $E\left\{\left|s_1\right|^2\right\} = E\left\{\left|s_2\right|^2\right\} = \frac{Es}{2}$. Therefore, the instantaneous SNR is given by:

h region	M_j
$0 \leq h < 2$	0
$2 \leq h < 4$	2
$4 \leq h < 8$	4
$8 \leq h < 16$	8

$$\gamma(t) = \frac{\left(\frac{Es}{2}\right)\left(\alpha_1^2 + \alpha_2^2\right)^2}{No\left(\alpha_1^2 + \alpha_2^2\right)} = \frac{Es}{No}\frac{\alpha_1^2 + \alpha_2^2}{2} = \bar{\gamma}\frac{\alpha_1^2 + \alpha_2^2}{2} \quad \text{where } \bar{\gamma} = \frac{Es}{No} \qquad (5.20)$$

Thus, AM + STTD is equivalent to a single transmission antenna system with the channel:

$$h = \sqrt{\frac{\left(\alpha_1^2 + \alpha_2^2\right)}{2}}, \qquad \text{where} \qquad \alpha_1^2 = |h_1|^2 \qquad \text{and} \qquad \alpha_2^2 = |h_2|^2$$

(5.21)

Therefore, the constellation size of AM + STTD scheme is selected based on $\sqrt{\frac{\left(\alpha_1^2 + \alpha_2^2\right)}{2}}$.

Therefore, the constellation size M_j is selected based on the above formula and the fade levels as shown in Table II.

Table II. Constellation Size Selection for 4 regions.

5.4. Feedback Scheme

Adaptive space-time transmit diversity is a combination of open-loop and closed loop transmit diversity. It took the space-time block encoder from the STTD scheme and the transmit weights and the feedback channel from TXAA scheme. The channel characteristics are estimated in the channel estimator at the receiver and these channel estimates will be feedback to the transmitter through a dedicated feedback channel. The feedback channel must have high accuracy, low bandwidth, and lower delay and free from error. So far, we have assumed that the transmit weights can be made to perfectly and instantaneous fulfill the equality expressed in equation (5.5). For this assumption to be valid, the transmitter must have perfect and instant access to the channel coefficients.

In an FDD system, the beamforming STTD system has to retrieve the channel information through a separate feedback channel from the receiver. The introduction of a feedback channel to send channel information from the receiver to the transmitter immediately invalidates the assumption of perfect and instant access to channel information at the transmitter.

Table III lists the different factors that will make the channel information at the transmitter non-perfect and outdated.

Table III. Factors Causing Delay and Errors in Channel Feedback

Errors	Delay
• Channel parameter estimation i receiver.	• Estimation Processing
• Quantization of the channel estimates	• Quantization Processing
• Errors in feedback channel	• Feedback transmission & reception

After making the assumption that the receiver can perfectly estimate the channel parameters, there exist four sources of errors in the channel information available to the transmitter: [5, 6, and 7]

- Feedback delay
- Feedback period
- Quantization error in feedback
- Feedback errors

The effects caused by these feedback non-idealities are given below:

- The transmitter is therefore forced to decide on the transmit weights based on delayed information.
- The channel information in the transmitter cannot be updated for every bit transmission due to bandwidth restriction on the feedback channel, i.e., feedback is only sent periodically.
- The feedback cannot contain the full channel estimates but must be quantized due to bandwidth restriction.
- There will be errors in the feedback channel, causing the transmitter to decide the quantized channel data wrongly.

To mitigate the effects of these feedback non-idealities some techniques are proposed:

1) To mitigate the effects of quantization error and feedback period:
    - Quantize the complex feedback coefficient to 1 bit of magnitude and 3 bits of phase and send them over successive slots [5]
    - Feedback only the phase information for the complex coefficients. Set partitioning is done on the phase constellation, and the transmit weighting is calculated by filtering over multiple feedback bits [5]

2) To mitigate the effects of feedback error:
    - The feedback bits are not protected through FEC; hence, the weights applied at the BS transmitter antennas might be different from the weights the MS expects it to apply. This causes the channel estimates at the MS receiver to be in error. In order to avoid this situation, *verification* of the weights is necessary at the MS [37].
3) To mitigate the effects of feedback delay [38]:
    - One possible solution to this problem is to use the fact that the fading channel can be modeled as an autoregressive (AR) process. Linear prediction techniques can be used to estimate the AR coefficients and also to predict the future state of the channel. The mobile can calculate the feedback based on the predicted future channel state, thus reducing the effects of feedback delay.

In this chapter, we have discussed the schemes employed in adaptive space – time transmit diversity. Adaptive power allocation scheme that allocates more power to one of the transmitting antennas with better fading condition will improve the system performance and the other scheme which is adaptive space-time modulation will vary the constellation size in order to improve the system performance. The next chapter will show the simulation results of these two schemes of adaptive space-time transmit diversity.

Chapter 6

Simulation Results & Discussion

This section focuses on the simulation results and discussion of adaptive space time transmit diversity schemes, that is, adaptive power allocation scheme and adaptive space-time modulation scheme and finally, combined adaptive power and modulation for the space-time block coded systems.

The signal –to- noise ratio (SNR) performances of these schemes will be investigated and evaluated on a flat Rayleigh fading channel, and compared with the space-time transmit diversity. This work is based on simulation with MATLAB version 7.0. The system modeling is described in detail in the subsequent sections.

6.1. Space-Time Transmit Diversity (STTD)

The system block diagram is given below, figure 6.1,

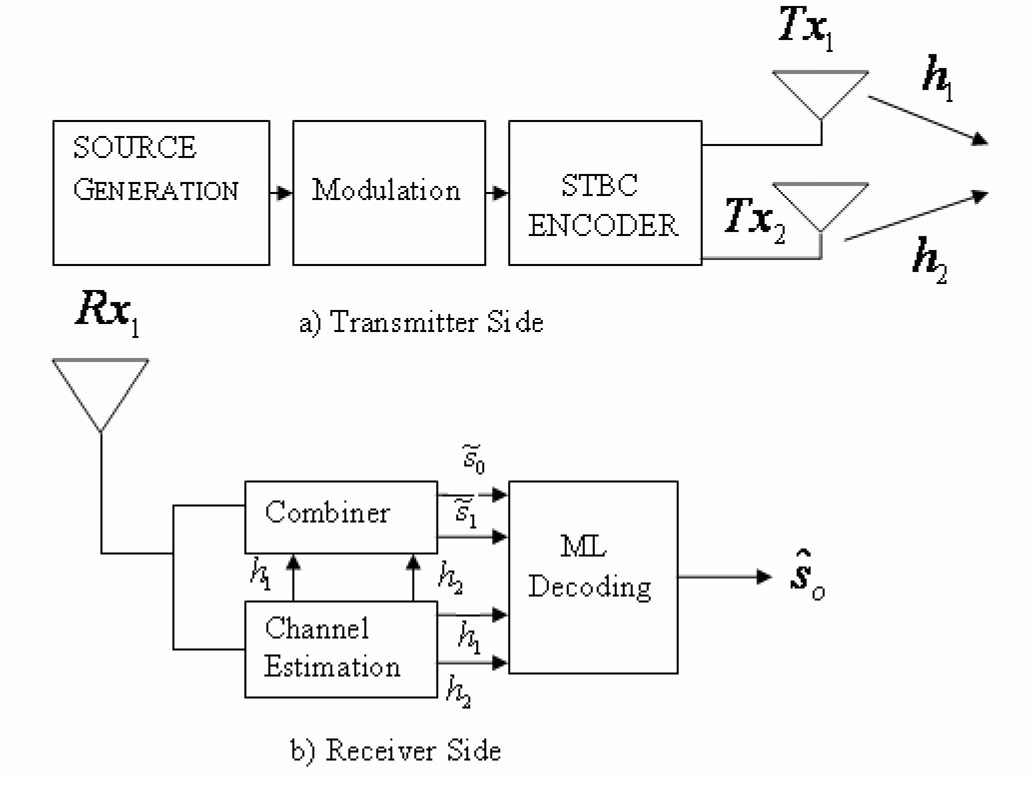


Figure 6.1. Space Time Transmit Diversity system

Forward Link:

Space – time transmit diversity is an open loop transmit diversity scheme so that it doesn't require a feedback link. The system modeling is given below:

1) Random bits are produced by some digital source, with output bit stream: $\{b_i\}$
2) The bit stream is BPSK- modulated and projected into the signal space, with output symbols:

$$\{s_i\},\ s_i \in \left\{\pm\sqrt{E_b}\right\}$$

$$b_i = '1' \rightarrow s_1 = \sqrt{E_b}$$

$$b_i = '0' \rightarrow s_2 = -\sqrt{E_b}$$

3) The symbols are encoded using space-time block (STBC) encoder and written as:

$$\begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} \qquad \text{(Space- Time Coding)}$$

4) The encoded symbols are transmitted on the two different transmit antennas, spaced enough (0.5λ) to fade independently [Uncorrelated Channel].
5) The output signals from each of the two antennas are all, independent, experiencing a flat Rayleigh fading channel. As they add up in space and arrive at the single receive antenna, AWGN is added, resulting in the received signal sequence:

$$r_1 = h_1 s_1 + h_2 s_2 + n_1$$

$$r_2 = -h_1 s_2^* + h_2 s_1^* + n_2$$

6) The channel model here is a flat Rayleigh fading channel and no other fading channel model is considered.
7) Assuming the receiver has perfect knowledge of the channel, the output of the combiner, $\tilde{s}_1$ and $\tilde{s}_2$, that are sent to the maximum likelihood detector:

$$\tilde{s}_1 = h_1^* r_1 + h_2 r_2^*$$

$$\tilde{s}_2 = h_2^* r_1 - h_1 r_2^*$$

8) The ML- detector makes decisions to choose s_i according to the decision rule:

$$d^2(\tilde{s}_1, s_i) \leq d^2(\tilde{s}_1, s_k) \quad \forall i \neq k$$

9) Calculates the bit error rate by dividing the number of bits in error by number of bits generated.

The simulation result of the given system is shown below:

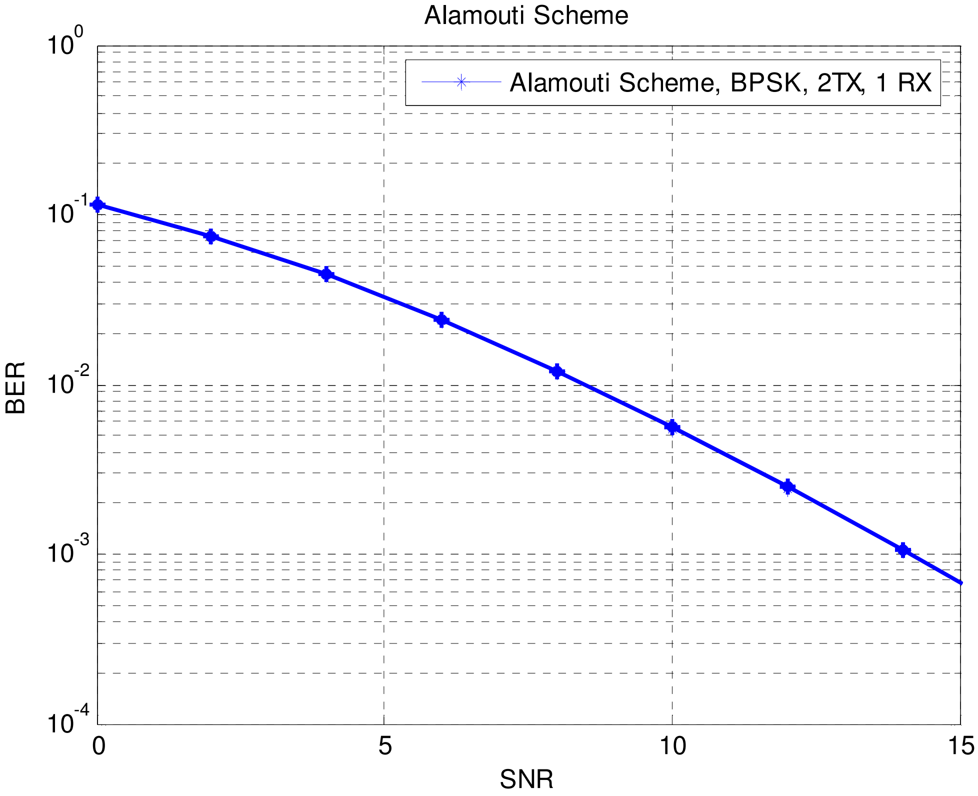
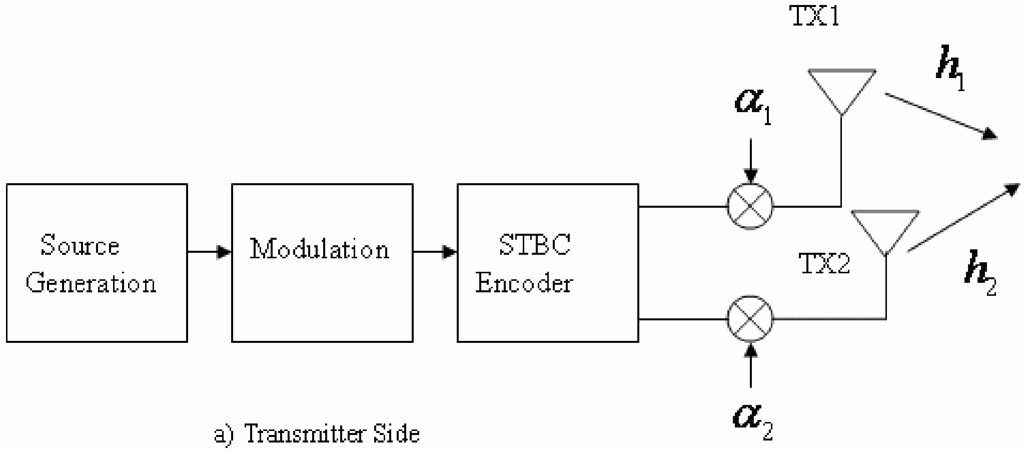


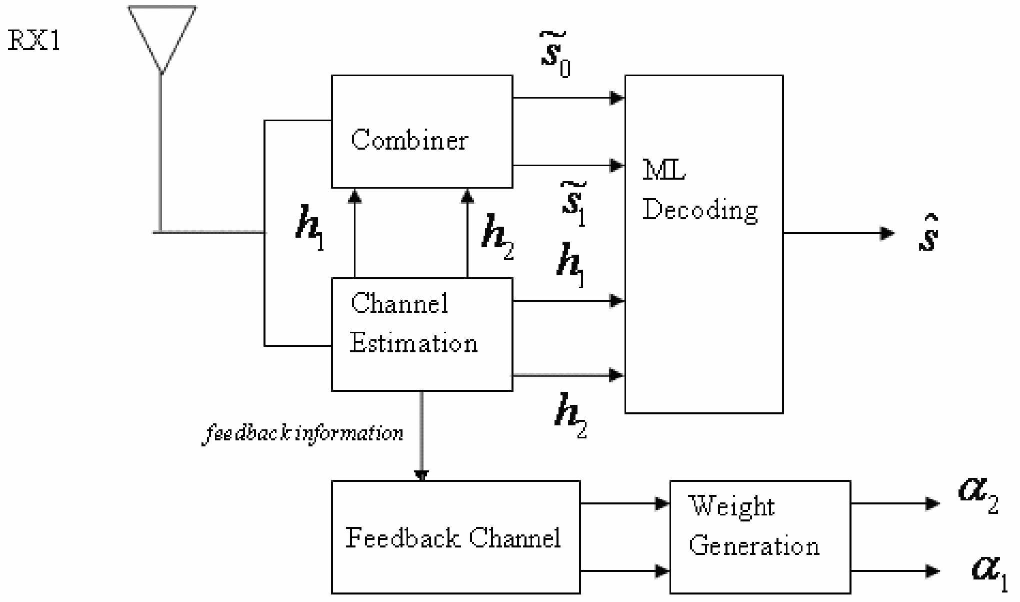
Fig. 6.2 Bit error rate (BER) versus signal-to-noise ratio (SNR) of Alamouti scheme (2TX, 1RX, BPSK).

6.2. Adaptive Power Allocation for space time coded systems

The system block diagram is given below:



a) Transmitter Side



b) Receiver Side

Fig. 6.3 Block Diagram for adaptive power allocation scheme for ST block coded systems

Forward Link:

Based on the platform of space-time transmit diversity system modeling, we can model the system for adaptive power allocation scheme in the following way:

1) Random binary bits are produced by some digital source, with output bit stream: $\{b_i\}$
2) The bit stream is BPSK- modulated and projected into the signal space, with output symbols:

$$\{s_i\},\ s_i \in \left\{\pm\sqrt{E_b}\right\}$$

$$b_i = '1' \rightarrow s_1 = \sqrt{E_b}$$

$$b_i = '0' \rightarrow s_2 = -\sqrt{E_b}$$

3) The symbols are encoded using space-time block (STBC) encoder and written as:

$$\begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} \text{(Space- Time Coding)}$$

4) Prior to transmission, the encoded symbols are multiplied with transmit antenna weights, α_1 and α_2, producing the output sequence $\{s_i\alpha_i\}$ from each of the antennas.

$$\begin{bmatrix} \alpha_1 s_1 & -\alpha_1 s_2^* \\ \alpha_2 s_2 & \alpha_2 s_1^* \end{bmatrix}$$

5) The output signals from each of the two antennas are all, independent, experiencing a flat Rayleigh fading channel. As they add up in space and arrive at the single receive antenna, AWGN is added, resulting in the received signal sequence:

$$\begin{bmatrix} r_1(n) \\ r_2(n) \end{bmatrix} = \begin{bmatrix} \alpha_1 s_1 & -\alpha_1 s_2^* \\ \alpha_2 s_2 & \alpha_2 s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} v_1(n) \\ v_2(n) \end{bmatrix}$$

6) The channel model here is a flat Rayleigh fading channel and no other fading channel model is considered.
7) Assuming the receiver has perfect knowledge of the channel, the output of the combiner, $\tilde{s}_1$ and $\tilde{s}_2$, that are sent to the maximum likelihood detector:

$$\hat{s}_1 = \alpha_1 h_1^* r_1 + \alpha_2 h_2 r_2^* = \left(\alpha_1^2 |h_1|^2 + \alpha_2^2 |h_2|^2\right) s_1 + \alpha_1 h_1^* v_1 + \alpha_2 h_2 v_2^*$$
$$\hat{s}_2 = \alpha_2 h_2^* r_1 - \alpha_1 h_1 r_2^* = \left(\alpha_1^2 |h_1|^2 + \alpha_2^2 |h_2|^2\right) s_2 + \alpha_2 h_2^* v_1 - \alpha_1 h_1 v_2^*$$

8) The ML – likelihood uses $\tilde{s}_1$ and $\tilde{s}_2$ as an input to decide which signal to select using the decision rule

$$d^2(\tilde{s}_1, s_i) \le d^2(\tilde{s}_1, s_k) \quad \forall i \ne k$$

9) Calculates bit error rate by dividing the number of bits in error by the number of bits generated.

Feedback Link:

1) The feedback processing starts in the channel parameter estimator on the receiver side. Periodically, once every 2 transmitted symbol in the forward link, the channel estimates are sent to the transmitter.
2) Due to the allocation of lower bandwidth for feedback channel, the feedback information in this case the channel estimates will be encoded (or quantized) and is transmitted on the feedback channel. As the feedback is received at the basestation, the encoded channel estimates will be decoded.
3) In the case of MFAS, the decoded channel estimates will be compared and the result of the comparison will decide the antenna over which the symbols are transmitted. But the transmit antenna weights are equal ($\alpha_1 = \alpha_2 = \frac{1}{\sqrt{2}}$, this equal division of power).
4) In case of adaptive transmit weights, the decoded channel estimates are used to calculate the transmit weights. The weights are chosen as:

$$\alpha_1 = \frac{1}{\sqrt{1 + \left(\frac{|h_2|}{|h_1|}\right)^4}}, \text{ and } \alpha_2 = \frac{1}{\sqrt{1 + \left(\frac{|h_1|}{|h_2|}\right)^4}}$$

The transmitter continues t use the same channel information to decide on the transmit weights until new feedback arrives and the channel information is updated.

The simulation result is shown below

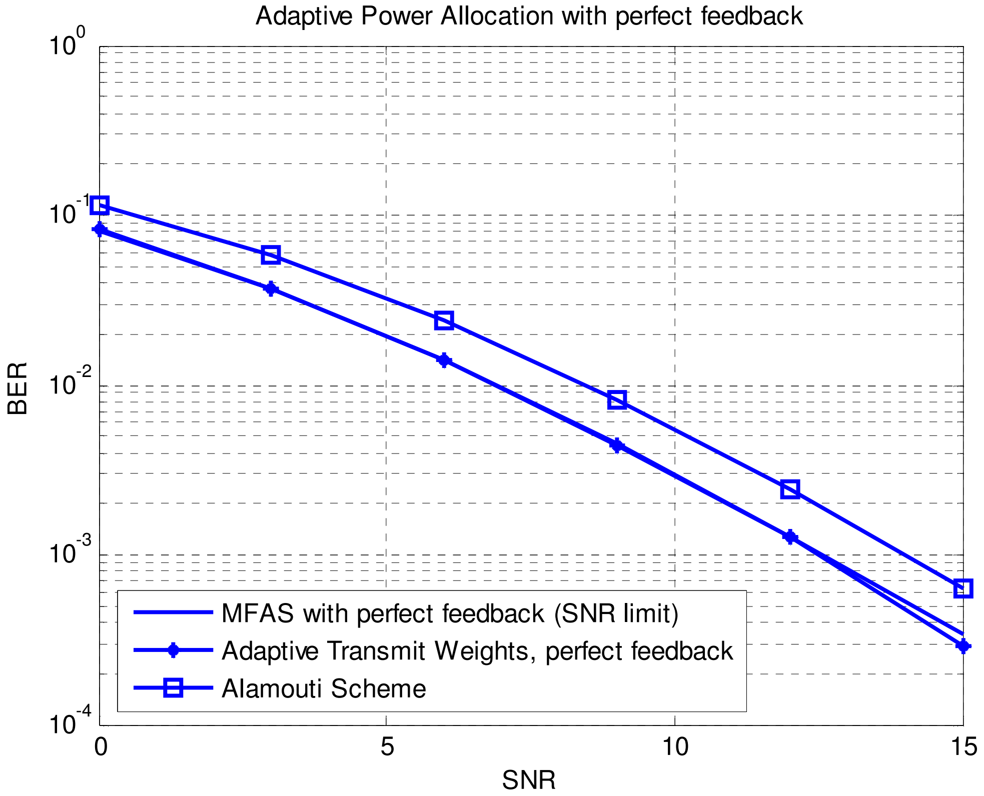


Figure 6.4 BER versus SNR curves for adaptive power allocation schemes with perfect feedback (2 TX, 1RX, BPSK).

Figure 6.4 shows the BER versus SNR performances of the three systems indicated above. As we can see from the plot, both adaptive power allocation schemes have the same BER performance and have better BER performance than the Alamouti scheme in case of perfect feedback. Both MFAS and ASTTD with adaptive transmit weights allocate all its power to the transmit antenna with better fading condition, but Alamouti scheme transmits its power without knowing the channel condition.

Further, if we take a BER $=10^{-3}$, we have a saving in SNR by 1.57 dB which is a good result since the maximum that one can save on the SNR for a (2, 1) system is 1.76 dB [47]. At the SNR of 12 dB, it can be seen from the result that both MFAS & ASTTD with adaptive transmit weights improves the BER of the Alamouti scheme by 48.86%.

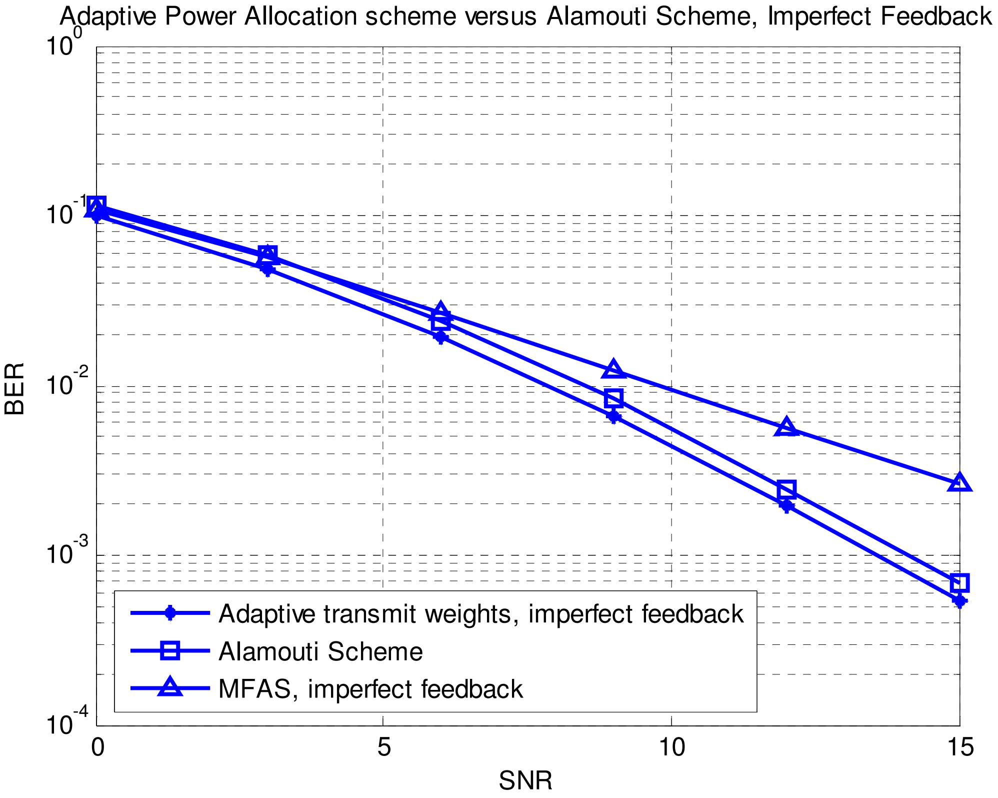


Figure 6.5 BER versus SNR curves for adaptive power allocation schemes with imperfect feedback (2 TX, 1RX, BPSK).

However, when there are feedback bit errors, the antenna selection scheme (MFAS) suffers than the ASTTD with adaptive transmit weights. It can be seen from Fig. 6.5, the saved SNR is reduced to 0.5 dB (for ASTTD with adaptive transmit weights) at a BER of 10^{-3}, but Alamouti scheme has a better SNR saving than the MFAS with imperfect feedback (about 1 dB) at a BER of 10^{-2}. At an SNR of 12 dB, it is obvious that ASTTD with adaptive transmit weights system has minimum error improvement than the Alamouti scheme, which is a 20.4% improvement. But Alamouti scheme has better error rate performance than MFAS in case of imperfect feedback. MFAS suffers from BER performance in case imperfect feedback because it may allocate all its power to the transmitting antenna with worse channel condition.

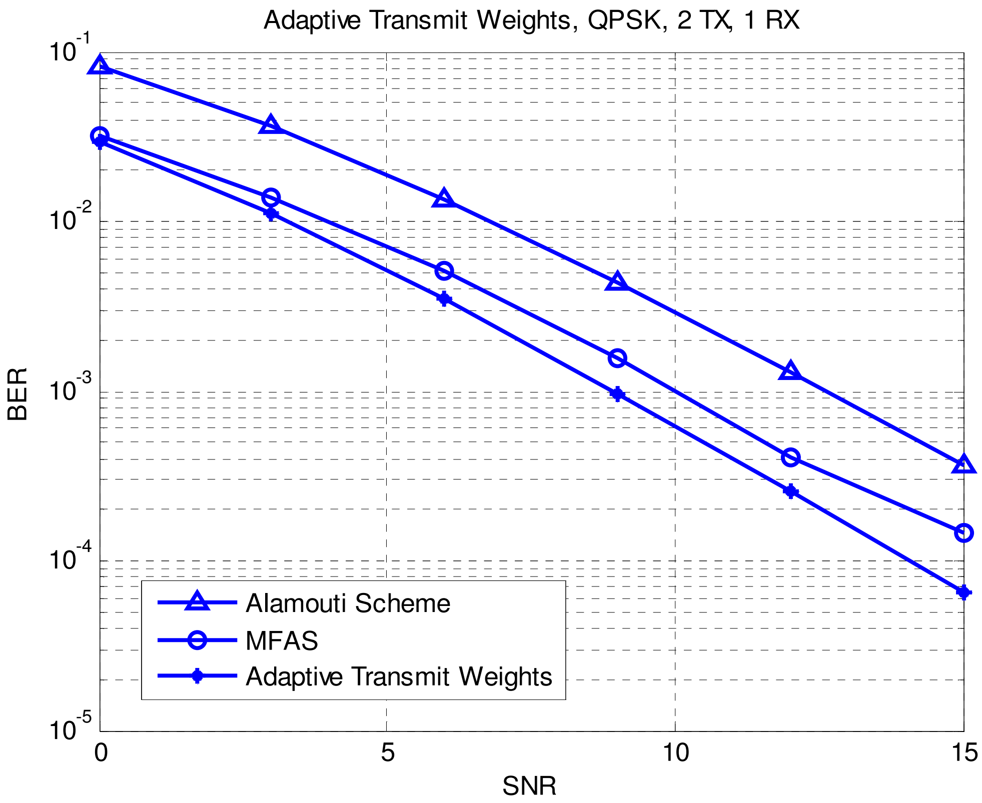


Figure 6.6 BER versus SNR curves for adaptive power allocation schemes with perfect feedback (2 TX, 1RX, QPSK).

What about the effects of rate (changing from the BPSK to QPSK)? Adaptive transmit weights scheme has a better error rate than the MFAS and Alamouti scheme. The simulation plot is shown below, in Figure 6.6.

At BER of 10^{-3}, ASTTD with adaptive transmit weights have a saving of 3.5 dB, MFAS have 2.5 dB SNR saving. At an SNR of 12 dB SNR, we can see that ASTTD with adaptive transmit weights will improve the error rate performance of the Alamouti scheme by 80% and, the MFAS scheme will improve it by 67.8%.

6.3. Adaptive Space-Time Modulation

The system block diagram is given below:

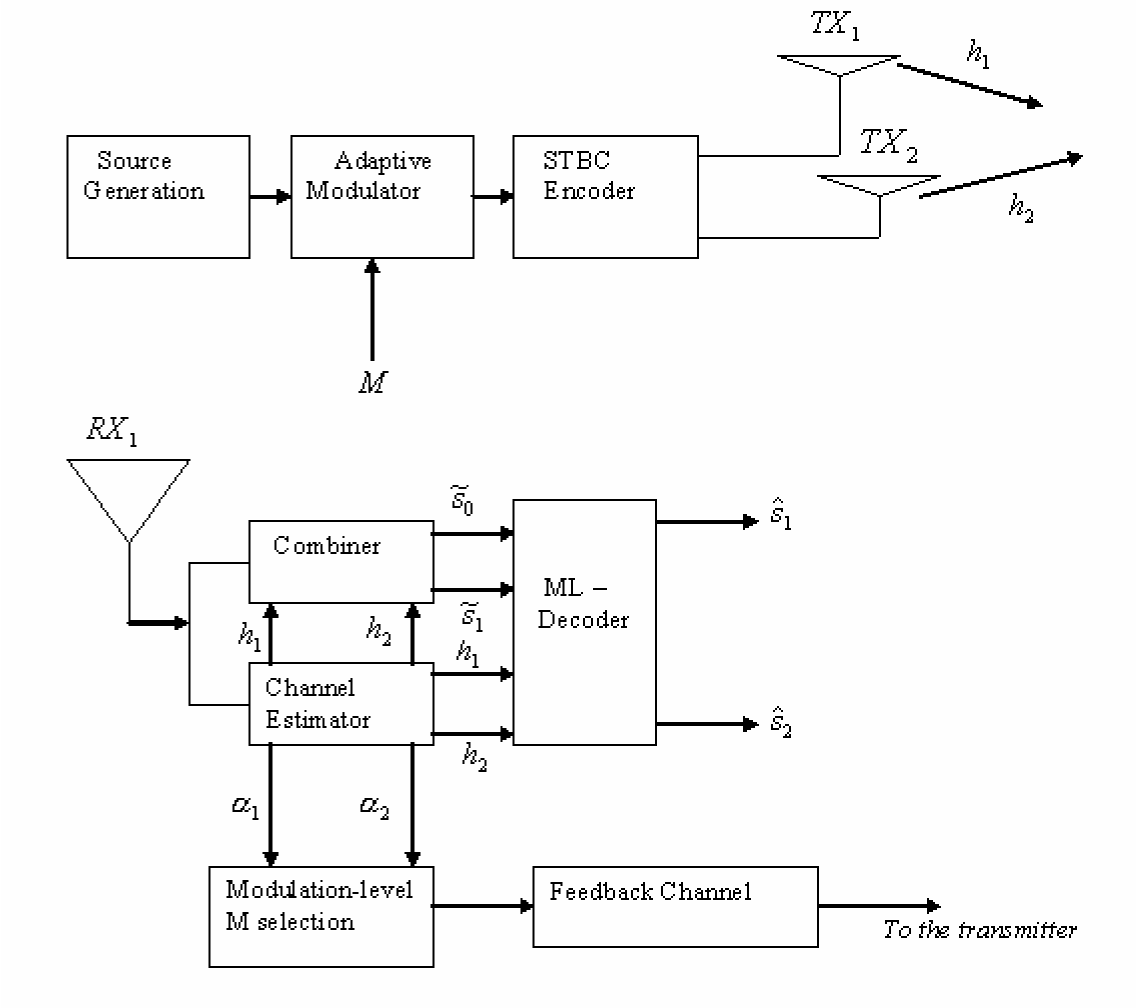


Figure 6.7 Adaptive Space – Time Modulation

Forward Link

Based on the platform of space – time transmit diversity system, we can implement the adaptive modulation.

1) Random binary bits are produced by some digital source, with output bit stream: $\{b_i\}$
2) The bits are modulated using M – PSK in which M is varied according to the channel condition.
3) After this process, the modulated symbols are encoded using space – time block encoder.
4) The encoded symbols are transmitted on the two different transmit antennas, spaced enough (0.5λ) to fade independently.

5) The output signals from each of the two antennas are all, independent, experiencing a flat Rayleigh fading channel. As they add up in space and arrive at the single receive antenna, AWGN is added, resulting in the received signal sequence:

$$r_1 = h_1 s_1 + h_2 s_2 + n_1$$
$$r_2 = -h_1 s_2^* + h_2 s_1^* + n_2$$

6) The channel model here is a flat Rayleigh fading channel and no other fading channel model is considered.
7) Assuming the receiver has perfect knowledge of the channel, the output of the combiner, $\tilde{s}_1$ and $\tilde{s}_2$, that are sent to the maximum likelihood detector:

$$\tilde{s}_1 = h_1^* r_1 + h_2 r_2^*$$
$$\tilde{s}_2 = h_2^* r_1 - h_1 r_2^*$$

8) The ML- detector makes decisions to choose s_i according to the decision rule:

$$d^2(\tilde{s}_1, s_i) \le d^2(\tilde{s}_1, s_k) \quad \forall i \ne k$$

9) Calculates bit error rate of the system. It can be calculated by dividing the number of bits in error by number of bits generated.

Feedback Link:

1) The feedback processing starts in the channel parameter estimator on the receiver side. Periodically, once every 2 transmitted symbol in the forward link, the channel estimates are sent to the transmitter.
2) The square of the channel estimates ($\alpha_1^2 = |h_1|^2$ and $\alpha_2^2 = |h_2|^2$) will be used to decide the constellation size of the adaptive modulator. M is selected based on the calculated value of '*h*' in which the system will search *h* and if it lies within the given fading region, the system will select the respective constellation size for modulation (refer to table II).
3) The selected constellation size will be feedback to the transmitter.
4) The transmitter uses the same channel information to decide on the transmit weights until new feedback arrives and the channel information is updated.

The simulation result is shown below (Fig. 6.8):

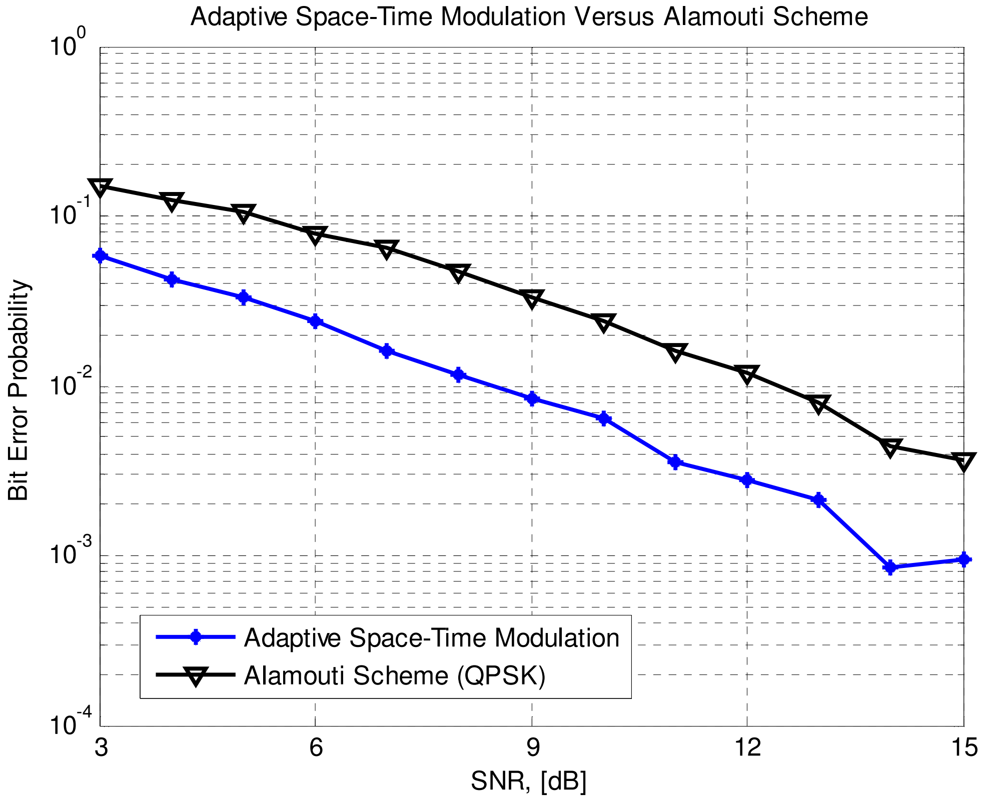


Figure 6.8 Comparison of Adaptive Space Time Modulation with Alamouti Scheme (QPSK).

Adaptive space – time modulation (ASTM) can improve the system BER performance as it is shown above. ASTM selects the appropriate modulation (BPSK, QPSK, e.t.c) depending on the favorable channel condition. Figure 6.8 and 6.9 shows the bit error rate improvement which is done by adaptive space – time modulation and compared with Alamouti scheme for the case of QPSK and BPSK respectively.

It is found out that the adaptive modulation schemes reach the target BER (10^{-3}) at a lower SNR than the Alamouti scheme (QPSK). This means for AM + STTD to reach the target BER, it will take an SNR of 14 dB whereas for Alamouti scheme (QPSK) it doesn't attain the target BER at this SNR. But for the BER of10^{-2}, adaptive space – time modulation scheme has a SNR saving of 4 dB. It can also be shown that at an SNR of 12 dB, it is found that AM + STTD with perfect feedback improves the bit error rate of the Alamouti scheme by 76.98%.

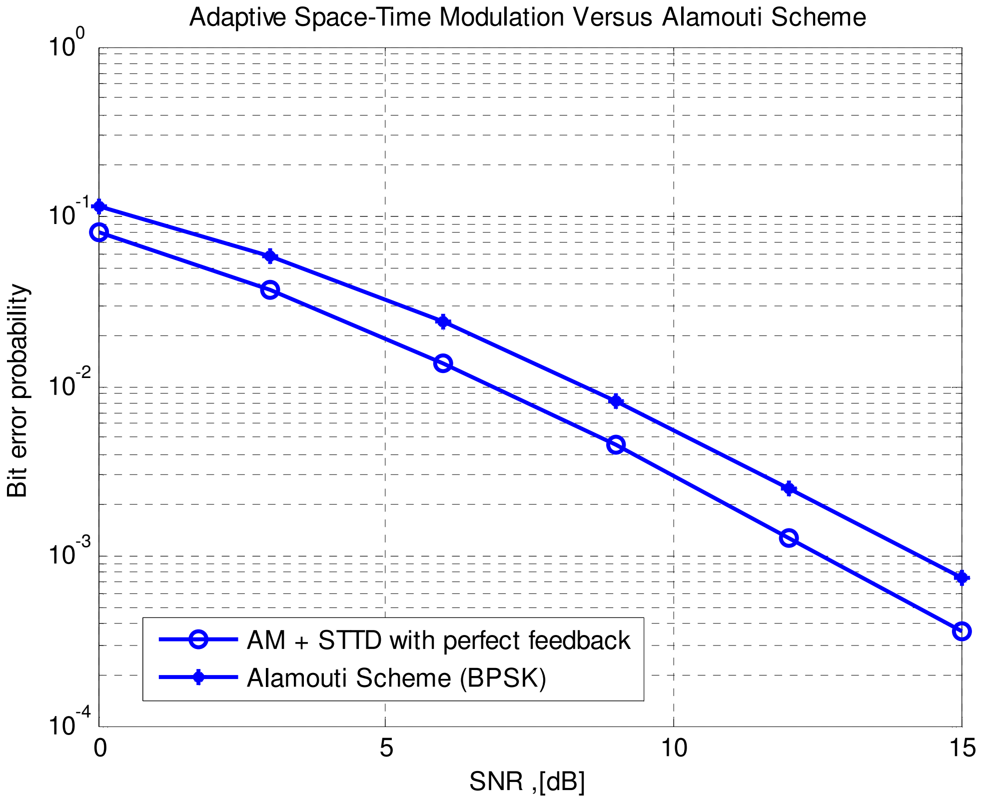
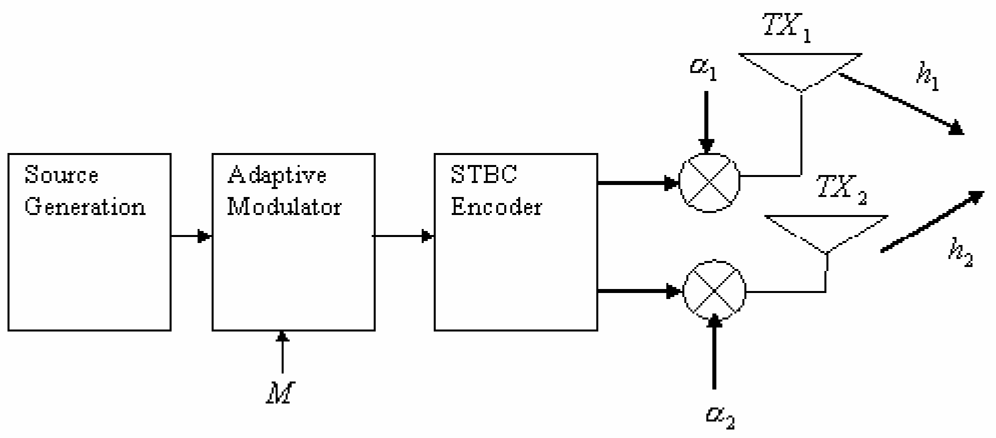


Figure 6.9. Comparison of adaptive space-time modulation with Alamouti (BPSK).

It is found out that the adaptive modulation schemes reach the target BER (10^{-3}) at a lower SNR than the Alamouti scheme (BPSK). This means for AM + STTD to reach the target BER, it will take an SNR of 12.5 dB whereas for Alamouti scheme (BPSK) it attain the target BER at an SNR of 14.25 dB. Adaptive space – time modulation scheme has a SNR saving of 1.75 dB. It can also be shown that at an SNR of 12 dB, it is found that AM + STTD with perfect feedback improves the bit error rate of the Alamouti scheme by 49.1%.

6.4. Combined adaptive modulation and power allocation for space-time block coded systems.

The system block diagram is shown below:



a) Transmitter Side

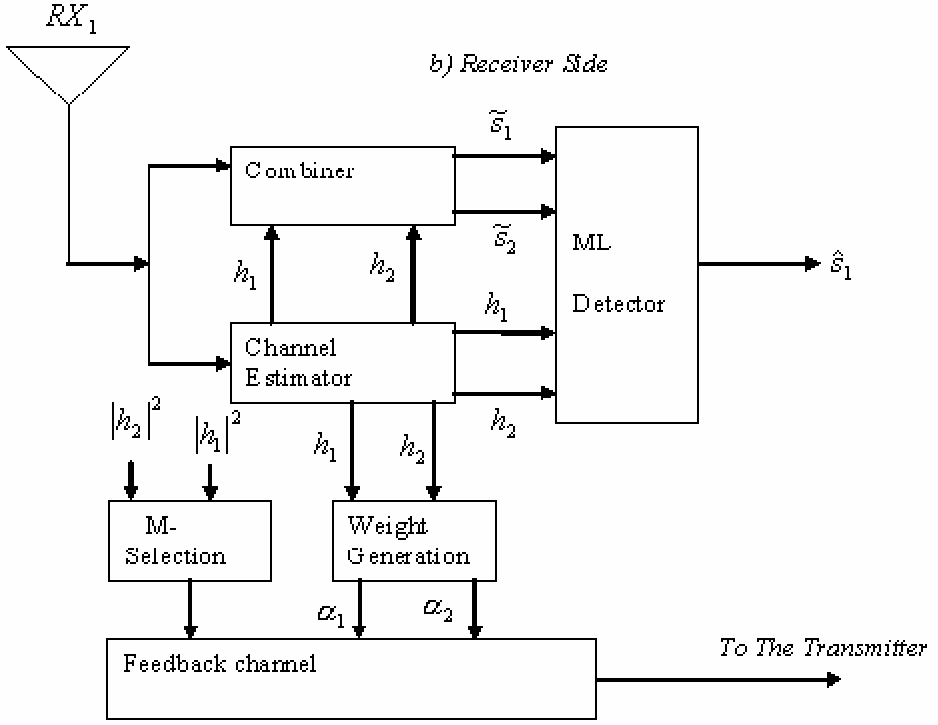

b) Receiver Side

Figure 6.10 System Model for the given combined adaptive scheme.

Forward Link:

1) Random binary bits are generated with output bit stream $\{b_i\}$
2) The bits are modulated using an adaptive modulation that uses a varying constellation size (M-PSK)
3) The symbols coming from the modulator are encoded using a space – time block encoder.
4) Prior to transmission, the encoded data will be multiplied by adaptive transmit weights, α_1 and α_2, producing an output sequence from each of the antennas.
5) The output signals from each of the two antennas are all, independent, experiencing a flat Rayleigh fading channel. As they add up in space and arrive at the single receive antenna, AWGN is added, resulting in the received signal sequence:

$$\begin{aligned} r_1 &= h_1 s_1 + h_2 s_2 + n_1 \\ r_2 &= -h_1 s_2^* + h_2 s_1^* + n_2 \end{aligned}$$

6) The channel model here is a flat Rayleigh fading channel and no other fading channel model is considered.
7) Assuming the receiver has perfect knowledge of the channel, the output of the combiner, $\tilde{s}_1$ and $\tilde{s}_2$, that are sent to the maximum likelihood detector:

$$\begin{aligned} \tilde{s}_1 &= h_1^* r_1 + h_2 r_2^* \\ \tilde{s}_2 &= h_2^* r_1 - h_1 r_2^* \end{aligned}$$

8) The maximum likelihood detector decides which symbols to receive

$$d^2(\tilde{s}_1, s_i) \leq d^2(\tilde{s}_1, s_k) \quad \forall i \neq k$$

9) Calculates the bit error rate of the system. In the simulation, the bit error rate is calculated by dividing the number of bits in error by the total number of bits generated.

Feedback Link:

1) The feedback processing starts in the channel parameter estimator on the receiver side. Periodically, once for every 2 transmitted symbol in the forward link, the channel estimates are sent to the transmitter.
2) The decoded feedback channel estimates will decide the constellation size of the adaptive modulator. M is selected based on the calculated value of '*h*' in which the

system will search *h* and if it lies within the given fading region, the system will select the respective constellation size for modulation. The constellation size of AM + STTD scheme is selected based on $\sqrt{\frac{(\alpha_1^2+\alpha_2^2)}{2}}$, where $\alpha_1^2 = |h_1|^2$ and $\alpha_2^2 = |h_2|^2$.

3) In case of adaptive transmit weights, the decoded channel estimates are used to calculate the transmit weights. The weights are chosen as:

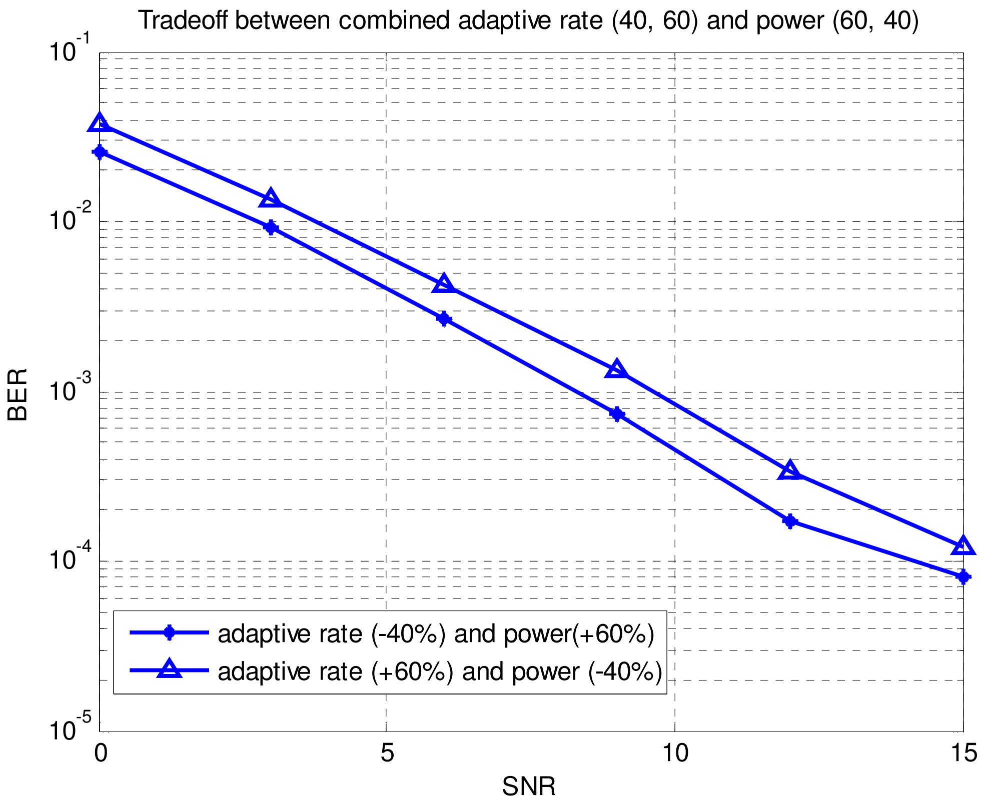
$$\alpha_1 = \frac{1}{\sqrt{1+\left(\frac{|h_2|}{|h_1|}\right)^4}}, \text{ and } \alpha_2 = \frac{1}{\sqrt{1+\left(\frac{|h_1|}{|h_2|}\right)^4}}$$

Combined adaptive rate and power scheme	Percentage (%) of system 1 (randomly selected)	Percentage (%) of system 2 (randomly selected)
Percentage by which we increase the rate	+ (60, 70, 80)	- (40, 30, 20)
Percentage by which we increase the power	- (40, 30, 20)	+ (60, 70, 80)

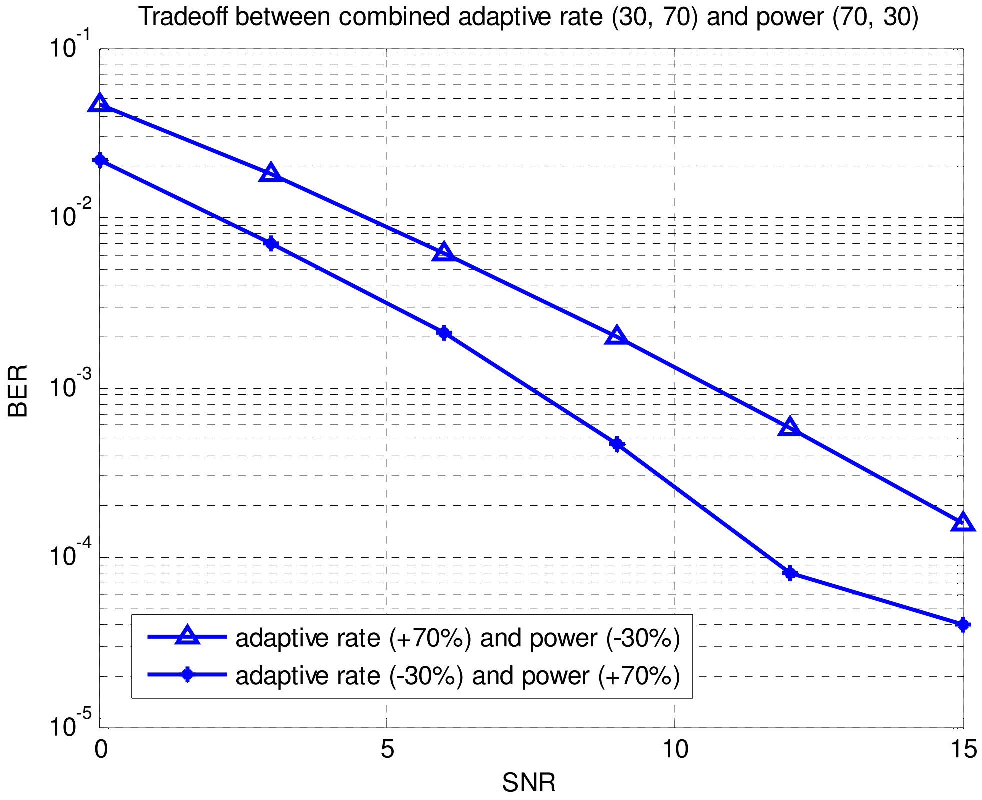
The transmitter uses the same channel information to decide on the transmit weights until new feedback arrives and the channel information is updated. Here, decision variable for the selection of the constellation size and the above transmit weights, α_1 and α_2, will be multiplied by randomly selected percentage (refer Table IV)

5) When the system needs more rate and less power for transmission it increases the rate by 60%, 70%, 80% and decrease the power by 40%, 30%, 20% and vice versa.

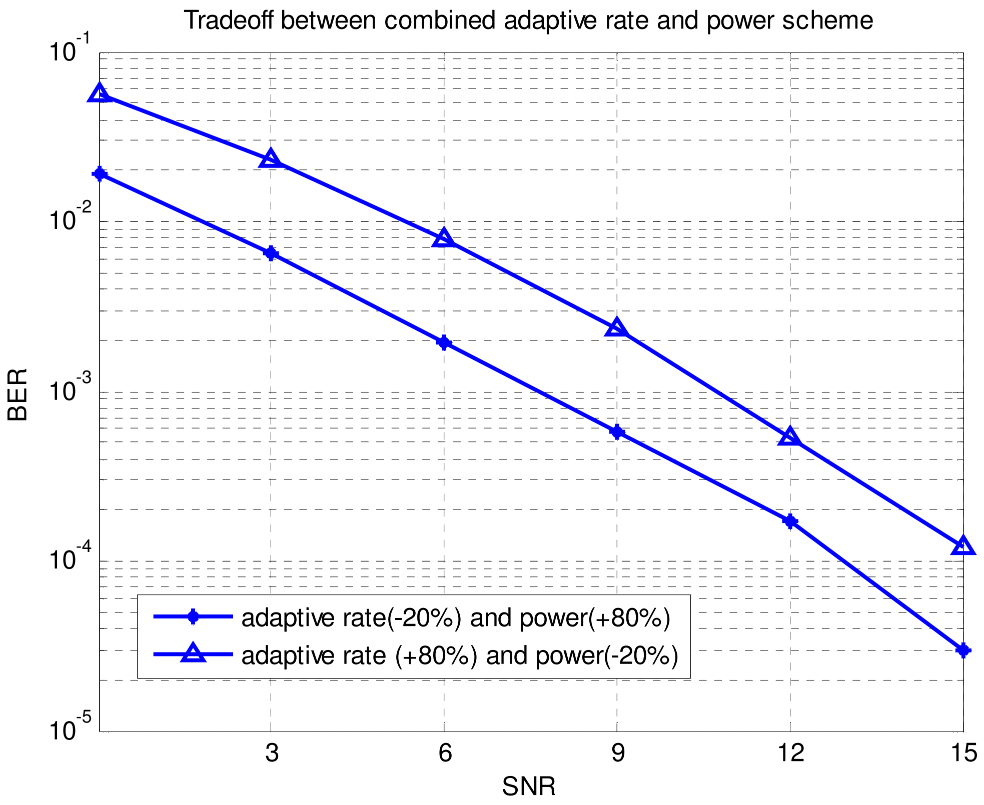
Table IV. Random Percentage Used for adapting the rate and power.


Tradeoff between combined adaptive rate (40, 60) and power (60, 40)
BER
SNR
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
5
10
15
adaptive rate (-40%) and power(+60%)
adaptive rate (+60%) and power (-40%)

(a)


Tradeoff between combined adaptive rate (30, 70) and power (70, 30)
BER
SNR
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
5
10
15
adaptive rate (+70%) and power (-30%)
adaptive rate (-30%) and power (+70%)

(b)



(c)

Figure 6.11. Tradeoff between different percentages of adaptive rate and power schemes.

The above systems are used to vary both the data rate and the transmitted power of the system with different percentage. It is found that increasing the power (and reducing the rate) has better error rate performance than increasing the rate (and reducing the power) of the system.

Complexity Comparison:

This work investigated the performance of adaptive space – time transmit diversity schemes and compared it with space – time transmit diversity. The simulation results show that adaptive space – time transmit diversity scheme has a better error rate performance than the open loop transmit diversity. To achieve this improved performance we should pay the price in bandwidth, processing time, hardware complexity and feedback delay.

1) Bandwidth

Since adaptive space – time transmit diversity has a dedicated feedback channel which needs allocated bandwidth for transmission. The bandwidth allocated for adaptive space – time transmit diversity is greater than space – time transmit diversity even if the feedback channel is limited in bandwidth. Quantization of the feedback information is recommended to save bandwidth.

2) Processing Time

It is clear that adaptive space – time transmit diversity needs much processing time than the space – time transmit diversity. This adaptive scheme will perform comparison, selection, generation of transmit weights and allocation of power so that it takes long processing time than the Alamouti scheme. Prediction algorithm such as long range channel fading prediction enable the system to overcome the effects of feedback non-idealities as well as reducing the processing time.

Schemes	Alamouti Scheme	Adaptive Power Allocation	Adaptive Space – Time Modulation
Processing Time	184.06 seconds	362.85 seconds	398.5 seconds

Table V. Processing Time for the schemes used in the analysis.

3) Hardware Complexity

Due to the allocation of external feedback channel in the adaptive space – time transmit diversity systems it is more hardware complex than the space – time transmit diversity. The techniques we employ to improve the feedback non-idealities will incur additional hardware complexity to the system.

Chapter 7

Conclusion & Future Work

Conclusion

In this work, we provide analysis of adaptive space-time transmit diversity schemes. Our analysis is evaluated on a flat Rayleigh fading channel model. Especially, we consider two adaptive space-time transmit diversity schemes and try to compare them with the open loop transmit diversity (non-adaptive transmit diversity).

This work had two parts: in the first, which came mainly in chapter 4, we discussed the principles and classifications of transmit diversity. We mainly focus on the classical Alamouti scheme for the open loop transmit diversity and adaptive transmit array (TXAA) for the closed loop transmit diversity. Based on the principles we mentioned for transmit diversity; it is showed that a closed loop schemes which are adaptive in nature provide a better error rate performance than the open loop transmit diversity.

Also in the second part of this work we discussed adaptive space-time transmit diversity schemes which came in two ways: adaptive power allocation scheme and adaptive space-time modulation. We have shown that under ideal perfect feedback condition; adaptive schemes provide better error rate performance. We also showed that adaptive schemes suffer in error rate performance in case of imperfect feedback.

This work tried to show the tradeoff between the combined adaptive rate and power scheme and it is shown that increasing the power and reducing the rate has better error rate performance than reducing the rate and increasing the power. This kind of improvement has achieved by paying the price in bandwidth, processing time and hardware complexity.

Future Work

The research presented in this thesis has been concentrated on adaptive space-time transmit diversity schemes. The simulation showed that ASTTD schemes have a better bit error rate (BER) performance than the open loop transmit diversity in case of a perfect feedback. This work can be extended to:

- One can also examine a scheme which combines ASTTD schemes with adaptive long-range fading channel prediction (LRP) algorithm for improving the bit error rate performance in case of imperfect feedback.
- In this work, adaptive space – time transmit diversity used space – time block code for the encoder and one can investigate this scheme using space – time trellis coding.
- One can investigate how to improve the feedback non-idealities (error, delay, and quantization error and feedback period impact) of adaptive space-time transmit diversity systems.
- One can investigate the effect of signal – to – noise ratio (SNR) improvement on the data rate of the system.
- One can investigate these ASTTD schemes using more than two antennas at the transmitter side and more than one antenna at the receiver which is the case of MIMO systems.

  - Including Near – far problem and more number of users.