The Chinese University of Hong Kong

Space-Time Block Coding in Wireless Communications

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Abstract

Wireless technology has become vital in modern life as it provides various applications to users. Entertainment, workplace duty, social connection and many more functions are all supported by one single mini smartphone and the wireless communication scheme it employed. This thesis reviews the multi-input-multi-output wireless transmission model and multi-input-single-output broadcasting schemes. With the incentive to reduce the number of antennas required on the receiver side to match the real-life limitation in mobile cellular communication, space-time coding is developed. In particular, the Alamouti code, the orthogonal space-time block codes, the quasi-orthogonal space-time block codes and the diagonal algebraic space-time codes are studied and their respective fundamentals, together with simulation results, are examined, presented and discussed. Stochastic beamforming technique, as another approach to achieve common information broadcasting, is also introduced in this thesis. The evaluation on the Error Rate to SNR performance reveals that the choice of a STBC implementation is basically the trade-offs between the four parameters: rate, diversity, simplicity and performance. Moreover, SBF is able to provide a very promising result.

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Chapter 1

Introduction

Ever since the promotion of cellular communication in the telecom industry, wireless communication technology has long been established and the system performance has been enhanced due to the maturity of multiple antenna transceiver technology, famously known as Multiple-Input Multiple-Output (MIMO) technology. In modern days, wireless mobile devices have become an essential element of human life, that one can access the librarian-like internet through a palm-sized devices like smartphone. Through wireless technologies, satellite networks even enable people to communicate across borders and information is hence distributed globally, whereas financial and economic industry take the benefit of perfect information, which is a desirable condition for market economy. The vision of a better world can be accomplished with communication technology advancement.

With more functions that a single devices can achieve, the next generation of wireless communication technology is expected to support some key features such as faster transmission, higher band efficiency, wider coverage and availability.

One advantage of applying MIMO in wireless communication systems is the nature of spatial multiplexing, that is, the maximum number of data streams being sent at every time instance can be multiplied by the number of antenna at the transmitter side. However, parallel transmission of multiple signals in wireless channel may cause interference between streams, and with the occurrences of the channel fading effect the data streams may be severely distorted and message reconstruction can be a very challenging problem. Therefore, different detection schemes designed for MIMO communication schemes are developed to encounter such channel distortion. For instance, Zero-Forcing detection and Maximum-likelihood detection are two exemplary detection methods. Moreover, adopting various transmission schemes, such as beam-forming, precoding and space-time coding, causes various performance trade-offs.

In most situations, the size limitation and cost affordability of the base station is far better than the user terminal since it is rare for mobile users having a device attached with the same number of antennas of the base station, which will result in a large physical size. With such presumption, recent developments in smartphone furthered the demand in a transmission scheme where less antenna number is required on receiver devices so that the magnification in physical size of the mobile phone could be prevented. Space-time block coding are hence proposed to handle drawbacks in size of remote units while enjoying the benefits of multiple antenna systems.

This thesis focuses on the discussion where common information is broadcast through a wireless quasi-static fading channel, where the downlink open-loop scenario is assumed. We also assume that perfect channel state information (CSI) is available at the receiver but not at the transmitter. In such a scenario, the base station needs to broadcast messages to the air blindly, without regard to the position and channel state of the user terminal. Space-time block coding is a technique which is suitable to and commonly employed in common information broadcasting scenarios.

The objective of this thesis is to delve into the principles of space-time block codes, and to examine the performance through simulations. Different types of space-time block codes will be introduced and their respective performance will be analyzed. Further studies on other methods for blind broadcasting will also be included and respective performance will be compared to space-time block codes.

Chapter 2

Background

2.1 Wireless Multiple Antenna Systems

In a one-to-one wireless communication system, signals are sent through an unpredictable environment and it may arrive receiver through several channels. Due to the obstacles between transmitter and receiver, each pathway has its own behaviour and channel response is varied in terms of amplitude attenuation, time delay variation, incident angle deviation, and so on. Moreover, if there are more than one user accessing the same frequency channel, signals may distort each other. Seriously distorted signals lead to poor system performance in the sense of error probability, and therefore wireless communication systems must be designed with the capability to resist such multipath fading and cochannel interference.

To enhance wireless system performance, multi-antenna systems are adopted to increase data reliability. With multiple antennas at the receiver side, it is obvious that multiple copies of the desired signal are received and hence average signal to noise ratio is enhanced, resulting in lower error probability and better system performance. Furthermore, as spatial diversity can be attained with multiple antenna located in either side of transmitter or receiver, multi-antenna systems are therefore widely adopted in wireless communications to accomplish better system performance.

Multi-antenna wireless systems can be categorized in four types, with regards to the number of antenna embedded on the transmitter and receiver side respectively. The categories are single-input single-output (SISO), single-input multi-output (SIMO), multi-input single-output (MISO) and multi-input multi-output (MIMO), where MIMO is the most generalized case of the other three cases, therefore MIMO is the terminology most widely used to refer multi-antenna communication systems. In this project, we mainly focus on MISO system since the number of receiver antenna attached to remote unit is often limited while base station can support massive number of transmitter antenna.

2.2 The MIMO System Model

To understand MIMO system, consider the following case of which there are two antenna per transceiver in a communication system as depicted in Figure 2.1. Let the channel coefficient between path ith transmitter and the jth receiver be denoted as $h_{i,j}$ for $(i,j) = \{1,2\}^2$. Assume the first antenna is sending symbol streams $x_1(t)$ while the second is sending another stream $x_2(t)$. The received signals at first antenna of the receiver is

$$y_1(t) = h_{1,1}x_1(t) + h_{2,1}x_2(t) + \nu_1(t)$$

and similarly for the second receive antenna

$$y_2(t) = h_{1,2}x_1(t) + h_{2,2}x_2(t) + \nu_2(t)$$

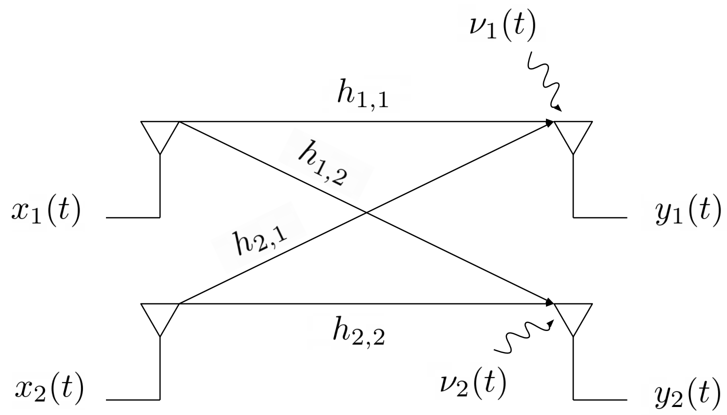


Figure 2.1: Illustration of Two Signals being Transmitted to Two Users

where $\nu_i(t)$ for $i = 1, 2$ are the background noise component added in during the transmission. Here, $h_{i,j}$'s are some *channel coefficients*, which arbitrarily scales up or down the signal strength of the respective signals. More specifically, it is often assumed that those $h_{i,j}$'s follows complex Gaussian distribution. For convenience, we rewrite the I/O relationship in a matrix-vector form:

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} \nu_1(t) \\ \nu_2(t) \end{bmatrix}$$

or, more compactly,

$$\mathbf{y}(t) = \mathbf{H}\mathbf{x}(t) + \boldsymbol{\nu}(t). \tag{2.1}$$

More generally, it is comfortable to extend the 2-by-2 case to the N-by-N case. Let us drop the time-indexing variable t so as to focus on one time instance, that is, we will only state equation (2.1) as $\mathbf{y} = \mathbf{H}\mathbf{x} + \boldsymbol{\nu}$ for simplicity. Observe that (2.1) is of matrix-vector form, suggesting the problem of any dimension N-by-N can still be modelled by (2.1).

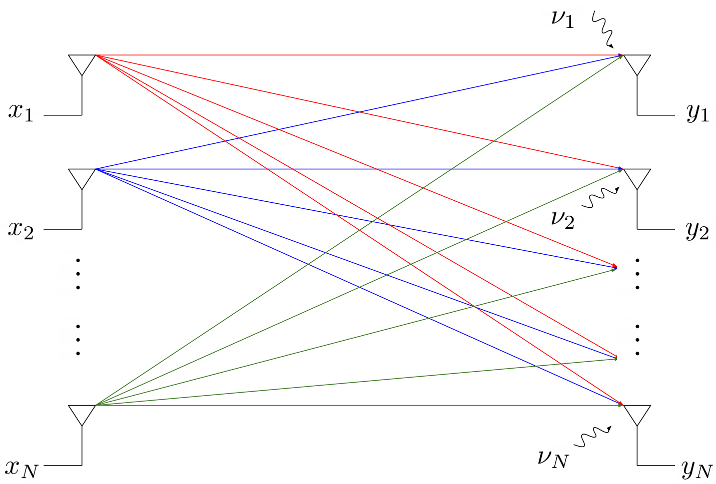


Figure 2.2: Illustration of a N-by-N MIMO System

In fact, it is obvious when you write down those n equations painfully:

$$\begin{aligned}
y_1 &= h_{1,1}x_1 + h_{1,2}x_2 + \cdots + h_{1,N}x_N + \nu_1 \\
y_2 &= h_{2,1}x_1 + h_{2,2}x_2 + \cdots + h_{2,N}x_N + \nu_2 \\
&\vdots \\
y_N &= h_{N,1}x_1 + h_{N,2}x_2 + \cdots + h_{N,N}x_N + \nu_N
\end{aligned}$$

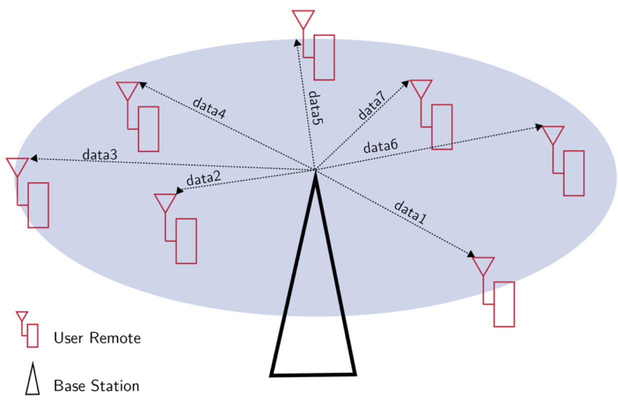
and then translate them into the following vector-matrix form:

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N,1} & h_{N,2} & \dots & h_{N,N} \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} \nu_1 \\ \nu_2 \\ \vdots \\ \nu_N \end{bmatrix}}_{\boldsymbol{\nu}}$$

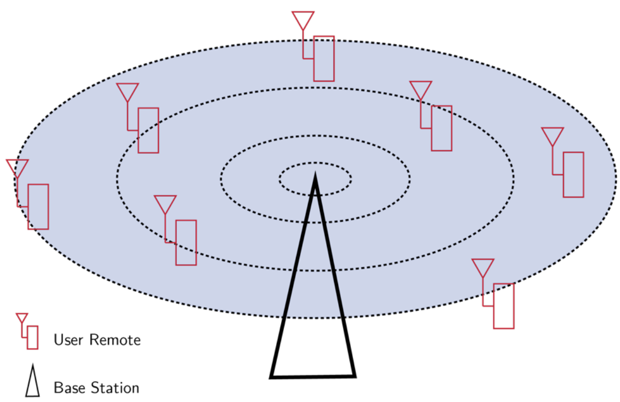
where $\mathbf{H}$ is channel matrix providing channel coefficients of each links between transmit to receive antennas; $\mathbf{x}$ denotes the transmitted signal vector; and the additive noise component is $\boldsymbol{\nu}$.

2.3 Common Information Broadcasting

In this project, as mentioned, we are considering a common information broadcasting system where the base station does not have any CSI and user remote positions. That is, without any prior knowledge on the channel characteristics and target receiver status, the transmitter at the base station cannot employ directional beamforming or precoding techniques to deliver signal with a specified scaling with respect to CSI or the optimal angle to the receiver position, in order to resist channel distortion. Under such a scenario, the transmitter can only send the signal out blindly, in other words, the signal is sent out by all angles. On the other hand, since signals are broadcasted, any remote user with one receive antenna located within the area of coverage should be able to retrieve the information. In contrast to unicast, where individual remote users are allocated with different data streams, common information are provided to any user within the network coverage under the scenario of interest. Figure 2.3a and 2.3b illustrates unicasting and broadcasting scenarios respectively.



(a) Unicast



(b) Broadcasting

Figure 2.3: Illustration of Unicast and Broadcast.

Chapter 3

Space-Time Block Coding

Space-time block coding (STBC) techniques are popular among mobile cellular systems. By employing STBC in MISO systems, data transmission reliability can be improved robustly. The idea of STBC is to send redundant copies of symbols by multiple transmission antennas, and over the time slots necessary for transmitting the same length of data stream in an SISO wireless systems. This is suggesting that STBC does not introduce any increase in transmission rate, but in fact it may even cause a slowdown in transmission speed under the employment of certain codewords without full rate.

It is also worth-mentioning that STBC schemes requires, or assumes, the wireless transmission channel to be static during the total period used to transmit the number of symbols regarding the number of transmit antennas, and essentially known by the receiver in advanced.

The importance of employing STBC, particularly in mobile cellular, is that STBC does not require the same number of antennas on both the transmitter and receiver side. The minimum distance between antennas

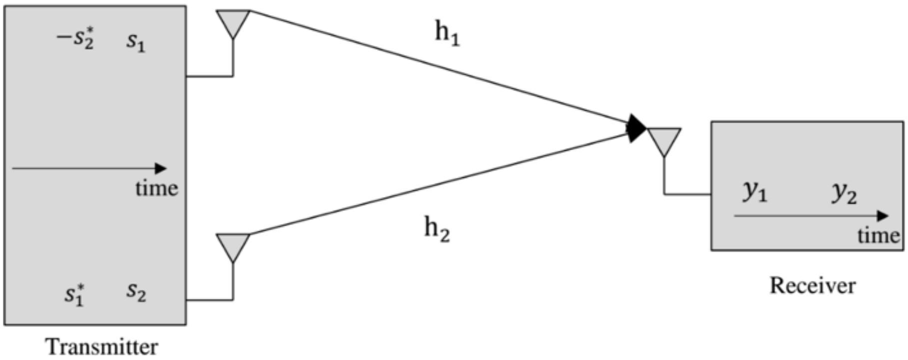


Figure 3.1: Illustration of the coding function of the Alamouti code (3.1)

is restricted by the wavelength of the spectrum being used, and hence mobile phones cannot afford to have many antennas embedded due to the physical size limitation. With only one receive antenna required, STBC schemes are suitable for cellular communication as it reduces the physical size and the average cost of each cell unit. Moreover, although multiple antennas are required on the transmitter side, base stations are capable of carrying far more antennas then cell units due to the much larger physical size. In addition, serving numerous user cell units, the economy of scale also made the average cost of the base stations with many antennas more affordable to each service users.

Among many STBC schemes, the principles of the Alamouti code, the orthogonal space-time block codes (OSTBCs), the quasi-orthogonal space-time block codes (QSTBCs), and diagonal algebraic space-time codes (DAST), which are the most general popular ones, will be discussed in this session.

3.1 Alamouti Code

The Alamouti code is the first space-time block code introduced that achieves full rate and full diversity [1]. It considers a case as illustrated in Figure 3.1. Assuming two symbols, s_1 and s_2, are being transmitted through the two channels, h_1 and h_2, during two time slots. Alamouti code will encode the transmission symbols as in the form

$$\mathbf{C}(\mathbf{s}) = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{3.1}$$

where the operation $z^* = \Re(z) - \mathrm{j}\Im(z)$ is the complex conjugate of z. To illustrate how the code works, let the data stream transmitted by antenna 1 and 2 during the time frame $t = 1, 2, \ldots, T$ be $\{x_1(t)\}_{t=1}^{T}$ and $\{x_2(t)\}_{t=1}^{T}$ respectively, we can obtain the actual transmission signal frame

$$\left\{ \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \right\}_{t=1}^{T} = \begin{bmatrix} s_1 & -s_2^* & s_3 & -s_4^* & s_5 & -s_6^* & \ldots & s_{T-1} & s_T^* \\ s_2 & s_1^* & s_4 & s_3^* & s_6 & s_5^* & \ldots & s_T & -s_{T-1}^* \end{bmatrix}$$

for the targeted symbol stream

$$\mathbf{s} = [s_1, s_2, \ldots, s_T]^T.$$

Each row of the codeword represents the signals transmitted at each time instant, while each column represents each data stream sent by each transmit antenna. The corresponding received signal model will be:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix},$$

or more compactly,

$$\mathbf{y} = \mathbf{C}(\mathbf{s})\mathbf{h} + \boldsymbol{\nu}. \tag{3.2}$$

Note that elements of $\mathbf{y}$ are not received at the same instance, but were simultaneously collected by the receive antenna. Here, for simplicity, $y(1)$ and $y(2)$ are represented by y_1 and y_2 respectively.

Alamouti code itself does not act like MIMO communication, but interestingly, through some linear operations, the code demonstrates similarities with the spatial multiplexed signal model (2.1). The key is to find the equivalent virtual MIMO channel matrix (EVCM), which can be obtained by taking complex conjugate on y_2:

$$\begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} \nu_1 \\ \nu_2^* \end{bmatrix},$$

or simply put

$$\widetilde{\mathbf{y}} = \mathbf{H}_{\mathsf{EVCM}}\mathbf{s} + \widetilde{\boldsymbol{\nu}}. \tag{3.3}$$

The EVCM enables the 2×1 STBC system to perform as a general 2×2 MIMO system. As compared to the regular random MIMO channels, EVCM of Alamouti code is orthogonal by nature:

$$\mathbf{H}_{\mathsf{EVCM}}^H\mathbf{H}_{\mathsf{EVCM}} = \begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix} \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} = \|\mathbf{h}\|_2^2\mathbf{I}.$$

Using such orthogonality, the Alamouti code can be decoded *linearly*:

$$\mathbf{s}^\star = \mathbf{H}_{\mathsf{EVCM}}^H\widetilde{\mathbf{y}} = \|\mathbf{h}\|_2^2 \cdot \mathbf{s} + \mathbf{H}_{\mathsf{EVCM}}^H\widetilde{\boldsymbol{\nu}}$$

which is approximately a scaled version of $\mathbf{s}$ when the background noise term $\boldsymbol{\nu}$ is negligible. Although the maximum-likelihood detector can also be applied to Alamouti coded signals, the above approach offers a detection method with much lower complexity by simply making use of orthogonal properties.

3.2 Orthogonal Space-time Block Code

With the inspiration of the Alamouti code, researches on higher order orthogonal space-time block code were conducted. For general real orthogonal designs, full rate code exist for any $N \times 1$ systems. However, it has been proven that complex orthogonal design only exists for order 2 STBCs, which is the Alamouti code [15]. It has also been shown that in order to obtain orthogonality, transmission rate has to be reduced for $N > 2$ [11]. In pursuing higher order OSTBC, the codeword for $N = 3$ and $N = 4$ with rate 1/2 and 3/4 are proposed in [15]:

$$\mathbf{C}_3^{1/2}(\mathbf{s}) = \begin{bmatrix} s_1 & s_2 & s_3 \\ -s_2 & s_1 & -s_4 \\ -s_3 & s_4 & s_1 \\ -s_4 & -s_3 & s_2 \\ s_1^* & s_2^* & s_3^* \\ -s_2^* & s_1^* & -s_4^* \\ -s_3^* & s_4^* & s_1^* \\ -s_4^* & -s_3^* & s_2^* \end{bmatrix} \text{ and } \mathbf{C}_4^{1/2}(\mathbf{s}) = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix}.$$

Here, $\mathbf{C}_3^{1/2}(\mathbf{s})$ and $\mathbf{C}_4^{1/2}(\mathbf{s})$ are transmitting 4 symbols during 8 time slots using 3 and 4 antennas respectively; while

$$\mathbf{C}_3^{3/4}(\mathbf{s}) = \begin{bmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3^*}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{(-s_1 - s_1^* + s_2 - s_2^*)}{2} \\ \frac{s_3^*}{\sqrt{2}} & \frac{-s_3^*}{\sqrt{2}} & \frac{(s_1 - s_1^* + s_2 + s_2^*)}{2} \end{bmatrix}$$

transmits 3 symbols in 4 time slots using 3 antennas; and

$$\mathbf{C}_4^{3/4}(\mathbf{s}) = \begin{bmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3^*}{\sqrt{2}} & \frac{-s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{(-s_1-s_1^*+s_2-s_2^*)}{2} & \frac{(s_1-s_1^*-s_2-s_2^*)}{2} \\ \frac{s_3^*}{\sqrt{2}} & \frac{-s_3^*}{\sqrt{2}} & \frac{(s_1-s_1^*+s_2+s_2^*)}{2} & \frac{(s_1+s_1^*+s_2-s_2^*)}{2} \end{bmatrix}$$

does the same using 4 antennas. These orthogonal designs are clear enough to verify the trade-off between data rate and orthogonality. However, for rate = 3/4, the signal transmission power is unevenly distributed among the space-time domain. Addressing this problem, the revised version of order 4 OSTBC that provide is proposed in [5]:

$$\mathbf{C}_{4,\mathsf{revised}}^{3/4}(\mathbf{s}) = \begin{bmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_3 \\ -s_3^* & 0 & s_1^* & -s_2 \\ 0 & -s_3^* & s_2^* & s_1 \end{bmatrix}.$$

The above code has same transmission power among the whole space-time domain with respect to each instance when antenna is active. Power among active antenna and time slots is equally distributed.

Nevertheless, the unsolved problem of higher order OSTBC is the incapability to achieve full rate transmission. In fact, previous researches have proven that orthogonal space-time block code with complex number constellation can only achieve the maximum rate of 3/4 for , despite the existence of full rate code for real orthogonal designs [15].

In order to combat the slower code rate in exchange of orthogonality, a special approach in data vector generation has to be employed when comparing this code with full rate codes. Assume that the data constellation employed in other comparable schemes is BPSK, so each symbol carries one bit. For a system attached with 4 transmit antennas, the symbol vector carries 4 bits in total. Then the modified symbol vector of OSTBC shall be

$$\mathbf{s} = \begin{bmatrix} s_1 & s_2 & s_3 \end{bmatrix}^T$$

where

$$(s_1, s_2) \in \{-1, 1\}^2, \qquad \text{and} \qquad s_3 \in \{1 + \mathrm{j}, 1 - \mathrm{j}, -1 + \mathrm{j}, -1 - \mathrm{j}\}.$$

With the first two symbols employed with BPSK, while 4-ary QAM, having 2 bit/symbol, employed by the last symbol, the modified data stream is carrying 4 bits in total, which fits with the data rate of the symbol vector of other comparable schemes. While it is slightly more complicated in the sense of symbol vector generation, bit rate equality is however maintained for OSTBC to compare with other spatial multiplexing schemes.

Having said so, the attempt to seek for full rate code for $N > 2$ still intrigues researchers. Quasi-orthogonal space-time block code (QSTBC) is hence developed. In the next section, the principles of QSTBC will be discussed.

3.3 Quasi-Orthogonal Space-time Block Code

The quasi-orthogonal space-time block codes were first introduced in [7]. The idea behind is simply extending the Alamouti code into a codeword of order 2^k, implying that a QSTBC only exists for systems of transmit antenna number $N = 2, 4, 8, 16$ and so on. QSTBCs are able to provide full transmission rate for complex constellation signals, but of no full diversity except for $N = 2$. An order 4 QSTBC codeword can be defined as follows:

$$\begin{aligned}
\mathbf{C}_4^{\mathsf{QOSTBC}}(\mathbf{s}) &= \begin{bmatrix} \mathbf{C}_2^{\mathsf{Alam}}(s_1, s_2) & \mathbf{C}_2^{\mathsf{Alam}}(s_3, s_4) \\ -[\mathbf{C}_2^{\mathsf{Alam}}(s_3, s_4)]^H & [\mathbf{C}_2^{\mathsf{Alam}}(s_1, s_2)]^H \end{bmatrix} \\
&= \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -s_4^3 & s_3^* \\ -s_3^* & -s_4^* & s_1^* & s_2^2 \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix}
\end{aligned} \tag{3.4}$$

which transmits 4 symbols via 4 antennas during 4 time-slots, desirably fulfils the objective of attaining full rate transmission. The signal model is demonstrated as

$$\mathbf{y} = \mathbf{C}_4^{\mathsf{QOSTBC}}(\mathbf{s})\mathbf{h} + \boldsymbol{\nu}. \tag{3.5}$$

By the same analysis in Alamouti code, obtaining the equivalent virtual MIMO channel matrix to model space-time codes is desirable in analysis. Through linear transformation, the QSTBC signal model becomes

$$\underbrace{\begin{bmatrix} y_1 \\ y_2^* \\ y_3^* \\ y_4 \end{bmatrix}}_{\widetilde{\mathbf{y}}} = \underbrace{\begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_2^* & -h_1^* & h_4^* & -h_3^* \\ h_3^* & h_4^* & -h_1^* & -h_2^* \\ h_4 & -h_3 & -h_2 & h_1 \end{bmatrix}}_{\mathbf{H}_{\mathsf{EVCM}}} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix} + \underbrace{\begin{bmatrix} \nu_1 \\ \nu_2^* \\ \nu_3^* \\ \nu_4 \end{bmatrix}}_{\widetilde{\boldsymbol{\nu}}}.$$

Note that $\mathbf{H}_{\mathsf{EVCM}}$ is non-orthogonal this time. However, observe

$$\mathbf{H}_{\mathsf{EVCM}}^H \mathbf{H}_{\mathsf{EVCM}} = \begin{bmatrix} \|\mathbf{h}\|_2^2 & 0 & 0 & \beta(\mathbf{h}) \\ 0 & \|\mathbf{h}\|_2^2 & \beta(\mathbf{h}) & 0 \\ 0 & \beta(\mathbf{h}) & \|\mathbf{h}\|_2^2 & 0 \\ \beta(\mathbf{h}) & 0 & 0 & \|\mathbf{h}\|_2^2 \end{bmatrix}$$

with $\beta(\mathbf{h}) = 2 \cdot \Re(h_1^* h_4 - h_2^* h_3)$ being a real-valued function. As shown in the term β, $\{h_1, h_4\}$ and $\{h_2, h_3\}$ appear in couple pairs, indicating pairwise decoding is possible [8].

In further discussions, a wireless system with larger quantity of transmit antenna will be considered. Fortunately, higher order QOSTBC codeword can simply be established based on the above construction steps. Take the order 8 QOSTBC codeword as an illustration example:

$$\mathbf{C}_8^{\mathsf{QOSTBC}}(\mathbf{s}) = \begin{bmatrix} \mathbf{C}_4^{\mathsf{QOSTBC}}(s_1, s_2, s_3, s_4) & \mathbf{C}_4^{\mathsf{QOSTBC}}(s_5, s_6, s_7, s_8) \\ -[\mathbf{C}_4^{\mathsf{QOSTBC}}(s_5, s_6, s_7, s_8)]^H & [\mathbf{C}_4^{\mathsf{QOSTBC}}(s_1, s_2, s_3, s_4)]^H \end{bmatrix}$$

is also constructed based on the Alamouti structure.

3.4 Diagonal Algebraic Space-time

Throughout the whole discussion on space-time coding and MIMO communications above, there has always been an assumption that the channel matrix $\mathbf{H}$ or $\mathbf{h}$ has non-zero components. In realistic situations, however, channel coefficients can be very small and approach zero, and the transmitted symbols may not survive such distortion. With serious attenuation, the received signal can never be restored and hence the performance of the system will be degraded.

Diagonal-algebraic space-time (DAST), therefore, aims at providing a linear transmission scheme where symbols are encoded in a way that each transmitted signals have a component of each symbols. Let $\mathbf{C}_N^{\mathsf{DAST}}(\mathbf{s})$ be the transmission codeword and $\mathbf{s}$ be a length N symbol stream that is actually required by the receiver:

$$\mathbf{C}_N^{\mathsf{DAST}}(\mathbf{s}) = \mathrm{diag}(\mathbf{U}\mathbf{s}). \tag{3.6}$$

To put it in a clearer way, denote $\mathbf{Us}$ as a set of complex-valued func-

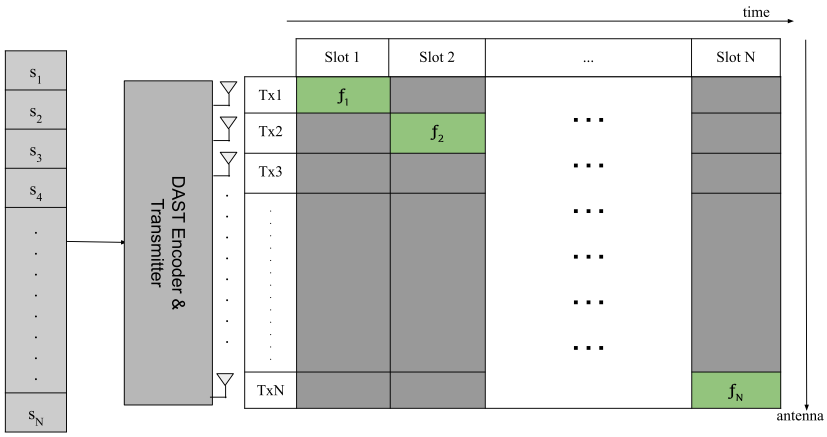


Figure 3.2: Illustration of the coding function of the DAST

tions $\{f_n(\mathbf{s})\}_{n=1}^{N}$, the transmission code matrix is

$$\mathbf{C}_N^{\mathsf{DAST}}(\mathbf{s}) = \begin{bmatrix} f_1(\mathbf{s}) & 0 & \dots & 0 \\ 0 & f_2(\mathbf{s}) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & f_N(\mathbf{s}) \end{bmatrix}.$$

Obviously, each diagonal element of the codeword $\mathbf{C}_N^{\mathsf{DAST}}(\mathbf{s})$ contains a portion of each target symbols, meaning that if any channel coefficient is unfortunately nulled, the receiver still has some chance of retaining the targeted symbol stream $\mathbf{s}$ back without a complete $\mathbf{C}_N^{\mathsf{DAST}}(\mathbf{s})$. Having the importance of discussed, some characteristics or requirement for the rotation matrix $\mathbf{U}$ should be clarified as it is an essential element to obtain the transmission vector. The DAST codeword depends on the term $\mathbf{Us}$, which has finite possibilities corresponding to the number of transmit antennas N and the modulation scheme employed. To prevent multiple roots in decoding process, $\mathbf{U}$ should fulfill the following assumption:

Assumption 1. *For any* $\mathbf{s}_i$ *and* $\mathbf{s}_j$ *in a constellation set, if* $\mathbf{s}_i \neq \mathbf{s}_j$*, then* $\mathbf{U}\mathbf{s}_i - \mathbf{U}\mathbf{s}_j$ *contains non-zero elements only.* ■

Moreover, the minimum distance between symbols is a criteria that should be considered in constellation evaluation. According to [14], the minimum distance between elements of can be maximized by choosing

$$\mathbf{U} = \frac{1}{\sqrt{N}} \cdot \begin{bmatrix} 1 & \omega_1 & \omega_1^2 & \dots & \omega_1^{N-1} \\ 1 & \omega_2 & \omega_2^2 & \dots & \omega_2^{N-1} \\ \vdots & \vdots & \ddots & \vdots & \\ 1 & \omega_N & \omega_N^2 & \dots & \omega_N^{N-1} \end{bmatrix}, \qquad \text{where} \qquad \omega_n = e^{\mathrm{j}\frac{4n-3}{2N}\pi}$$

for $n = 1, 2, \dots, N$; subject to $N = 2^k$ for $k \geq 1$. It is also worth mentioning that the DAST code uses only one transmit antenna to send data at each time-slot, which is also the reason why DAST is described as a linear transmission scheme. Despite such linear configuration, DAST, essentially, is of full rate as every signal sent by the transmitter carries information of all targeted symbols. Figure 3.2 explains how DAST code works by illustrating the DAST system model in a time versus spatial manner. At time slot k, antenna $\mathsf{Tx}n_{n=1}^{N}$ will send out a function $f_n(\mathbf{s})$, which contains every symbol with scaled portion. It is possible to elaborate $f_n(\mathbf{s})$ by expanding the term $\mathbf{Us}$ to see

$$\begin{bmatrix} f_1(\mathbf{s}) \\ f_2(\mathbf{s}) \\ \vdots \\ f_N(\mathbf{s}) \end{bmatrix} = \mathbf{Us} \quad \Longrightarrow \quad f_n(\mathbf{s}) = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \omega_n^{i-1} s_i.$$

Furthermore, the equivalent virtual MIMO channel matrix of DAST can be acquired through transforming the DAST signal model:

$$\mathbf{y} = \mathbf{C}_n^{\mathsf{DAST}}\mathbf{h} + \boldsymbol{\nu} = \mathrm{diag}(\mathbf{Us})\mathbf{h} + \boldsymbol{\nu} = \mathrm{diag}(\mathbf{h})\mathbf{Us} + \boldsymbol{\nu} = \mathbf{H}_{\mathsf{EVCM}}\mathbf{s} + \boldsymbol{\nu}$$

for $\mathbf{H} = \mathrm{diag}(\mathbf{h})\mathbf{U}$. Having obtained enables the DAST signal model to be decoded by an ML detector, which is favorable in performance analysis. Furthermore, the capability of achieving full diversity of DAST for more than 2 transmit antennas is proved in [2], therefore DAST has the common weakness of the previous mentioned codes overcame.

3.5 Summary

This chapter has studied four types of space-time codes, namely the Alamouti code, the orthogonal space-time block codes, the quasi-orthogonal space-time block codes and the diagonal algebraic space-time codes. The orthogonal property of the Alamouti code provides energy gain to symbols when performing linear decoding, and yet it serves as a barrier to attain full rate code in higher order orthogonal designs. Quasi-orthogonal space-time coding is able to achieve full rate, yet with complex symbols constellation full diversity does not exist for QSTBC with order higher than two. Considering the potential severe attenuation caused by the channel, the diagonal algebraic space-time coding is developed to deal with distortion due to path loss. DAST has also been proven to be able to provide full diversity. The codeword construction and the signal model of the above mentioned schemes are delivered as well.

Chapter 4

Stochastic Beamforming

In the previous section, we have introduced different space-time block coding schemes, which provide non-directional signal transmission as a broadcasting technique. Under a MIMO system, a random user can obtain good performance once CSI is perfectly known in advance, regardless of their position in the coverage area. In contrast to such blindly broadcasting techniques, transmit beamforming can be employed to direct signals to a particular angle, and hence to prevent severe distortion if the users' position is informed. Intuitively, if we can generate a random-in-time beamformer to direct signals to different positions at each transmission, given that the system transmits a long enough message, the beamformer directs signals to nearly all directions from the base station, then the resultant effect can be regarded as virtual blind broadcasting technique as well. Such strategy is regarded as Stochastic Beamforming (SBF) [18].

Figure 4.1a describes the signal transmission of ordinary STBCs while Figure 4.1b explains how SBF can virtually attain similar results. Consider SBF, where at different time instances the base station employs a random beamformer (represented by different colors) to send the signal out to the air. If the data being transmitted is long enough, eventually the whole area of coverage will be reached by those random beamformers, reaching similar situation as in ordinary blind broadcasting scenario.

To consider a SBF system model, consider a block of bits $\mathbf{b} \in \{0,1\}^B$ to be transmitted to users at some unknown positions. The bits are then channel coded and modulated into the symbol stream $\{s(t)\}_{t=1}^{T}$. In our discussion, the random beamformer $\mathbf{w}(t)$ follows complex Guassian distribution. Figure 4.2 outlines the system diagram of SBF. In contrast to previous discussions on STBCs, SBF transmission model considers the signal vector:

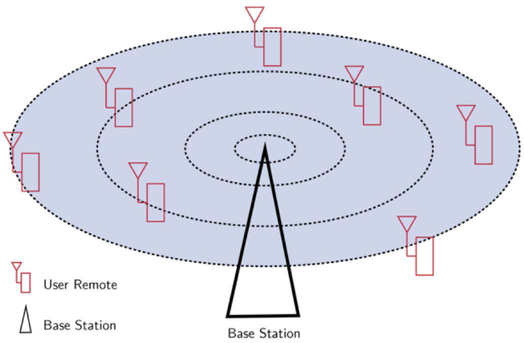
$$\mathbf{x}(t) = \mathbf{w}(t) \cdot s(t)$$

which is apparently different from symbol vector. Hence the corresponding received signal model will be:

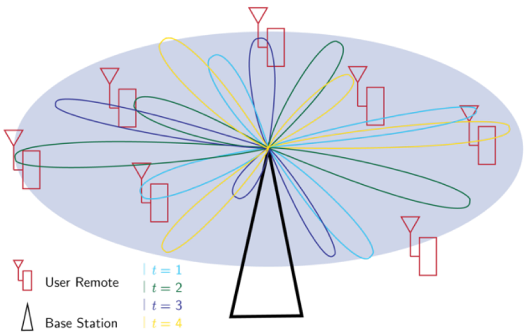
$$y(t) = \mathbf{H}^H \mathbf{x}(t) + \nu(t) = \mathbf{H}^H \mathbf{w}(t) \cdot s(t) + \nu(t)$$

where $\mathbf{H}$ is a block fading channel, which means it remains unchanged over the whole transmission period for the symbol stream $\{s(t)\}_{t=1}^{T}$. While it is, by nature, a slow fading channel, the BF vector $\mathbf{w}(t)$ is regenerated in every transmission instance t, altering the term $\mathbf{H}^H\mathbf{w}(t)$ into a virtually fast-fading channel. It is expected that in fast fading channel error correction code could give a better performance than a slow fading channel [17], therefore promising results are expected from SBF.

It should also be emphasized that the code rate is still 1 bit per time slot, which is comparable with full rate STBCs like QSTBC and DAST. Furthermore, unlike complex STBC schemes, SBF does not require ML



(a) Blind Broadcasting



(b) Stochastic Beamforming

Figure 4.1: Illustration of blind broadcasting and stochastic beamforming.

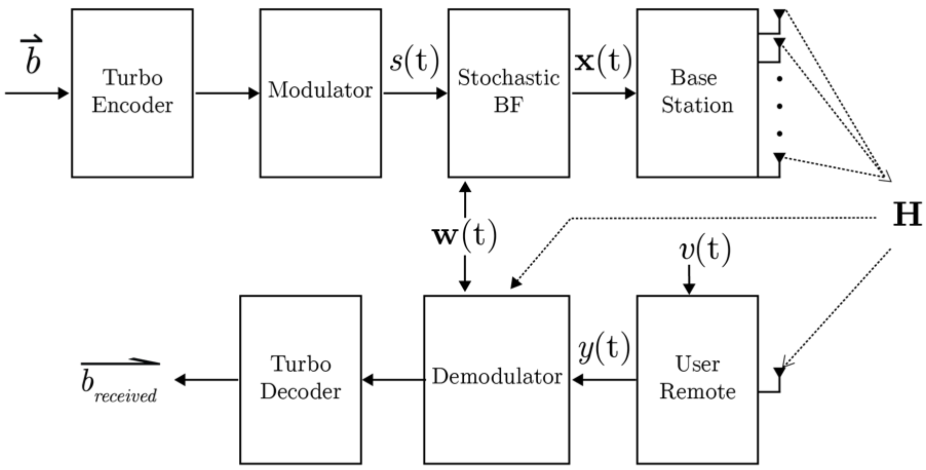


Figure 4.2: System Diagram of Stochastic Beamforming

detector to retrieve the symbol received as long as the BF vector and CSI are provided to the receiver, and hence far less computation power is demanded, especially in higher order MISO systems.

Chapter 5

Simulation Results

In this section, simulation results of the topics discussed above will be analyzed. The simulations are Monte-carlo simulations, collecting data on error rate with respect to different levels of signal-to-noise ratio (SNR). Simulations assumes the wireless MIMO channel to be a block fading channel, and therefore the channel coefficients are assumed unchanged within the time for transmitting one block of data. It is also assumed that the receiver has complete knowledge of the channel matrix. The noise item, an undesirable term which always exists, is assumed to be additive Gaussian white noise. All simulations employed with channel coding techniques are using Turbo code with rate 1/3. The average transmission power of each antenna is balanced. All the simulations presented in this thesis were performed on MATLAB.

The performance of the Alamouti code is simulated, with comparison to the MIMO spatial multiplexing. ML detection is employed at the receiver side. Figure 5.1 illustrates the simulation results for data constellations BPSK, 4-QAM and 16-QAM. It is shown that the Alamouti code performs better than the MIMO scheme regardless to data

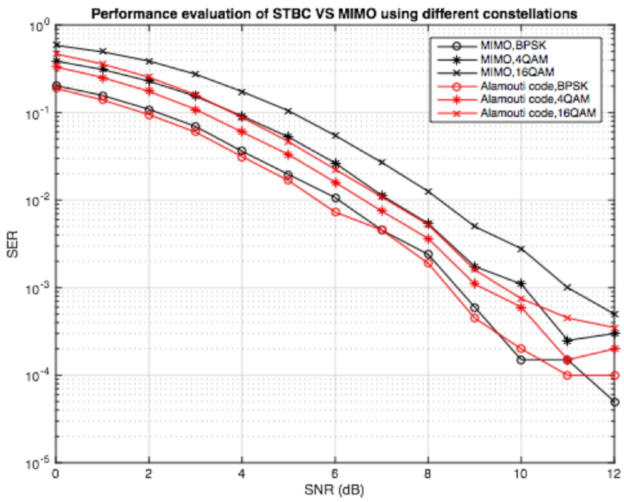


Figure 5.1: Symbol error rate versus SNR for Alamouti code.

constellation, suggesting the powerfulness of space-time block codes to achieve better performance with less antenna at the receiver.

It is a common practice to employ channel coding in the telecommunication industry, therefore the performance of STBC with channel coding employed is of interest. Figure 5.2 shows simulation results of the Alamouti code with the Turbo code employed under block fading channels, where the block length is set as 1024 bits/block. Rectangular 4-QAM constellation with symbol power normalized to 1 is employed and the decoder iteration number is set to be 8.

The performance of channel coded STBC has a 2dB code gain when compared to uncoded STBC. The powerfulness of channel coding cannot be shown in this case because the channel is a relatively slow-fading one. However, if we take Figure 5.3 into consideration, then it would be found that a 6dB code gain is shown in block error rate, which is a desirable result.

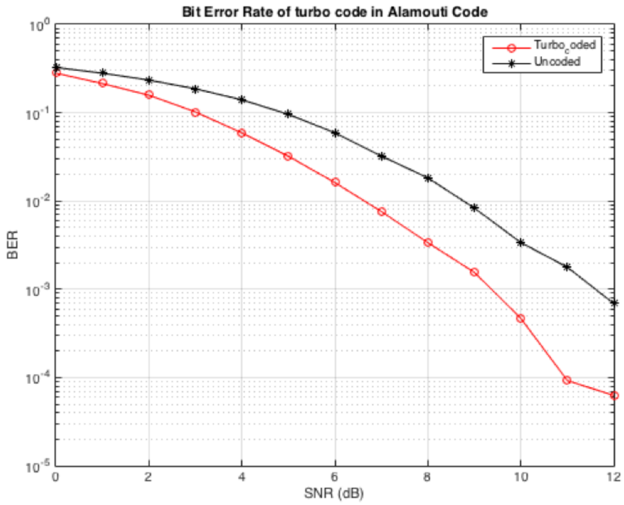


Figure 5.2: BER versus SNR for Alamouti code employed with Turbo Code.

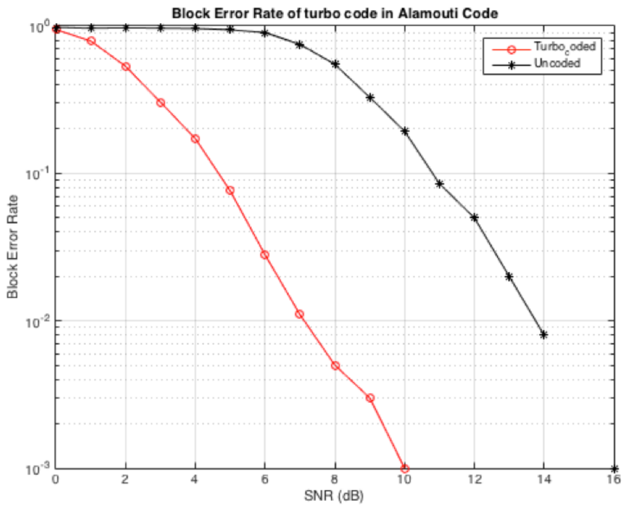


Figure 5.3: BLER versus SNR for Alamouti code employed with Turbo Code.

Figure 5.4 shows the simulation results of all the discussed space-time codes.

It is observed that all STBCs outperformed the ordinary MIMO approach. Both OSTBC and QSTBC are far more reliable than MIMO at any positive SNR value. DAST has similar performance with MIMO when SNR ¡ 6dB, and suddenly demonstrates a sharp drop in error rate when SNR ¿ 6dB.

The code gain difference with MIMO bound of OSTBC, QOSTBC and DAST are 7dB, 6.5dB and 4dB respectively at SER = 0.01. While OSTBC performs marginally better than QOSTBC at SNR ¿ 4dB, it is also an interesting finding that QOSTBC performs marginally better than OSTBC in the region dB.

After the above simulation results on space-time codes under four transmission antennas circumstances, a natural further question will be on how the performance of higher order space-time codes behave. Figure 5.5 presents the simulation results of DAST, QOSTBC and MIMO with 8 transmission antennas. It is observed that the dropping trend of the DAST curve at high SNR region is much sharper than other coding schemes, implying that DAST will eventually surpass QSTBC in the sense of SER-SNR performance somewhere in higher SNR region. The slope of the SER-SNR curve at high SNR region, according to [11], is the diversity. It is the reason why researches have been paying efforts to pursue full-diversity code as this set of codes have the potential to defeat all other codes in SER-SNR evaluation.

Figure 5.6 and 5.7 display simulation results of order 4 QSTBC and DAST combined with Turbo code, SBF scheme and the fundamental lower bound. Surprisingly, SBF outperformed STBCs and demonstrated excellent error rate performance, approaching the fundamental limit by 2dB, while QSTBC is 5dB away and DAST having 8dB away

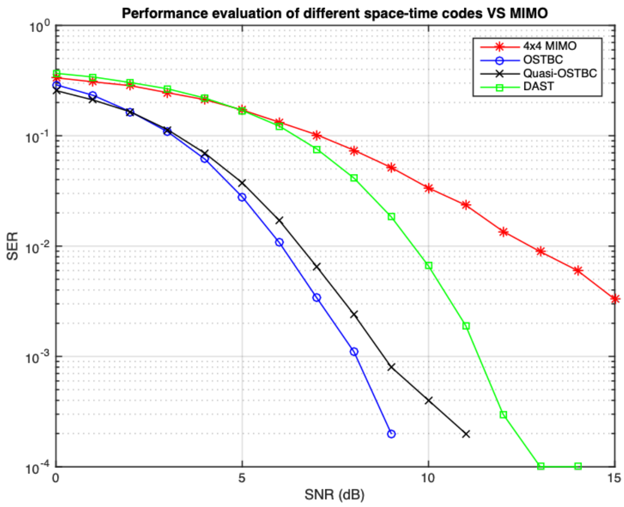


Figure 5.4: Symbol error rate versus SNR for different space-time codes and 4×4 MIMO using BPSK.

from the limit bound. The rationale of observing the block error rate performance is that in networking layer data are sent packet by packet rather than bit-wise, and broadcast scenarios are often transmitting video data which are coded in blocks, whereas a bit of error can ruin the whole block of data. Hence the BLER performance graph is also examined.

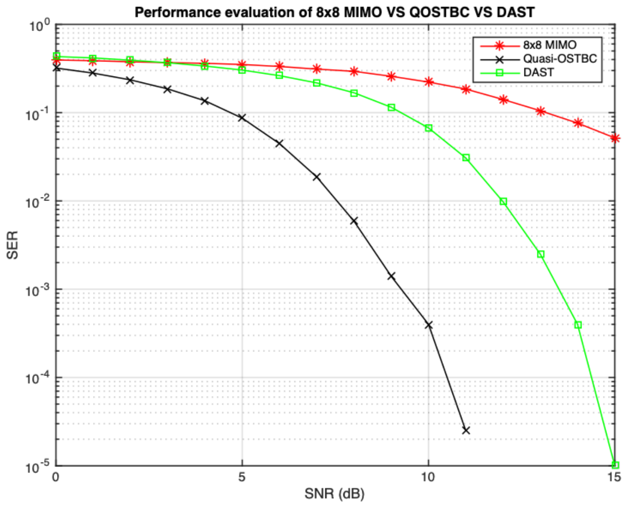


Figure 5.5: Symbol error rate versus SNR for QOSTBC, DAST and 8×8 MIMO using BPSK.

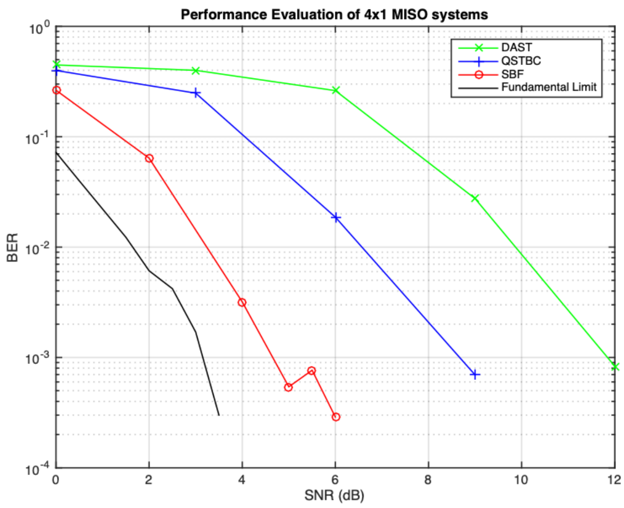


Figure 5.6: BER versus SNR for different order 4 blind broadcasting schemes using 4-ary QAM.

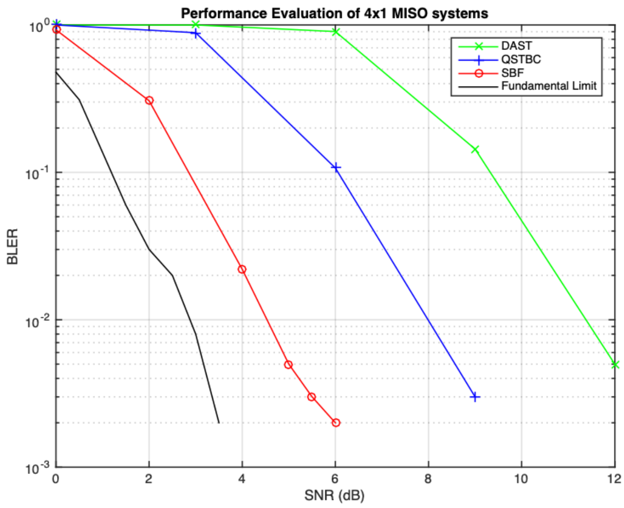


Figure 5.7: Block Error Rate versus SNR for different order 4 blind broadcasting schemes using 4-ary QAM.

Chapter 6

Discussions

Common information broadcasting is the main scope of this project, whereas space-time block coding is a popular method in realizing MIMO communication systems. It considers the scenario where the system has multiple transmit and one receive antenna, which made it particularly applicable in cellular communications as cell phones, as the receiver, are usually with one or two antennas embedded only while base stations, as the transmitter, can afford more antennas. In addition to STBCs, SBF is also investigated and both of their respective performances are studied in this thesis.

The Alamouti code, as the first introduced code with full-rate and full-diversity, outperforms typical MIMO transmission in the sense of SER. It is of orthogonal structure and hence linear decoding method is available. Simulation have shown that Alamouti code performs better than a normal MIMO system by attaining a smaller SER over the entire SNR axis. Similar to MIMO transmission, deviation in data constellation only affects the coding gain, which provides a rationale to test the codes thereafter in this thesis with BPSK and 4-ary QAM constellations to provide elementary trend studies.

The orthogonality of higher order space-time block codes demands the cost of transmission rate. The OSTBC for three or four transmit antennas can attain rate up to 3/4 and therefore simply compare it with other full rate codes will result in biased test. The method to conquer this problem is to use different data constellations between antennas to obtain the same number of bit per codeword. Simulation results on OSTBC suggest excellence in SER-SNR performance and, consistently with Alamouti code, the corresponding SER is always lower than that of 4×4 MIMO for all SNRs tested.

Concerning slower rate of OSTBCs, the quasi-orthogonal space-time block code class is developed to encounter the problem. It is described as an extension of the Alamouti code as the code construction is based on the prescribed code. Although simulation results have indicated that QSTBC performs just slightly worse than OSTBC in SER in high SNR region, the symbol vector construction requires nothing more than a regular symbol generator. Interestingly, QSTBC performs better than OSTBC in the low SNR region as captured by the simulation results.

Diagonal algebraic space-time tackles the problem when serious attenuation happens to a symbol because of one channel coefficient is unfortunately approaching zero. DAST proposes to transmit the whole symbol vector in every signal component so that it might has chance to conquer the situation concerned. DAST has also been proven to be a code that shares characteristics of full-rate and full-diversity at the same time, which researchers have been looking for a long while. However, the results of the simulation on the SER-SNR performance of DAST is the worst among all the previous discussed space-time codes. Yet, the curve trend in the simulation of the case with eight transmit antennas suggests that DAST may have the best chance to defeat other codes in a certain higher SNR region as it is of full diversity.

Stochastic beamforming, on the other end, is a different approach to realize common information broadcasting. By using random-in-time BF vector, the transmitter can pretend to perform a 360-degree broadcast if the data length is large enough. Further, although the wireless channel is block faded, the SBF technique can intuitively create a continuously changing channel, building a suitable state for channel coding to output utilized performance. Simulation results have shown that SBF performance is generally the nearest scheme to reach the optimal limit of MISO system when compared to different broadcasting techniques.

Chapter 7

Conclusion

We have conducted detailed examination on two types of MISO downlink broadcasting techniques: STBC and SBF. Different behavior and characteristics depend on the type of space-time block codes. Among STBCs, Alamouti code shares nearly all the benefits of STBCs, yet these qualities do not hold for cases of more than two transmit antennas; orthogonal designs trade transmission rate for orthogonality, or it has to employ complex symbol vector construction; quasi-orthogonal space-time block codes maintain full rate at the cost of losing full diversity; diagonal algebraic space-time successfully accomplished full diversity and full rate, yet it performs poorly under the SNR region of interest. Meanwhile, simulation results have also revealed that SBF demonstrates excellent error rate performance.

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