DISTRIBUTED SPACE TIME BLOCK CODING FOR ASYNCHRONOUS COOPERATIVE COMMUNICATION SYSTEMS

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ABSTRACT

Multiple-Input-Multiple-Output (MIMO) communication techniques have been an important area of focus for 4th generation wireless systems. This is mainly because of their potentials for high capacity, increased diversity, and interference suppression.

The cooperative communication techniques can avoid the difficulties of implementing actual antenna arrays and convert the single-input single-output (SISO) system into a virtual MIMO system. In this scheme, the user explores its other neighbor users to act as relaying nodes and forming virtual MIMO system.

Space-Time Block Coding (STBC) is used to improve the transmission reliably and spectral efficiency of MIMO systems. When STBC is applied to a cooperative diversity, the system termed as Distributed Space Time Block Code (D-STBC). Most of the existing research assumes perfect synchronization among cooperative users in D-STBC. This means that they have identical timing, carrier frequency, and propagation delay, which is almost impossible to be achieved. The lack of common timing reference can badly influence the performance of the D-STBC system. There are different research efforts to overcome this problem; most of which have high decoding complexity.

In this research, two low decoding complexity detection schemes of D-STBC have been proposed and they have proven their efficiency in mitigation the impact of imperfect synchronization between the relay nodes. The first one is based on Parallel Interference Cancellation (PIC) method and the other is based on Successive Interference Cancellation (SIC) method.

أنظمة الترميز الزمكانية المتكتلة المتوزعة
لأنظمة الاتصالات التعاونية الغير متزامنة

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الملخص

تعتبر تقنيات الاتصالات متعددة المداخل والمخارج (MIMO) من أكثر التقنيات المثيرة للاهتمام والبحث لتطبيقها في الجيل الرابع من أنظمة الاتصالات اللاسلكية, وذلك بسبب دورها الكبير في زيادة السعة لقناة الاتصال (Channel Capacity) وقدرتها على إخماد التداخل والتشويش وأيضا تقليل معدل الخطأ في النظام.

أنظمة الاتصالات التعاونية يمكنها تجنب أهم مشكلة لتقنيات الاتصالات متعددة المداخل والمخارج (تدشين هوائيات متعددة على المرسل/المستقبل الواحد) حيث تقوم بتحويل النقاط وحيدة المدخل والمخرج (SISO) إلى نظام افتراضي متعدد المداخل والمخارج (Virtual MIMO). في هذه الأنظمة يقوم المستخدم (المرسل/المستقبل) وحيد المدخل والمخرج بمحاولة استكشاف المستخدمين المجاورين له داخل النظام لكي يعملوا كنقاط إعادة بث لإشارته وبالتالي يتم تكوين نظام افتراضي متعدد المدخل والمخرج.

الترميز الزمكاني الكتلي (Space Time Block Coding–STBC) يستخدم لتحسين كفاءة البث ومدى كفاءة استخدام النطاق الترددي(spectral efficiency) في الأنظمة متعددة المداخل والمخارج ويمكن أيضا أن يتم تطبيقه على أنظمة الاتصالات التعاونية حيث يسمى حينها الترميز الزمكاني الكتلي المتوزع (Distributed–STBC). معظم الأبحاث التي تمت في هذا الموضوع افترضت التزامن التام بين المستخدمين المتعاونين الموزعين, بمعنى أن لهم نفس توقيت بدء ووصول البث ونفس التردد الحامل, وهذا ما يعتبر غالبا مستحيل التحقق. فقدان التزامنية يؤدي إلى سوء كفاءة البث (معدل الخطأ في النظام Error rate) بشكل كبير في النظام. هناك جهود مختلفة للتغلب على هذه المشكلة ولكنها بالغالب تؤدي إلى زيادة تعقيد النظام.

في هذا البحث سنقدم طريقتان للكشف قليلتا التعقيد واللتان ومن خلال البحث وعمل المحاكاة اللازمة سيتم إثبات كفاءتهم في إزالة أثار عدم التزامن بين المتوزعات في النظام, الأولى تعتمد على خوارزمية إلغاء التداخل المتوازية (Parallel Interference Cancellation−PIC) والأخرى تعتمد على خوارزمية إلغاء التداخل المتراكبة أو التسلسلية (Successive Interference Cancellation−SIC).

DEDICATIONS

To my country, Palestine

To my parents

Who taught me the value of study and perseverance ethic and have given me endless support.

To my wife and my sisters

Who encouraged me through the work of this thesis.

To my sweet daughter, Arjan

For her lovely smile.

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Mohammed Taha O. El Astal

February, 2011

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LIST OF ABBREVIATIONS

AF	**Amplify and Forward protocol**
AM	**Amplitude Modulation**
AWGN	**Additive White Gaussian Noise**
BER	**Bit Error Rate**
CDMA	**Code Division Multiple Access**
CP	**Cyclic Prefix**
DF	**Decode and Forward protocol**
D-STBC	**Distributed Space Time Block Coding**
DT	**Direct Transmission**
EGC	**Equal Gain Combining**
FDMA	**Frequency Division Multiple Access**
FM	**Frequency Modulation**
MBWA	**Mobile Broadband Wireless Access**
MIMO	**Multiple Input- Multiple Output**
ML	**Maximum Likelihood**
MRC	**Maximal Ratio Combining**
OFDM	**Orthogonal Frequency Division Multiplexing**
PEP	**Pair-wise Error Probability**
PIC	**Parallel Interference Cancellation**
PSK	**Phase Shift Keying**
SC	**Selection Combining**
SDF	**Selective Decode and Forward protocol**

SIC	**Successive Interference Cancellation**
SISO	**Single Input-Single Output**
SNR	**Signal to Noise Ratio**
SSC	**Switch and Stay Combining**
STBC	**Space Time Block Coding**
STC	**Space Time Coding**
STTC	**Space Time Trellis Coding**
TDMA	**Time Division Multiple Access**

Chapter 1

Introduction

1.1 Introduction:

Wireless communications are one of the most attractive research areas which have seen enormous growth in the last several years. After the first appeared, in 1897 when Marconi succeeded to contact with ships sailing in the English canal by the radio, wireless communications has experienced many milestones, for example, the use of AM and FM communication systems for radios [1], and the development of the cellular phone system from its first generation in the 1970s to the fourth generation, which we are about to use soon [2], in chapter two of [3].

Figure (1.1): Wireless communication applications. [4]

Wireless Communication has been one of the fastest growing technologies so there is a large amount of researches and investment about it, that's due to the emerging applications and services over it. Nowadays, wireless devices in anywhere around us: cell phone, PDA, wireless INTERNET, FM/AM radio, etc.

In this chapter, a motivation to choose this topic to search will be considered, and then we will illustrate some background concepts which it required to the remains of this research, such as, wireless channel propagation effects. Also, some basics of our issue will be introduced. Finally, the organization of this thesis and its contributions will be listed.

1.2 Motivation:

The growing demands of wireless communications due to new emerging applications, introduce many technical challenges in developing the modern wireless communication systems. The main two challenges are the capacity; how much information can go through the channel between the clients of the system, and the pair wise error probability (PEP); the probability of mistaking the transmitted signal with another one.

Based on Shannon theory, the capacity of wireless communication channel has an upper bound which considers the ultimate goal of any communication system designer. The main issue that prevents the designer to reach the Shannon capacity is the multiple-path propagation in wireless channels which cause the capacity to be very low. There are many research efforts to reach the Shannon bound, such as frequency reuse in chapter three of [3], OFDM [5], and channel coding such as turbo codes [6] have been invented to increase the bandwidth efficiency.

Moreover, the wireless channel suffers from another great disadvantage beside the low capacity: it’s the high error rate and it decreases nearly linearly with the increasing of the signal-to-noise ratio (SNR) not exponentially decay like a wired communication channel that also is due to multipath effect [7]. Therefore, to achieve the same performance, a much longer code or much higher transmit power is needed for wireless communication systems than a wired system.

As noticed, the main cause of the previous disadvantages of wireless communication is the multiple-path propagation phenomena in wireless channels, so we need a system that can deal with the impact of this issue to meet the rising demand on the high data rate and the quality of the wireless communication systems. Recently, the Multiple Input - Multiple Output (MIMO) communication system provides a feasible solution for some challenges such as low channel capacity and high probability of errors. It uses the multiple antennas at the transmitter and the receiver to turn multiple-path propagation, which is the disadvantage of wireless communications, into a benefit to the clients. In 1996 and 1999, Foschini and Telatar proved in [8] and [9] that communication systems with multiple antennas have a much higher capacity than single antenna systems. Also, it can be used to improve the BER of the wireless system, and there is a tradeoff between these two objectives, you can find more details in chapter eight of [10].

The features expected from MIMO system can be maximized when a suitable algorithm was merged with the system, for example, in a system with two transmit antennas, if Alamouti's scheme [11] is used, a PEP inversely proportional to SNR^2 is obtained not like if identical signals are transmitted from both antennas at a time where a PEP is inversely proportional to SNR is obtained. Therefore, it is important to develop algorithms that take advantage of the spatial diversity provided by multiple antennas, for example, diversity combining methods ,more details in chapter seven of [3] and also in the same chapter number in [10][12], and the most successful one which is space-time coding (STC). It extended from Alamouti scheme by Tarokh, Seshadri and

Calderbank in [13] and it achieves a PEP that is inversely proportional to SNR^{MN}, where M is the number of transmit antennas and N is the number of receive antennas.

During the last few years, the technology of multiple antennas and space-time coding has been improved greatly, and there is much effort to overcome the need of multiple antennas in a client device. Among different techniques proposed, the use cooperative schemes have been widely studied in recent years. It creates virtual MIMO system using distributed single-input single-output (SISO) system [14]. The cooperative scheme (Virtual MIMO) has advantage over a conventional MIMO that it exploits other client antennas to serve source client and form virtual multiple antennas instead of physical multiple antennas on the client handset which always consider impractical.

When the space time block coding applied at the cooperative network is called Distributed-Space Time Block Coding (D-STBC). However, these systems require a perfect synchronization which if it has not been realized, it may cause a significant degradation on the system performance. Therefore, most of the designed space-time codes are no longer valid for cooperative diversity.

There are increasing demands on developing distributed space time codes which has low decoding complexity and can work when the signals are not synchronized at the receiver, at any delay profile.

1.3 Wireless Communication Channel:

The signal through a wireless channel experiences many factors, such as noise, attenuation, distortion and interference which may cause the result of detection at the receiver done in a wrong way. It is then useful to briefly summarize the main impairments that affect the signals.

1.3.1 Additive white Gaussian noise:

Additive white Gaussian noise (AWGN) is a noise term which generally used to model background noise in the channel as well as noise introduced at the receiver front end and it is the most common noise model in communication systems [15]. The term additive comes from that the effect of this noise to the original signal is additive in nature, this is clear in the relation between the output of the channel (*y(t)*) and the input *x(t)* signal which is given by equation (1.1) and illustrated in figure (1.2).

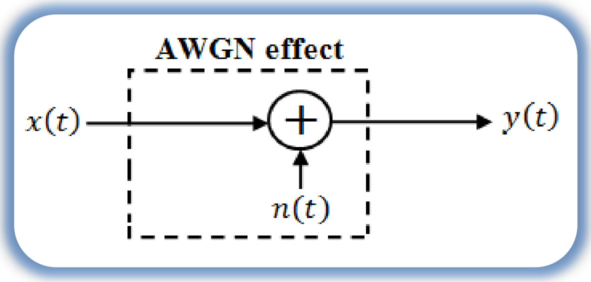

Figure (1.2): The AWGN channel effect.

$$y(t) = x(t)/\sqrt{\Gamma} + n(t)$$

where Γ is the loss in power of the transmitted signal *x(t)* and *n(t)* is the AWGN noise.

White term means that the frequency spectrum is continuous and uniform for all frequency bands. The term, white, originated from the fact that white light contains equal energy over the visible frequency band. Finally, the term Gaussian comes from that the additive noise *n(t)* is modeled as a random variable with a Gaussian distribution.

1.3.2 The propagation effects:

The transmitting signal in wireless channel suffers from two main categories propagation effects which are large-scale fading effects and small-scale fading effects. Figure (1.3) shows the power (in dB) of the signal at a moving receiver which moves far away from the transmitter.

From this figure, you can observe there are two types of changes of the signal power, decay over a curve with increasing in the distance and a repaid variation over the curve, which are the effect of the two types will be consider. Here, a summary of these effects will be illustrated, more details can be found in chapter four and five of [3], chapter two in [10], and in [16].

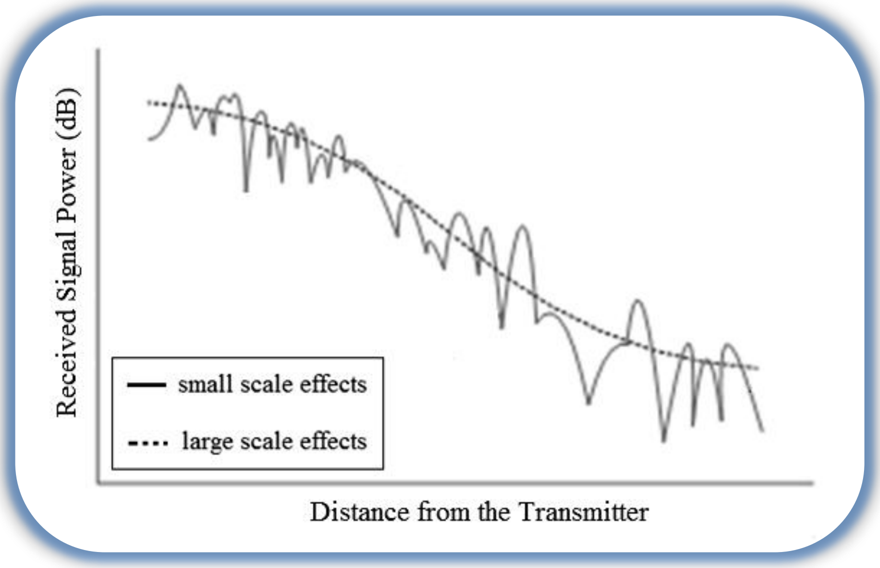

Figure (1.3): The propagation effects through wireless channel.

1.3.2.1 Large-scale fading effects:

It refers to the loss of the transmitting signal power due to distance between the transmitter node and the destination node, also it is called path loss and measured in decibels (dB) of the ratio between the transmitted and received signal power.

The path loss is proportional to the distance; it means that the attenuation increases as the signal propagates from the transmitter to the receiver. Due to that the degradation occurs slowly in time and phase over the distance, it classified as large-scale propagation effects. These variations occur over distances of hundreds of meters and involve variation up to around 20 dB.

1.3.2.2 Small-scale propagation effects

While the signal propagates through the wireless channel it will experience random reflectors, scatterers, and attenuators, which is resulting a multiple copies of the signal arriving at the receiver after each has traveled through different paths, this channel known as a multipath channel, this scenario shown in figure (1.4).

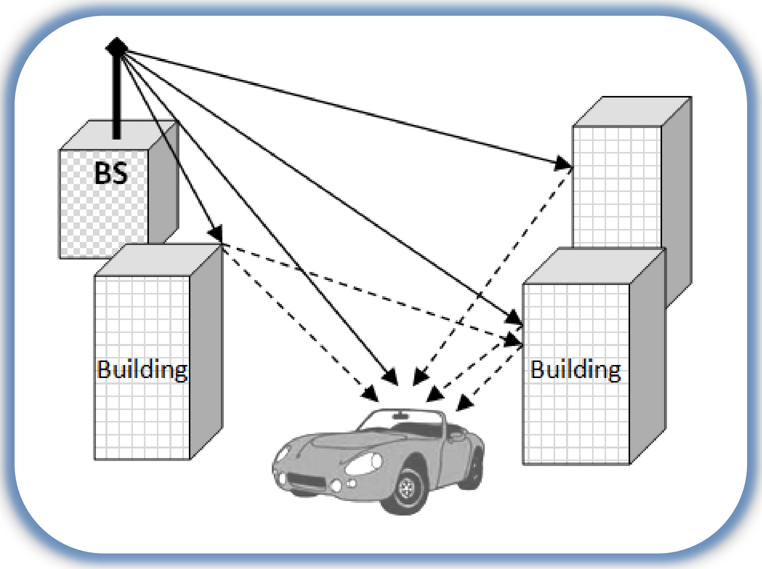

Figure (1.4): Signal propagation over a wireless channel.

When the multiple copies arrive at the destination, they will be added up and creating either constructive or destructive interference with each other that is due to that each signal copy having a different amplitude, phase, and delay. This result in a received signal has shape changes rapidly over time, so this effect is referred as small-scale propagation effects.

The multipath fading channel can be modeled as follow, if we denote the transmitted signal by $x(t)$ and the received signal by $y(t)$:

$$y(t) = \sum_{i=1}^{L} h_i(t)x(t - \tau_i(t)),$$

where $h_i(t)$ is the attenuation of the i^{th} path at time t, $\tau_i(t)$ is the corresponding path delay, and L is the number of resolvable paths at the receiver.

The multipath fading channel is classified according to its effect over the time (Slow and Fast Fading) and over the frequency (Frequency-Flat and Frequency Selective Fading).

I. Slow and Fast Fading:

This classification is based on the coherence time T_c of the channel, which measures the period of time over which the fading process is correlated (have the same effect). The fading is said to be slow if the transmitted symbol time duration T_s is smaller than the channel's coherence time T_c; otherwise it is considered to be fast. Slow fading mean that each one symbol time or more have the same multipath channel effect whereas fast fading mean that one symbol will have different effect over the time.

II. Frequency-Flat and Frequency-Selective Fading:

The channel will be frequency-flat fading (frequency-nonselective fading) if all the spectral components of the transmitted signal will have the same effect (fading), whereas the channel will be frequency selective fading if the spectral components of the transmitted signal are affected by different amplitude gains and phase shifts.

The key factor in this classification is what so-called channel coherence bandwidth B_c which is the frequency range over which the fading process is correlated. The fading is said to be flat if the transmitted signal bandwidth B_s is smaller than the channel's coherence bandwidth B_c; otherwise it is considered to be a frequency selective channel.

1.4 Distributed Space Time Block Coding:

Space Time Coding is a method employed time and space diversity to improve the reliability of data transmission in wireless communication systems. There are two main categories of space time coding: Space time trellis coding (STTC), and Space–

time block codes (STBCs) where they differ in the way of coding process. Coherent and non coherent are other categories due to another classification. In coherent STC, the receiver knows the channel model, but in non coherent STC, the receiver does not know the model. This research will deal only with coherent STBCs.

Alamouti [11] was proposed the first code which implements the concept of exploring the time and space diversity simultaneously, then the concept was extended by Tarokh, Seshadri and Calderbank in [13] to start what so called space time block coding. To explore a spatial diversity through the STBC system, you will require a system to have nodes held with multiple antennas (Figure (1.5)) which is usually considering unrealistic condition in many situations.

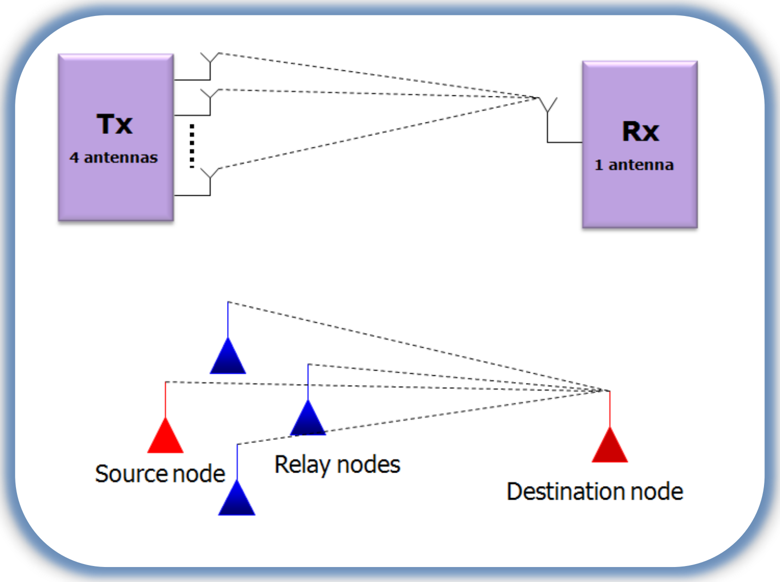

Figure (1.5): MIMO system and its corresponding cooperative scheme.

The cooperative scheme has been proposed in order to create virtual MIMO system using distributed single-input single-output (SISO) system [14] which will consider as a solution for the impediment of STBC with MIMO network. In cooperative scheme , the source node uses its neighbor node's antenna to gain the benefits of MIMO system by firstly broadcast the signal to the neighbor nodes, also called relay nodes, and then they are forward it to the destination, the ideal is very clear in figure (1.5) which model 4 × 1 MIMO by cooperative technology. There are many cooperative protocols that specify the process done in the relay nodes, such as: amplify and forward, decode and forward, and other.

The term Distributed-STBC system is referred to a wireless communication system which implementing the space time block codes over cooperative network. The cooperative network creates a virtual MIMO system instead of real physical MIMO system. Cooperative mechanism in Distributed-STBC done through two transmission phases as follows [17]:

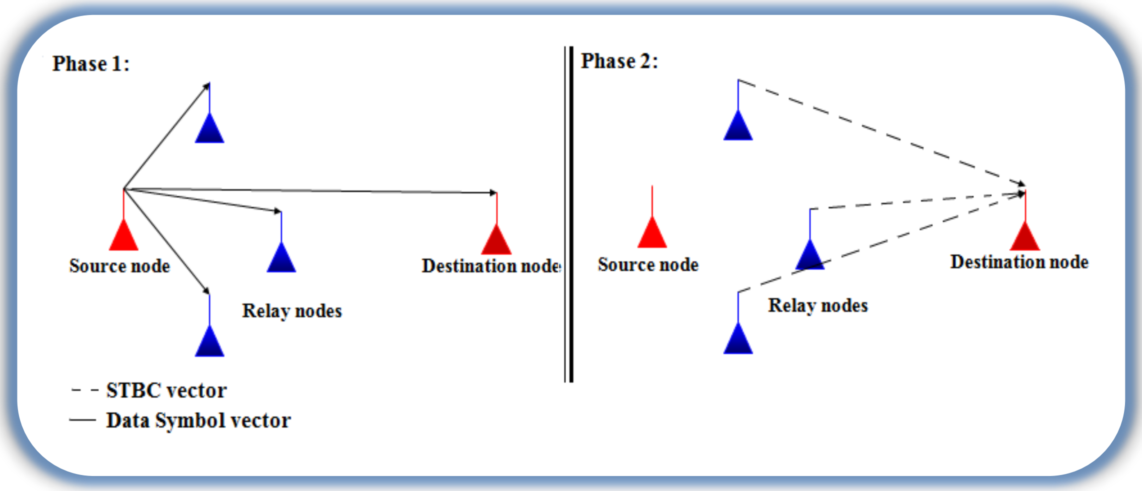

Figure (1.6): Distributed-STBC transmission phases.

Phase 1 (also called the broadcasting phase)**:** a source transmits original data to all relay nodes and also to the destination node.

Phase 2 (also called the relaying phase)**:** all relays which have received the data will form a STBC version of data, and then transmit it to the destination.

These two phases are done through either TDMA or FDMA. Some schemes allow the source node to be active in the phase 2 but our concern in this thesis is limited to the case when the source node is not active in the second phase.

1.5 Problem Statement:

It seems to be easy to apply STBC with cooperative communication to form distributed-STBC and gain the features of STBC and cooperative scheme, but this is not the case .There is a big challenge where distributed STBC required perfect synchronization among cooperative relays as a conventional STBC required. This means that all relays are assumed to have the identical timing, carrier frequency and propagation delay [18]. Unfortunately, perfect synchronization is almost impossible to be achieved because that the relay nodes will be in random locations and their transmissions will be affected by random different conditions. The lack of a common timing reference can affect the structure of the code matrix and result in a rank deficient space-time code [18].

1.6 Literature Review:

There are many research efforts on performance analysis and implementing of D-STBC system. Some of them implement a Decode and forward protocol on the distributed relay node [19]-[21], and other it uses an amplify and forward protocol [22],[23]. Most of the existing research assumes perfect synchronization among cooperative users which is almost considered impossible to be achieved. Therefore, most of the designed space-time codes are no longer valid for cooperative diversity unless they are delay tolerant [24]. There are different research efforts to overcome this problem; we list here a brief for some of them:

- In [24], a delay tolerant code was proposed. It has ability to face the imperfect synchronization and can mitigate its effect, but it has high decoding complexity.
- In [25], [26], and [27], a detection scheme proposed for the case of two relay nodes under imperfect synchronization; it depends on the PIC approach to

mitigate the impact of the time misalignment. The disadvantages of this scheme are: it suitable just for two relay nodes scheme, it assume there are perfect knowledge about the amount of time misalignment which is unrealistic condition, relatively need to 3-4 iterations to gain a suitable performance.

- In [28], the problem of imperfect synchronization between just four relay nodes is overcome by applying a PIC detection scheme at the destination node and introduces a feedback channel. The disadvantages of this scheme are the same as the previous one and additionally it needs a feedback channel where it sometime consider unrealistic requirement.
- In [29], Robustness against the effects of random delays at the relay nodes is enhanced through the use of a low-rate feedback channel and the using of orthogonal frequency division multiplexing (OFDM) with cyclic prefix (CP) at the source node to combat the timing errors at the relay nodes. The disadvantages of this method are: the inherited disadvantages of OFDM system, such as any frequency offset will degraded the system performance, and also it require additional feedback channel.

1.7 Thesis Contribution:

The primary contributions of this thesis are summarized as follows.

- New proposed Distributed-STBC detection scheme based on successive interference cancellation (SIC) algorithm. It has ability to mitigate the impact of imperfect synchronization between the distributed relay nodes. The simulation result shows that there will be a great improvement in error rate over the conventional detection scheme of D-STBC, and it faster than PIC approach proposed in [27] (2 iterations of SIC approach have the performance of 3 iteration of PIC approach).

- Modify the PIC approach proposed in [27] to be more realistic and proposed a general form of the approach to suitable for any number of relay nodes instead of just 3 or 4 nodes.
- In this thesis, we have simulated most of the performance curves shown here even in the background chapters and all using MATLAB software.

1.8 Thesis organization:

The thesis is mainly concerned with the imperfect synchronization issue in the Distributed STBC system and reviews the basics of this system as follow:

- In chapter 2: we discuss the space time block coding basics by firstly analyze the Diversity techniques, then explain and simulate the Alamouti Schemes which is suitable just for two transmit antennas, then review the concept for the high order STBCs, finally we brief a systematic steps design for complex STBC codes which will be used in the new proposed schemes.
- In chapter 3: we analyze and simulate the cooperative schemes, its relaying protocols such as: Amplify and Forward, Decode and Forward, and others. Also, Distributed-STBC system will be discussed and simulated, and then we will brief our big challenge issue which is the imperfect synchronization between the relay nodes.
- In chapter 4: The imperfect synchronization in the D-STBC system will be analyzed, modeled, and simulated to show the impact of this issue on the performance of the system, then discuss and simulate the PIC approach that proposed in [27] to mitigate the effect of the issue, then we proposed a general form of the PIC approach to be suitable for any number of relay nodes. Finally,

new Distributed-STBC detection scheme based on successive interference cancellation (SIC) algorithm has been proposed. It has ability to mitigate the impact of imperfect synchronization between the distributed relay nodes more than what the PIC approach achieves.

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Chapter 2

Space Time Block Codes

2.1 Introduction:

Most of modulation schemes have a poor performance over Rayleigh wireless channel, the error probability decays very slowly over increasing the value of signal to noise ratio (SNR). The main cause of that poor is that all schemes rely on the strength of single signal path which have a significant probability to face a deep fade. To overcome that problem, a system rely on receiving the data from multiple channels must be created .The probability to face deep fading at the same time of the transmission is reduced because of the diversity. There are many forms of diversity, such as space, time, polarization and frequency diversity. Diversity schemes are implemented in different ways, but all of them aim to the same objective which is providing multiples uncorrelated copies of transmission to the receiver. The receiver will select the better copy or will coherently combine the independent fading paths so that the effects of fading are reduced [1].

In space diversity the transmitting signal extend over space by multiple antennas, and when it is extend over time (transmit multiple copy over time) the diversity known as time diversity, but when the transmitting signal extends over space and time simultaneously, the model of space time coding will be created. *Space Time Coding* is a method to employ time and space diversity to improve the reliability of data transmission in wireless communication systems. There is two main categories of space time coding: *Space time trellis coding (STTC)*: which transmits a trellis code version of the data over multiple time slot and multiple antennas and, *Space–time block coding (STBC)*: which acts on a block of data at once like block coding. *Coherent* and *Non Coherent* are other categories that STC can be classified into. In coherent STC, the receiver knows the channel model, but in non coherent STC, the receiver does not know the model but knows the statistics of the channel. In differential space–time codes neither the channel nor the statistics of the channel are available [2].

The organization of this chapter will be as follow: Diversity techniques will be explained, then analysis of the Alamouti Schemes. Generalization of the concept for the high order STBC is introduced with the present codes for real constellation, then for complex constellation. Finally brief systematic steps design for complex STBC codes is explained.

2.2 Diversity

In wireless communications, the transmission over a single path has a large probability to face a deep fading which will cause a large amount of error in the data. The diversity techniques are widely used to overcome this problem. These diversity techniques aim to provide a multiple replicas of the transmitted signals at the receiver; all multiples carrying the same information but with small correlation. So, at the receiver there will be multiple independent samples of the signal which faded in an uncorrelated manner which mean; some of them are severely faded while the other is less faded. Using a proper combination technique of these samples, the multipath fading effect will be reduced and the reliability of the transmission will improved without increasing the transmitted power or sacrificing the bandwidth. There are many combining techniques, for example, Selection Combining (SC), Switch and Stay Combining (SSC), Maximal Ratio Combining (MRC), and Equal Gain combining (EGC), some of them select only the best branch, and other try to combine the branches to have a better performance ([3], [4]).

There are two performance gain associated with diversity schemes which are ([4]): Diversity Gain: which defined as the increased in averaged combined SNR over the average branch SNR, or how much the transmission power can be reduced when a diversity scheme is used without a performance loss, and Array Gain: which defined as the average increase in the (SNR) at the receiver that arises from the coherent combining effect of multiple antennas at the receiver or transmitter or both. The diversity can be accomplished in many forms of diversity, for example space diversity, time diversity, and frequency diversity.

2.2.1 Space Diversity/MIMO system:

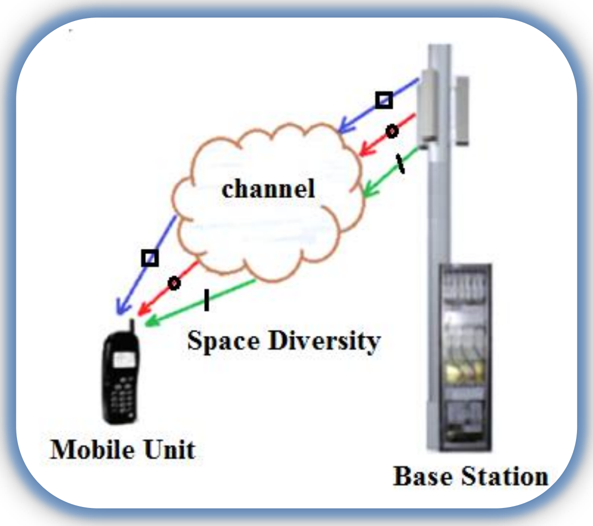


Figure (2.1): The Space diversity scheme.

Space diversity ([3], [4], and [5]) is also called antenna diversity. It is implemented using multiple antennas arranged together at transmitter and/or at the receiver , Figure (2.1). These antennas are separated physically by distance to produce signals which are uncorrelated. The value of this physical separation depends on many factors such as antenna height, propagation environment and frequency. In space diversity, there is no loss in bandwidth, data rate and transmitting power, since it is not use the time or frequency to provide a replica of signal. Depending on whether multiple antennas are used for transmission or reception, we can classify space diversity into two categories: receive diversity and transmit diversity. These multiple antennas can be used to increase data rates through multiplexing instead of diversity which improve the performance, so there are a tradeoff between diversity and multiplexing.

2.2.2 Time Diversity

Time diversity ([3], [4], and [5]) can be done by transmitting same signals in different time slots separated by at least the coherence time of the channel, which will produce uncorrelated fading signals at the receiver, Figure (2.2).

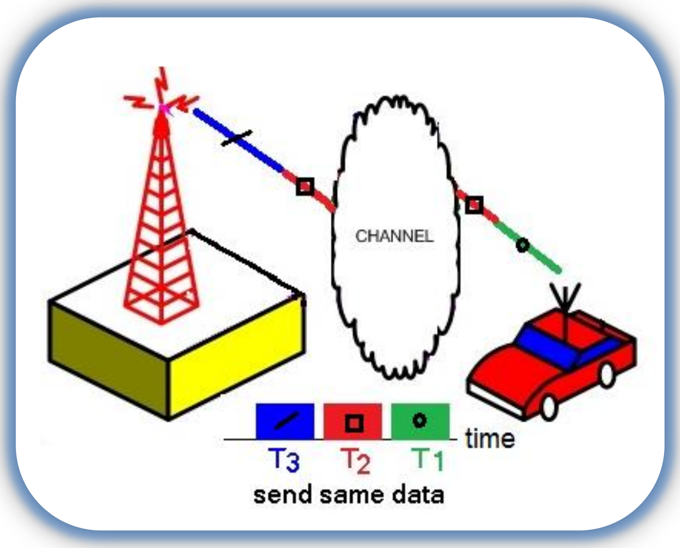


Figure (2.2): The Time diversity scheme.

The coherence time [6]: is a statistical measure of the period of time over which the channel fading process is correlated.

2.2.3 Frequency Diversity

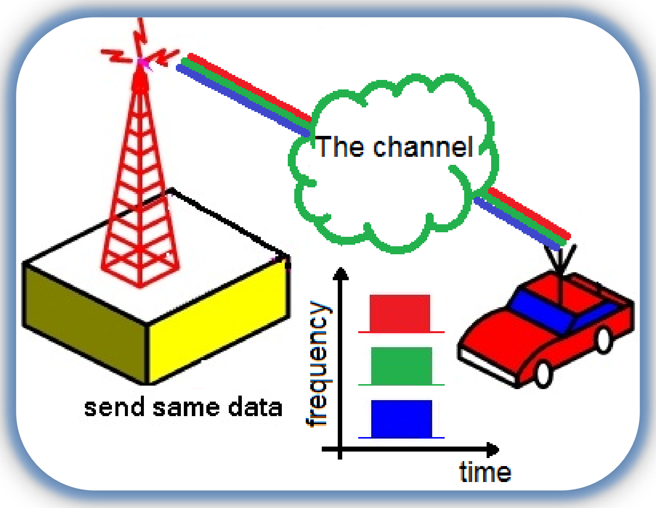


Figure (2.3): The Frequency diversity scheme.

In frequency diversity ([3],[4],[5]), a multiple of identical data are transmitting using different frequencies with enough frequency separation between them to have uncorrelated fading signal at the receiver as shown in Figure (2.3). In order to have independent fading signal, the frequency separation must be larger than the coherence bandwidth. *The coherence bandwidth* [6]*:* is a frequency bandwidth where the channel may be considered relatively constant. The coherence bandwidth is different for different propagation environments.

2.3 Alamouti Space Time Code:

Alamouti schemes (October 1998) was considered as the basis of space time block codes (STBCs), and it is a full rate and a full transmitted diversity. Alamouti proposed two new schemes, two branches transmit diversity with one antenna at receiver, and two branches transmit diversity with M antennas at receiver [7]. The two schemes will be considered here.

1. Two-Branch Transmit Diversity with One Antenna at Receiver [7], [8], [9]:

In this scheme, two antennas will be used at the transmitter, and one antenna at the receiver. The analysis will be divided into three stages, at the transmitter, the channel effect, and at the receiver.

At the transmitter:

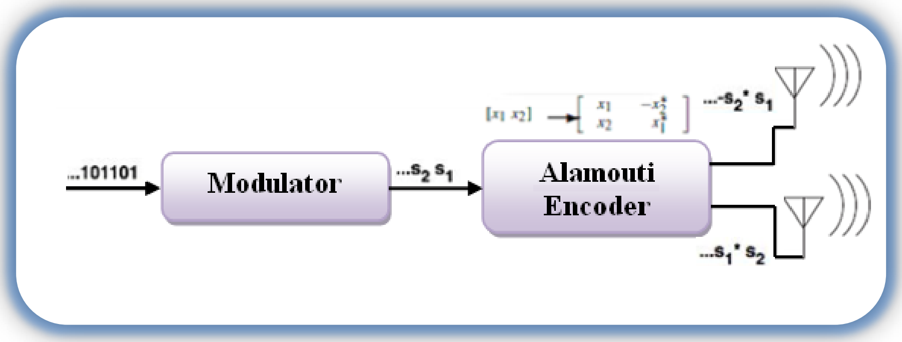


Figure (2.4): Alamouti transmitter

The data will be processed as follow:

1. The data is modulated; any modulation type can be used.
2. The encoding is performed as:
    a. *1st symbol period*: Two signals will be sent simultaneously from the two transmitter antennas: from the first antenna the transmitter will send S_1, and from second antenna it will send S_2.
    b. *2nd symbol period*: also two signals will be sent, $-S_2^*$ from the first antenna, and S_1^* from the second antenna.
    c. Repeat the same manner over whole data.

These encoding process summarized in the following table:

Table (2.1): Alamouti transmitted symbols.

	Antenna 1	Antenna 2
First period	S_1	S_2
Second period	$-S_2^*$	S_1^*

As shown in the previous paragraph, the encoding process has been accomplished in both space and time; it is also can be accomplish in both space and frequency (space-frequency coding). In space frequency coding, the transmission done by two different carrier frequency in the same period instead of two symbol period.

Channel effect:

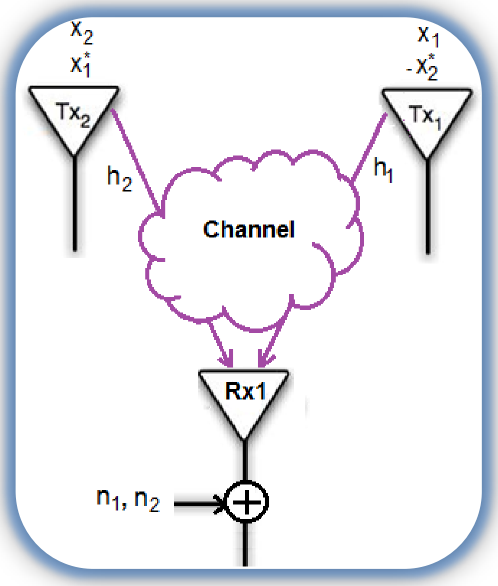


Figure (2.5): The channel effects at the Alamouti scheme (A).

The signal will be under the effect of Rayleigh fading channel and Additive White Gaussian noise (AWGN), Figure (2.5).The notation used in Figure (2.5) can be found in Table (2.2):

Table (2.2): Alamouti scheme-A channel model notation

	Fading gain		AWGN noise
From 1st antenna to the receiver	$h_1(t)$	**Noise in 1st period**	n_1
From 2nd antenna to the receiver	$h_2(t)$	**Noise in 2nd period**	n_2

Assuming the fading will be block flat fading (constant) across the two consecutive symbol periods, so we can write:

$$h_1(t) = h_1(t+T) = h_1 = \alpha_1 e^{j\theta_1} \quad (2.1)$$

$$h_2(t) = h_2(t+T) = h_2 = \alpha_2 e^{j\theta_2} \quad (2.2)$$

where T is the symbol period, $\alpha_i \; and \; \theta_i$ are the amplitude and phase factor for the channel gain.

So the received signal can be model as follow:

$$r_0 = r(t) = h_1 S_1 + h_2 S_2 + n_1 \qquad (2.3)$$
$$r_1 = r(t+T) = -h_1 S_2^* + h_2 S_1^* + n_2 \qquad (2.4)$$

where r_0 is the received signal at time t, r_1 is the received signal at time t+T, n_1 and n_2 are random variable of AWGN noise

At the receiver:

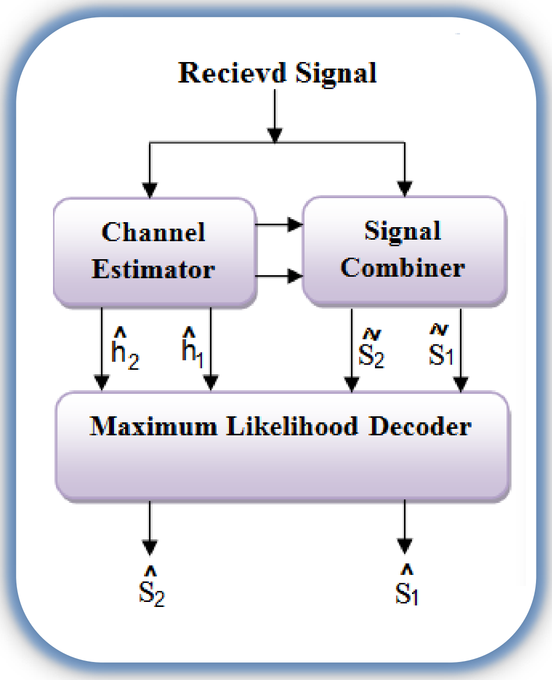


Figure (2.6): Alamouti Scheme (A) receiver.

The proposed Alamouti receiver shown in Figure (2.6), and contain three basic components which are:

1. Channel estimator: which tries to find an estimation value of paths gain
2. Signal combiner: as all diversity schemes, the basic function of combiner are to try to mitigate the fading in the signal using all the available copies of the transmitted signal.

3. ML decoder: finds out which symbol was transmitting using minimum distance.

The combining process will be as follow:

$$\hat{S}_1 = h_1^* r_0 + h_1 r_1^*$$
$$= (\alpha_1^2 + \alpha_2^2) S_1 + h_1^* n_1 + h_2 n_2^* \quad (2.5)$$
$$\hat{S}_2 = h_2^* r_0 - h_1 r_1^*$$
$$= (\alpha_1^2 + \alpha_2^2) S_2 - h_1 n_2^* + h_2^* n_1 \quad (2.6)$$

From previous equation, you can see that there is mitigation of fading effect (diversity order = 2), since there is an addition of channel gains. The combined signal will be then process by maximum likelihood (ML) detector to make a decision which symbol was transmit. The ML detector has a linear complexity as it relies on the following decision rule:

Choose s_i if and only if:

$$d^2(\hat{s}_1, \hat{s}_i) \le d^2(\hat{s}_1, \hat{s}_k) \;\; \forall i \ne k \quad (2.7)$$

Simulation result:

The simulation result of the BER performance of the Alamouti scheme (A) is shown in Figure (2.7). For sake of comparison, the BER of maximum ratio combining (MRC) when receiver space diversity applied (1×2) and the BER of direct transmission (DT) without coding or diversity are also shown in the same figure. This simulation assumes that the total transmit power from the two-antenna of Alamouti scheme is the same as the transmit power from the single antenna for MRC. Also it assumes that the receiver has a perfect knowledge of the channel.

From figure (2.7), it can be observed that the BER of both Alamouti scheme and MRC are greatly better than the BER of DT process. The gain of (A) or MRC (1×2) is at least 10 dB compared to the DT. The BER performance of both Alamouti and MRC are identical

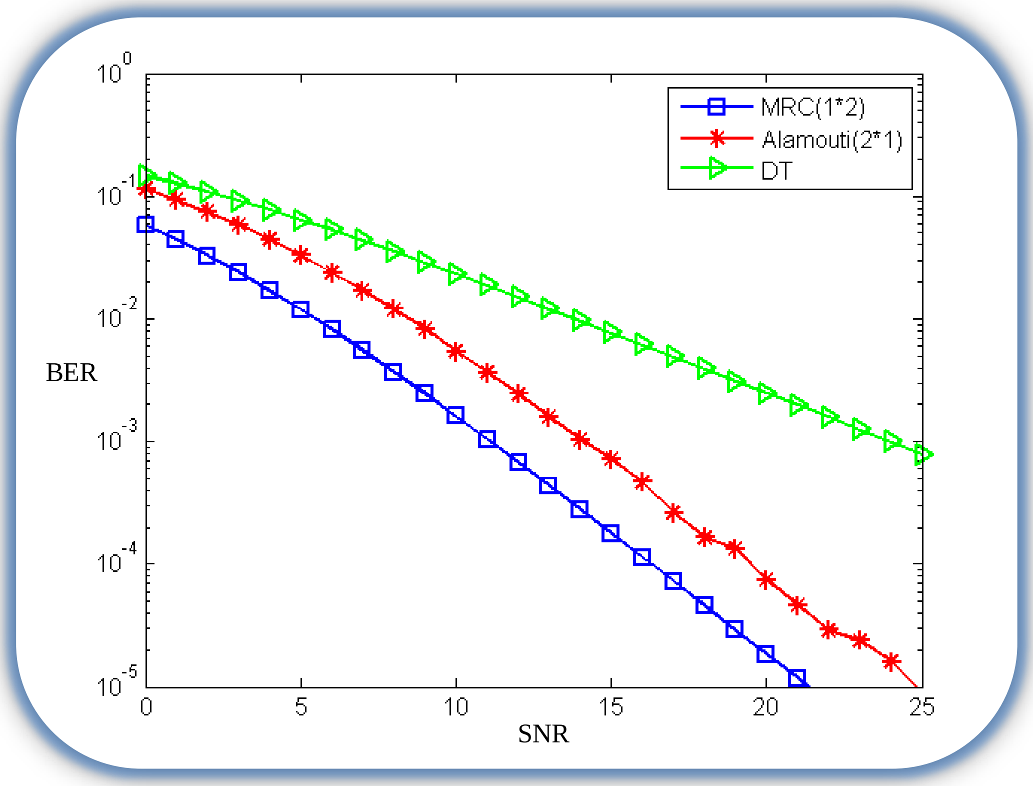


Figure (2.7): The BER performance curves of Alamouti scheme (A), MRC, and direct transmission.

Figure (2.7) gives the impression that that Alamouti scheme is worse than MRC by 3 dB. However, their performance are actually identical. The misleading 3 dB difference shown in the figure is because that Alamouti scheme applies transmit diversity so the total transmit power is divided by two; which is not the case for MRC where receive diversity is applied. We can conclude that if the BER was drawn against the SNR per transmit antenna, then the performance curves for Alamouti would shift 3 dB to the left and overlap with MRC.

When high order of diversity is required and there are feasible to have more than one antenna at the receiver, you can use the Alamouti scheme (part B) to have 2M of diversity order. This scheme also proposed by Alamouti, it will be considered in section B.

2. Two-Branch Transmit Diversity with M Receiver Antennas [7], [8], [9]:

Scheme (B) of Alamouti, consists of two-antenna at the transmitter and *M*-antenna at the receiver. The following analysis will be organized as scheme A, and it has *M* =2 as an example to illustrate the idea of the scheme. There is not any modification at the transmitter, so if you want to address the situation t the transmitter refer to part A.

Channel effect:

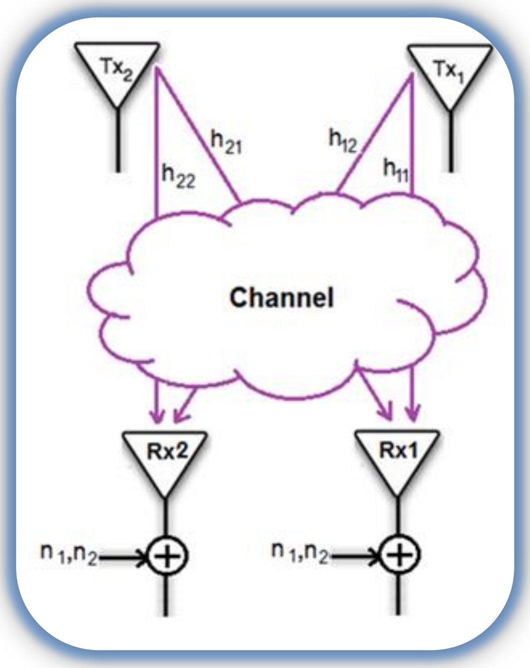


Figure (2.8): The channel effects at the Alamouti scheme (B).

The signal will be under the effect of Rayleigh fading channel and Additive White Gaussian noise (AWGN), shown in figure (2.8). The notation used in figure (2.8) shown here in Table (2.3):

Table (2.3): Alamouti scheme-B channel model notation

	To 1st Rx. antenna	To 2nd Rx. antenna		AWGN noise
From 1st Tx. antenna	$h_{11}(t)$	$h_{12}(t)$	**Noise in 1st period**	n_1
From 2nd Tx. antenna	$h_{21}(t)$	$h_{22}(t)$	**Noise in 2nd period**	n_2

Assuming the block flat fading, so we can write:

$$h_{11}(t) = h_{11}(t+T) = h_{11} = \alpha_{11}e^{j\theta_{11}} \quad (2.8)$$

$$h_{12}(t) = h_{12}(t+T) = h_{12} = \alpha_{12}e^{j\theta_{12}} \quad (2.9)$$

$$h_{21}(t) = h_{21}(t+T) = h_{21} = \alpha_{21}e^{j\theta_{21}} \quad (2.10)$$

$$h_{22}(t) = h_{22}(t+T) = h_{22} = \alpha_{22}e^{j\theta_{22}} \quad (2.11)$$

where α_{ij} *and* θ_{ij} are the amplitude and phase factor for the channel gain between the transmitter antenna (i) and the reciver antenna (j).

So the received signals can be modeled as the following:

$$r_0 = h_{11}S_1 + h_{12}S_2 + n_1 \quad (2.12)$$

$$r_1 = -h_{11}S_2^* + h_{12}S_1^* + n_2 \quad (2.13)$$

$$r_2 = h_{21}S_1 + h_{22}S_2 + n_1 \quad (2.14)$$

$$r_3 = -h_{21}S_2^* + h_{22}S_1^* + n_2 \quad (2.15)$$

where $r_0, r_1, r_2, and\ r_3$ as in table (2.4), $n_1\ and\ n_2$ are the random variable of AWGN noise

Table (2.4): received signal notation of Alamouti scheme (B)

	At 1st Rx antenna	At 2nd Rx antenna
Time *t*	r_0	r_2
Time *t+T*	r_1	r_3

At the receiver:

As shown in Figure (2.9), the received signal will be combining, and then the output of the combiner will be process through ML detector to carry out the estimated transmitted symbols. This can be done as follow:

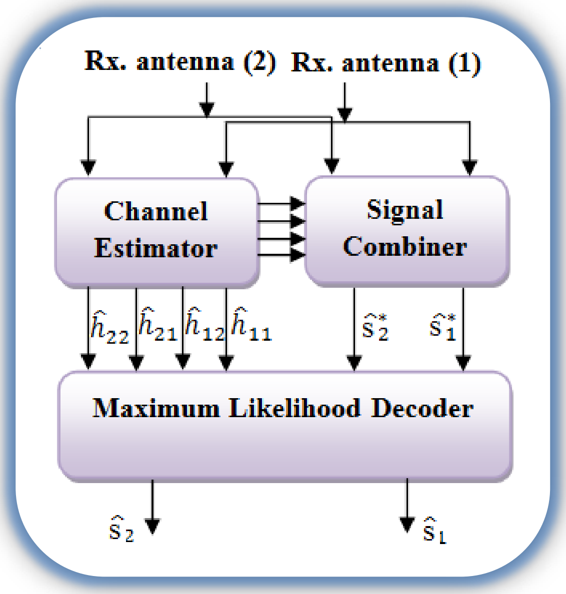


Figure (2.9): Alamouti Scheme (B) receiver.

The combiner builds the following two signals:

$$\hat{S}_1 = h_{11}^* r_0 + h_{12} r_1^* + h_{21}^* r_2 + h_{22} r_3^*$$
$$= (\alpha_{11}^2 + \alpha_{12}^2 + \alpha_{21}^2 + \alpha_{22}^2) S_1 + h_{11}^* n_1 + h_{12} n_2^* + h_{21}^* n_1 + h_{22} n_2^* \quad (2.16)$$

$$\hat{S}_2 = h_{12}^* r_0 - h_{11} r_1^* + h_{22}^* r_2 - h_{21} r_3^*$$
$$= (\alpha_1^2 + \alpha_2^2 + \alpha_3^2 + \alpha_4^2) S_2 - h_{11} n_2^* + h_{12}^* n_1 - h_{21} n_2^* + h_{22}^* n_1 \quad (2.17)$$

You can see that there is mitigation of fading effect using four paths. Then the combined signal process through ML detector as in part A.

Simulation results:

The BER of Alamouti scheme (B) is shown in Figure (2.10). Also, the BER performance of both space diversity (MRC (1×4)) and DT are included; it obtained using the existing functions in MATLAB toolboxes. There is a significant improvement in performance when scheme (B) is applied over that one when no coding or diversity applied (DT process), this observed from Figure (2.10).

For example, when DT applied, you require 15 dB over that when you use Alamouti scheme (B) or MRC (1×4). Alamouti schemes can be used just for a case where two antennas at transmitter, but in other cases you must to have a new code. Space-time block codes for any number of antennas will be discussed in the next section.

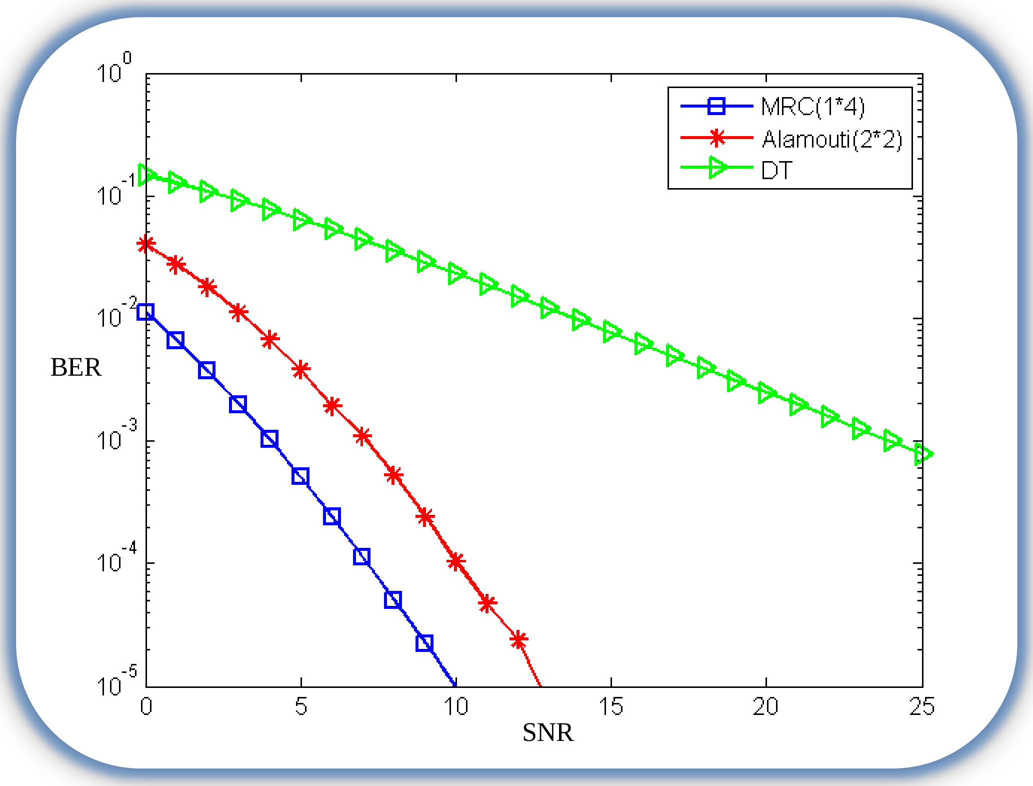


Figure (2.10): The BER performance curve of Alamouti Schemes

2.4 Space Time Block Coding:

As mentioned previously, the Alamouti scheme achieves full diversity with very simple ML detector, and this features attributed from the orthogonality between the sequences generated by the encoder to the antennas. Using the theory of orthogonal designs, you can generate codes to any arbitrary number of transmitting antennas [10]. These codes are known as space time block codes (STBCs), and it can achieve the full diversity with a very simple ML detector. This new encoding scheme of STBC can be modeled by $n_T \times n_{TX}$ matrix as follow:

Over the Tx Antennas →

Over the Time slots n_T ↓

$$\begin{bmatrix} s_{11} & s_{12} & \cdots\cdots & s_{1n_{TX}} \\ s_{21} & s_{22} & \cdots\cdots & s_{2n_{TX}} \\ . & \cdots\cdots & \cdots\cdots & . \\ . & \cdots\cdots & \cdots\cdots & . \\ s_{n_T 1} & s_{T2} & \cdots\cdots & s_{n_T n_{TX}} \end{bmatrix},$$

where n_T represent the number of time slots for transmission of one block of coded data and n_{TX} represent the number of antennas. Each column represents a transmission of single antenna over time, each row considered as a transmission at a given period over all transmitting antennas. s_{ij} is the modulated symbol to be transmitted at time slot i from antenna j.

STBC transmitter:

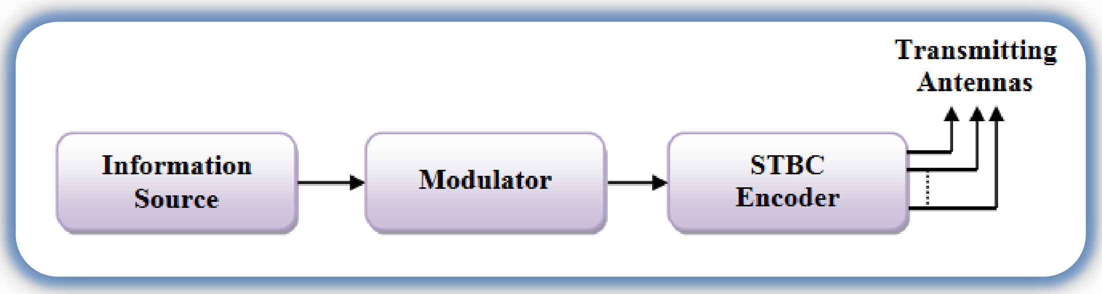


Figure (2.11): The STBC encoder.

STBC transmitter is shown in figure (2.11), and the procedure is listed as:

1. Take a block of $K \times M$ information bits, [b_1 b_2 b_3 ….b_{k*m}].
2. Map these bits into their signal cancellation where each group of m bits select a symbol according to the modulation type used, [x_1, x_2… x_k].
3. Encode the k modulated symbols by STBC code matrix to generate n_T parallel signal sequences of length T.
4. Transmit these sequences through n_{TX} antennas simultaneously in duration of n_T time slots.

The encoder takes k symbols at each encoding process and it requires n_T transmission periods to transmit their STBC symbols through the multiple transmit antennas. Usually n_T is greater (general case) than or equal(e.g.: Alamouti) k, so the definition of code rate arise here which is :

Code rate: the ratio between the numbers of symbols the encoder takes as its input (k) and the number of space-time coded symbols transmitted from each antenna (n_T) [11]. It is given by:

$$R = \frac{k}{n_T} \tag{2.18}$$

The code rate is a measure tool which provides an indication of how much there is a redundant data due to coding in the code word. R depends on the design of the code matrix. Process of designing code matrix is shown in the next sections. There is a lot of researches in this topic, so there are a lot of different space time block codes with different code rate, but most of them based on the orthogonality principle to have a full diversity and a simple decoding scheme. To illustrate the former problem, let us consider the following example:

One of the orthogonal STBC for four transmitting antennas is given by:

$$G_{4,3/4} = \begin{bmatrix} S_1 & S_2 & S_3 & 0 \\ -S_2^* & S_1^* & 0 & S_3 \\ -S_3^* & 0 & S_1^* & -S_2 \\ 0 & -S_3^* & S_3^* & S_1 \end{bmatrix} \tag{2.19}$$

From the code matrix (2.19), four time-slots are required to send three modulated symbols over 4 transmitting antenna, so the code rate is 3/4 which means that 0.25 of the transmitted data are redundant.

It has been proven that the highest rate for any n_{TX} antenna code can be achieved is [12]:

$$r_{\max} = \frac{n_0 + 1}{2n_0} \tag{2.20}$$

where $n_0 = \frac{n_{TX}}{2}$ or $n_0 = \frac{n_{TX}+1}{2}$

That's satisfied just if no linear processing is allowed in the code matrix, that's mean no mathematical operator allowable than conjugate and addition inverse.

STBC receiver:

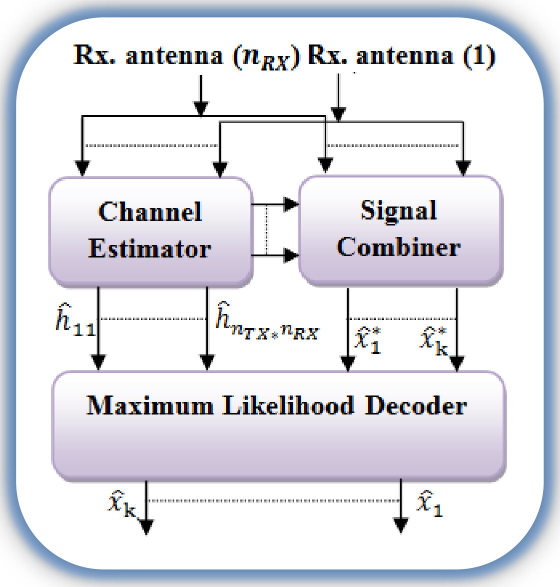


Figure (2.12): The STBC receiver.

As in Alamouti scheme B, the receiver in STBC can have n_{RX} antennas, so the receiver will have signals from $n_{TX} \times n_{RX}$ different paths the receiver. Depending on that's different paths, the receiver will have a large capability to face a deep fading. The receiver for code has k symbols per block, n_{TX} transmitting antennas, and n_{RX} receiving antennas will be as shown in Figure (2.12). As previously mentioned, since any column of the coding matrix is orthogonal with other columns, only linear processing will be used at the receiver. This implies a very simple detection algorithm at the receiver is used. To show that, a received mathematical model will be required, which we can model as the following [8], [13]:

At time *t*, the received signal at antenna *j* is:

$$r_t^j = \sum_{i=1}^{n_{TX}} h_{ij} S_t^i + n_t^i \qquad (2.21)$$

where h_{ij} is the path gain from Tx. antenna *i* to Rx. antenna *j*, S_t^i is the symbol transmitted from antenna *i* at the time period *t*, n_t^i is AWGN noise sample , n_{TX} is the number of Tx. antennas.

The maximum-likelihood detection rule is to form the decision variables:

$$R_i = \sum_{t=1}^{n_{TX}} \sum_{j=1}^{n_{RX}} r_t^j h^*_{\varepsilon_t(i)j} sign_t(i) \qquad (2.22)$$

where $sign_t(i)$ is the sign of S_i in the t^{th} row of the coding matrix, $\varepsilon_k(p) = q$denotes that S_p is (up to a sign difference, the (;,q) element of the coding matrix.

For $i = 1,2...n_T$ and then decide on constellation symbol s_i that satisfies:

$$S_i = \arg\min_{S \in \lambda}(|R_i - S|^2 + (-1 + \sum_{k,l} |h_{kl}|^2)|s|^2) \qquad (2.23)$$

where λs are the constellation alphabet. Despite its appearance, this is a simple, linear decoding scheme that provides a maximal diversity.

STBC performance result:

Simulation results for the performance of STBC on a Rayleigh fading channel will be presented here and it from [13]. In the simulation, 8-PSK modulation was used, and there is perfect channel state information at receiver. The bit error rate (BER) and the symbol error rate (SER) for STBC with 3 bits/s/Hz when there is 2, 3, and 4 transmitting antennas are shown in Figure (2.13) and (2.14). Also, the performance of an un-coded 8-PSK is plotted in the figures for comparison. These two figures show that there is a big improvement between coded and un-coded, and also when number of transmitting antenna increases.

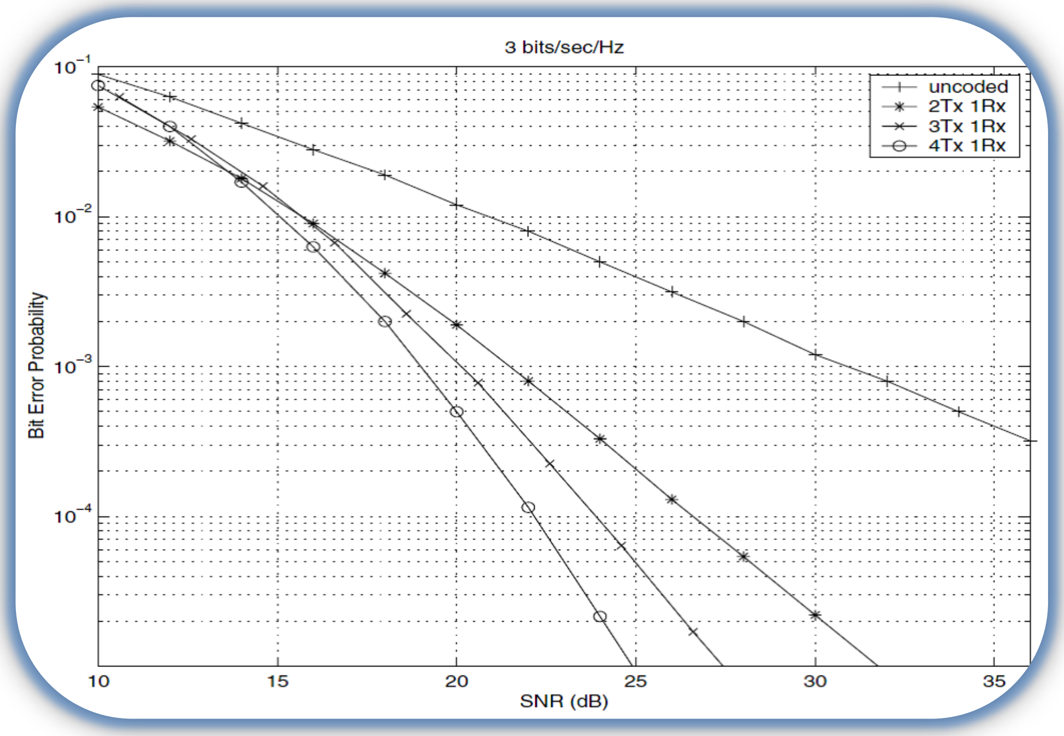


Figure (2.13): The BER performance curve of STBC for nTX = 2, 3, and 4.

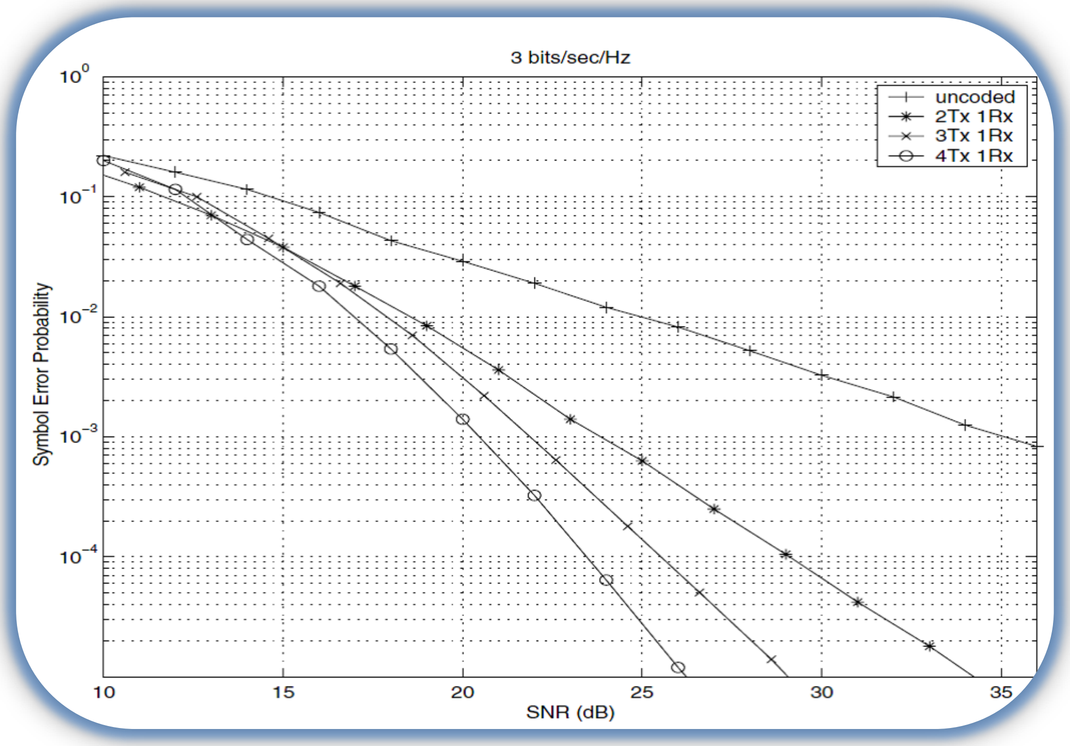


Figure (2.14): The SER performance curve of STBC for nTX =2, 3, and 4.

2.5 Design of STBC coding matrix [8], [10]:

The key feature of Alamouti scheme is that two parallel transmitted sequences are orthogonal which attribute to have a fully diversity system and very simple decoding algorithm at the receiver. So to have a code matrix for STBC (more than 2 antenna) the orthogonality also must be satisfied. The orthogonality condition can be modeled as follow:

$$G.G^H = (S_1^2 + S_2^2 + ... + S_k^2) \times I_{n_{TX}} \tag{2.24}$$

where S_1, S_2, S_3...S_k are the modulated symbols which are the input to the encoder per block.

The previous condition includes implicitly the following result:

$$x_i . x_j = \sum_{t=1}^{-T} x_{i,t} . x_{j,t}^* = 0 \qquad for\ i \neq j, i, j \in \{1, 2, ..., n_{TX}\} \tag{2.25}$$

where x_i is the transmitting sequence from the antenna i , x_j is the transmitting sequence from the antenna j, $x_{i,t}$ are the element of x_i vector , and $x_{j,t}$ are the element of x_j vector.

Based on the type of the signal constellation, space-time block codes can be classified into space-time block codes with real signals and space-time block codes with complex signals. These two categories will be considered in the next sections.

2.6 STBC for real signal constellation:

In [8], [9], [10], A full rate space time block codes for real signal cancellation has been presented and these codes has the minimum value of transmission periods n_T according to the following equation:

$$\min(2^{4x+y}) \tag{2.26}$$

where the minimization is taken over the set:

$$x, y \mid 0 \leq x, 0 \leq y \leq 4 and\ 8x + 2^y \leq n_{TX} \tag{2.27}$$

If (2.26 and 2.27) are evaluated for $n_{TX} \leq 8$, the minimum value of n_T is given as in table (2.5):

Table (2.5): Minimum values of T required to code matrix for n_T for $n_{TX} \leq 8$.

Number of *Tx* antennas	Minimum value of *T*
2	2
3	4
4	4
5	8
6	8
7	8
8	8

You can notice that only at 2, 4, or 8 the STBC will be a code with a full rate(*R=1*), and then the code matrix will be a square matrix. For the other n_T value the code rate will be less than one, and the code matrix will not be a square matrix. Some examples of coding matrices are listed below (from [3]):

For $n_{TX} = 4$:

$$G_{4,1} = \begin{bmatrix} S_1 & S_2 & S_3 & S_4 \\ -S_2 & S_1 & -S_4 & S_3 \\ -S_3 & S_4 & S_1 & -S_2 \\ -S_4 & -S_3 & S_2 & S_1 \end{bmatrix} \tag{2.28}$$

For $n_{TX} = 5$:

$$G_{5,1} = \begin{bmatrix} S_1 & S_2 & S_3 & S_4 & S_5 \\ -S_2 & S_1 & S_4 & -S_3 & S_6 \\ -S_3 & -S_4 & S_1 & S_2 & S_7 \\ -S_4 & S_3 & -S_2 & S_1 & S_8 \\ -S_5 & -S_6 & -S_7 & -S_8 & S_1 \\ -S_6 & S_5 & -S_8 & S_7 & -S_2 \\ -S_7 & S_8 & S_5 & -S_6 & -S_3 \\ -S_8 & -S_7 & S_6 & S_5 & -S_4 \end{bmatrix} \tag{2.29}$$

To illustrate how the symbols will be encoded using these matrices, let us take $G_{4,1}$ for three transmitting antennas as an example, the data will be processed and transmitted as follow:

As shown in (2.28), k (the number of symbols per block) is equal to 4 so every 4 symbols, the encoder do the following:

a. *From 1st antenna*: the transmitter will send S_1, then it will send $-S_2$, then $-S_3$, and finally it will send $-S_4$
b. *From 2nd antenna*: the transmitter will send S_2, then it will send S_1, then S_4 , and finally it will send $-S_3$
c. *From 3rd antenna*: the transmitter will send S_3, then it will send $-S_4$, then S_1 , and finally it will send S_2
d. *From 4th antenna*: the transmitter will send S_4, then it will send S_3, then $-S_2$, and finally it will send S_1
e. Repeat the same manner over whole data.

Note: For every symbol period, all antennas transmit here symbols simultaneously.

From (2.28) and (2.29), you can see that $R=1$ since there are k symbols will be transmitting in k time slots duration; it is a full rate code.

2.7 STBC for complex signal constellation [8], [9], [10]:

There is a lot of researches deal with this topic, so a lot of STBCs existing for the complex signal constellation. For example, Alamouti scheme has a code matrix as follow:

$$G_2^c = \begin{bmatrix} S_1 & S_2 \\ -S_2^* & S_1^* \end{bmatrix} \qquad (2.30)$$

This code provides a full diversity of 2 and a full code rate of 1. Alamouti is the only scheme that has a full rate, so the objective of the complex STBC design is to have a high rate code if the number of the transmit antennas is larger than two with low decoding complexity that achieve the full diversity. Here, some STBC example for different code rate for three and four transmit antenna (from [3]):

For code rate =1/2

$$G_{3,1/2}^{c}=\begin{bmatrix} S_1 & S_2 & S_3 \\ -S_2 & S_1 & -S_4 \\ -S_3 & S_4 & S_1 \\ -S_4 & -S_3 & S_2 \\ S_1^* & S_2^* & S_3^* \\ S_2^* & S_1^* & -S_4^* \\ -S_3^* & S_4^* & S_1^* \\ -S_4^* & -S_3^* & S_2^* \end{bmatrix} \tag{2.31}$$

$$G_{4,1/2}^{c}=\begin{bmatrix} S_1 & S_2 & S_3 & S_4 \\ -S_2 & S_1 & -S_4 & S_3 \\ -S_3 & S_4 & S_1 & -S_2 \\ -S_4 & -S_3 & S_2 & S_1 \\ S_1^* & S_2^* & S_3^* & S_4^* \\ S_2^* & S_1^* & -S_4^* & S_3^* \\ -S_3^* & S_4^* & S_1^* & -S_2^* \\ -S_4^* & -S_3^* & S_2^* & S_1^* \end{bmatrix} \tag{2.32}$$

For code rate =3/4

$$G_{3,3/4}=\begin{bmatrix} S_1 & S_2 & \frac{S_3^*}{\sqrt{2}} \\ -S_2^* & S_1^* & \frac{S_3^*}{\sqrt{2}} \\ \frac{S_3^*}{\sqrt{2}} & \frac{S_3^*}{\sqrt{2}} & \frac{-S_1-S_1^*+S_2-S_2^*}{2} \\ \frac{S_3^*}{\sqrt{2}} & \frac{-S_3^*}{\sqrt{2}} & \frac{S_2+S_2^*+S_1-S_1^*}{2} \end{bmatrix} \tag{2.33}$$

$$G_{3,3/4} = \begin{bmatrix} S_1 & -S_2 & \frac{S_3^*}{\sqrt{2}} & \frac{S_3}{\sqrt{2}} \\ S_2 & S_1 & \frac{S_3^*}{\sqrt{2}} & \frac{-S_3}{\sqrt{2}} \\ \frac{S_3^*}{\sqrt{2}} & \frac{S_3^*}{\sqrt{2}} & \frac{-S_1 - S_1^* + S_2 - S_2^*}{2} & \frac{-S_2 - S_2^* + S_1 - S_1^*}{2} \\ \frac{S_3^*}{\sqrt{2}} & \frac{-S_3^*}{\sqrt{2}} & \frac{S_2 + S_2^* + S_1 - S_1^*}{2} & \frac{-(S_1 + S_1^* + S_2 - S_2^*)}{2} \end{bmatrix} \qquad (2.34)$$

Note: superscript *c* stand for that this code matrix is for the complex signal constellation

The process to transmit symbols using any of previous coding matrices will be the same as the one explained in section 2.6. The only difference is that the process here will include conjugate operator.

2.8 Systematic design of High rate complex STBC [14]:

A systematic design method to generate high rate STBC codes from complex orthogonal designs for any number of transmit antennas was proposed in 2004 by Weifeng Su, Xiang-Gen Xia, and K. J. Ray Liu. This method guarantees that these codes achieve a full diversity and a very simple decoding algorithm. That's paper state 5 steps to create these codes. A summarization of their steps listed here as follow:

Let's define the following required variables:

P_{m-1} is number of row in G_{m-1}

$V_0 =$ number of nonconjugate rows of G_{m-1}

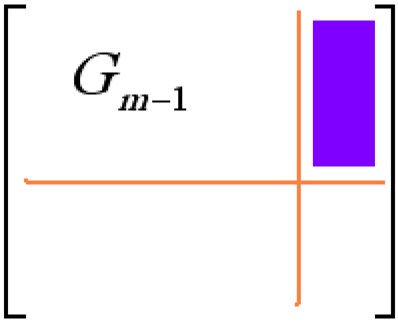
$V_1 =$ number of conjugate rows of G_{m-1}

$$\begin{bmatrix} \\ G_{m-1} \\ \\ \end{bmatrix}$$

1st step: Calculate: V_0, V_1

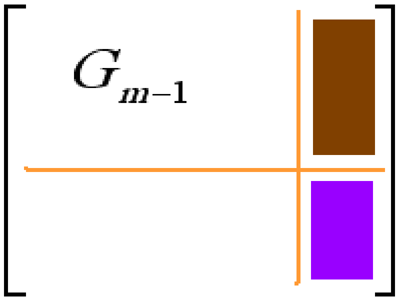
2nd step: Add new symbols to column *m* in rows from 1 to P_{m-1} as follow:

$$
\begin{aligned}
&if\ \ V_0 \geq V_1\\
&\Rightarrow add\ X_{k_{m-1}+1}, X_{k_{m-1}+2}, \ldots\ldots, X_{k_{m-1}+V_0}\\
&in\ nonconjugate\ rows.\\
&\Rightarrow add\ o\ else.\\
&if\ \ V_0 \prec V_1\\
&\Rightarrow add\ X^*_{k_{m-1}+1}, X^*_{k_{m-1}+2}, \ldots\ldots, X^*_{k_{m-1}+V_0}\\
&in\ conjugate\ rows.\\
&\Rightarrow add\ o\ else.
\end{aligned}
$$



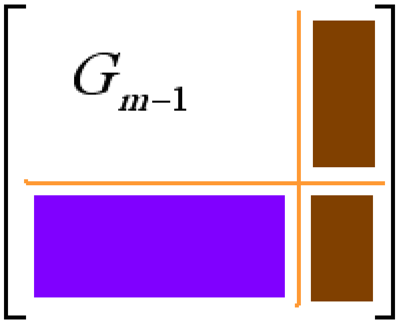
3rd step: Add new symbols to column *m* in rows after P_{m-1} as follow:

$$
\begin{aligned}
&if\ \ V_0 \geq V_1\\
&\Rightarrow add\ X^*_1, X^*_2, \ldots\ldots, X^*_{k_{m-1}}\ in\ thats\ rows.\\
&if\ \ V_0 \prec V_1\\
&\Rightarrow add\ X_1, X_2, \ldots\ldots, X_{k_{m-1}}\ \ in\ thats\ rows.
\end{aligned}
$$



4th step: Add new symbols to all columns except m in rows after P_{m-1} as follow:

$$
\begin{aligned}
&for\ element\ in\ G_{m-1} except\ 0\ do\ the\ following:\\
&if\ \ the\ sign\ of\ \ the\ element\ is\ \ +\\
&\Rightarrow G_m\,(P_{m-1} + value\ of\ \ element, col)\\
&= -G^*_m(row, m)\\
&if\ \ the\ sign\ of\ \ the\ element\ is\ \ -\\
&\Rightarrow G_m\,(P_{m-1} + value\ of\ \ element, col)\\
&= G^*_m(row, m)\\
&else\\
&\Rightarrow zero
\end{aligned}
$$



5th step: After Step 4, the m^{th} column is ready. However, we need to arrange some additional rows to ensure the orthogonality of the first *m*-1 columns. In the additional rows, simply put zeros at the m^{th} column, and for other column, refer to reference [3] step 5 to have full details. Step 4 and 5 guarantee that the resulting codes are orthogonal.

Note: we build a MATLAB GUI follows the previous step to create STBC code for any number of transmitting antennas.

Some codes generated by these steps are listed in (2.34) and (2.35):

$$G_4 = \begin{bmatrix} x_1 & x_2 & x_3 & 0 \\ -x_2^* & x_1^* & 0 & x_3 \\ -x_3^* & 0 & x_1^* & -x_2 \\ 0 & -x_3^* & x_2^* & x_1 \end{bmatrix} \tag{2.34}$$

In table (2.6), the number of symbols, time slots, and code rate are evaluated for $2 \le n_{TX} \le 18$, where n_{TX} is the number of transmitting antennas.

Table (2.6)[14]: n_{TX}, K, n_T, and R for $2 \le n_{TX} \le 18$

Number of transmitting antenna (n_{TX})	Symbols per block (k)	Number of time slots per block(n_T)	Code Rate (R)
2	2	2	1
3	3	4	3/4
4	6	8	3/4
5	10	15	2/3
6	20	30	2/3
7	35	56	5/8
8	70	112	5/8
9	126	210	3/5
10	252	420	3/5
11	462	792	7/12
12	924	1584	7/12
13	1716	3003	4/7
14	3432	6006	4/7
15	6435	11440	9/16
16	12870	22880	9/16
17	24310	43758	5/9
18	48620	87516	5/9

$$G_4 = \begin{bmatrix} s_1 & s_2 & s_3 & 0 & s_7 & 0 \\ -s_2^* & s_1^* & 0 & s_4^* & 0 & s_{11}^* \\ -s_3^* & 0 & s_1^* & s_5^* & 0 & s_{12}^* \\ 0 & -s_3^* & s_2^* & s_6^* & 0 & s_{13}^* \\ 0 & -s_4^* & -s_5 & s_1 & s_8 & 0 \\ s_4 & 0 & -s_6 & s_2 & s_9 & 0 \\ s_5 & s_6 & 0 & s_3 & s_{10} & 0 \\ -s_6^* & s_5^* & -s_4^* & 0 & 0 & s_{14}^* \\ -s_7^* & 0 & 0 & -s_8^* & s_1^* & s_{15}^* \\ 0 & -s_7^* & 0 & -s_9^* & s_2^* & s_{16}^* \\ 0 & 0 & -s_7^* & -s_{10}^* & s_3^* & s_{17}^* \\ -s_9^* & s_8^* & 0 & 0 & s_4^* & s_{18}^* \\ -s_{10}^* & 0 & s_8^* & 0 & s_5^* & s_{19}^* \\ 0 & -s_{10}^* & s_9^* & 0 & s_6^* & s_{20}^* \\ s_8 & s_9 & s_{10} & -s_7 & 0 & 0 \\ 0 & -s_{11} & -s_{12} & 0 & -s_{15} & s_1 \\ s_{11} & 0 & -s_{13} & 0 & -s_{16} & s_2 \\ s_{12} & s_{13} & 0 & 0 & -s_{17} & s_3 \\ 0 & 0 & s_{14} & -s_{11} & -s_{18} & s_4 \\ 0 & -s_{14} & 0 & -s_{12} & -s_{19} & s_5 \\ s_{14} & 0 & 0 & -s_{13} & -s_{20} & s_6 \\ s_{15} & s_{16} & s_{17} & 0 & 0 & s_7 \\ 0 & -s_{18} & -s_{19} & s_{15} & 0 & s_8 \\ s_{18} & 0 & -s_{20} & s_{16} & 0 & s_9 \\ s_{19} & s_{20} & 0 & s_{17} & 0 & s_{10} \\ -s_{13}^* & s_{12}^* & -s_{11}^* & -s_{14}^* & 0 & 0 \\ -s_{16}^* & s_{15}^* & 0 & s_{18}^* & -s_{11}^* & 0 \\ -s_{17}^* & 0 & s_{15}^* & s_{19}^* & -s_{12}^* & 0 \\ 0 & -s_{17}^* & s_{16}^* & s_{20}^* & -s_{13}^* & 0 \\ s_{20}^* & -s_{19}^* & s_{18}^* & 0 & s_{14}^* & 0 \end{bmatrix} \qquad (2.35)$$

From (table 2.6), we can observe that the rate of the designed codes satisfies the equation (2.20) which is the upper bound as stated in [9].Finally, this method which proposed in this section can be used for any number of n_{TX} with a high code rate, but for n_{TX} >10 the number of time slots per block (n_T) of generated code is large. Thus it is not practical.

2.9 Conclusion:

In this chapter, the concept of diversity techniques has been considered; then they generalized to introduce the concept of space time coding which explore the diversity of both the time and the space. More details in block coding class of this code are analyzed. A complete analysis and simulation of Alamouti schemes, which considered as the first space time code, has been analyzed. Some codes examples from real design and from complex design are listed. Finally, systematic steps to generate any orthogonal high rate space time block codes are summarized.

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Chapter 3

Distributed STBC

3.1 Introduction

The MIMO scheme can be used to combat multipath fading phenomena in wireless communications and/or to increase the data rate of the system [1]. In practice, not all applications are compatible with MIMO scheme because they either do not have multiple antennas installed on their small-size devices, or the propagation environment cannot support MIMO because, for example, there is not enough scattering [2] as shown in Figure (3.1).

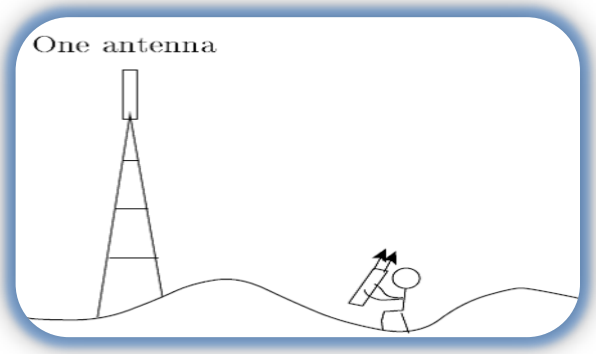

Figure (3.1): Hardware limitation of MIMO.

In the later case, even if the user has multiple antennas installed, MIMO is not achieved because the paths between several antenna elements are highly correlated. Recently, a new communication scheme, so-called cooperative MIMO, has been proposed in order to create virtual MIMO system using distributed single-input single-output (SISO) system [3]. The network that exploits the cooperative diversity is usually referred to as the cooperative network. It this network, the source node will use a number of nearby node, usually referred as relay nodes, as distributed antennas to create the virtual MIMO system. The transmission from the source and the relay nodes must be scheduled to prevent the interference, either by TDMA or FDMA. So, in any cooperative scheme, there are two phases: one used to transmit from source to both relay nodes and the destination, and the other used to forward the signal from the relay nodes to the destination. There are many different cooperative schemes; each one has its process that accomplished at the relay nodes to the signal received from the source node. The processing at the relay differs according to the employed protocol.

The STBC which used to improve the performance of MIMO system can be applied on the cooperative scheme. When STBC applied to cooperative diversity the system termed as Distributed Space Time Block Code (D-STBC) [4]. The term distributed comes from the fact that the multiple-antennas are distributed in random location.

In this chapter, we will discuss the cooperative diversity with its relaying protocols, and then D-STBC will be introduced

3.2 Cooperative Communications:

In last few years, there is a verity of services that's emerged recently over wireless communications behind the voice services, such as wireless broadband internet, gaming, and others. It requires a high data-rate to work properly, for example, in mobile broadband wireless access (MBWA) or IEEE 802.20; the downlink is 260 Mbps and 60 Mbps on the uplink [5]. These rates can be achieved by MIMO, shown in Figure (3.2), where there are multiple antennas at transmitter and receiver.

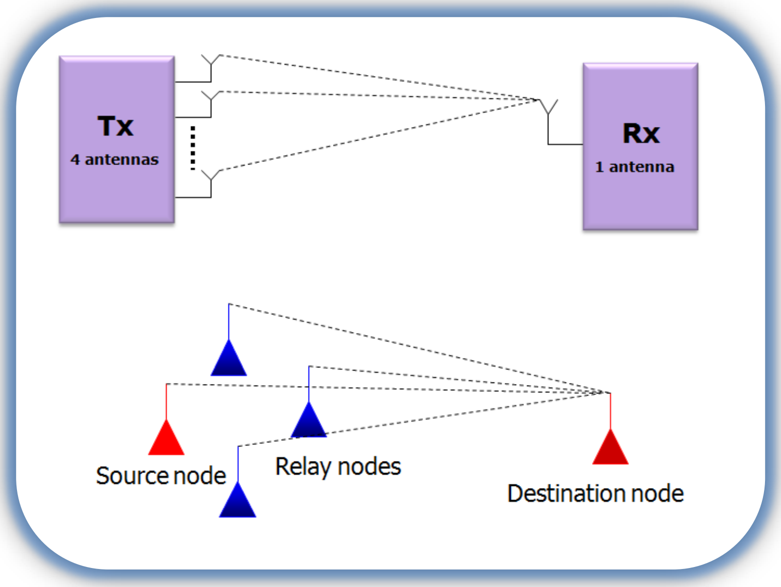

Figure (3.2): The MIMO system and Cooperative system.

In practice, not all users can guarantee such high rates because they either do not have multiple antennas installed on their small-size devices, or the propagation environment cannot support MIMO because, for example, there is not enough scattering. In the later case, even if the user has multiple antennas installed, MIMO is not achieved because the paths between several antenna elements are highly correlated. The cooperative communication is a new scheme that uses the neighbor nodes in the wireless system to act as distributed multiple-antenna to the source of transmission. Due to wireless communications nature, all nearby nodes receive the transmission between transmitter (source) and receiver (destination), so they can cooperate with each other and forwarding these messages to the intended destination. This scheme can avoid the difficulties of implementing MIMO by converting the single-input single-output (SISO) system into a virtual multiple-input multiple-output (MIMO) system [3]. Figure (3.2) also show the basic idea of the cooperative communication scheme.

In cooperative communications, the system depends on the relay channel to generate the independent paths between the source and destination. The relay channel can be thought of as an auxiliary channel to the direct channel between the source and destination [2]. The cooperative scheme almost done in two phases, either in TDMA or FDMA to avoid interference between them:

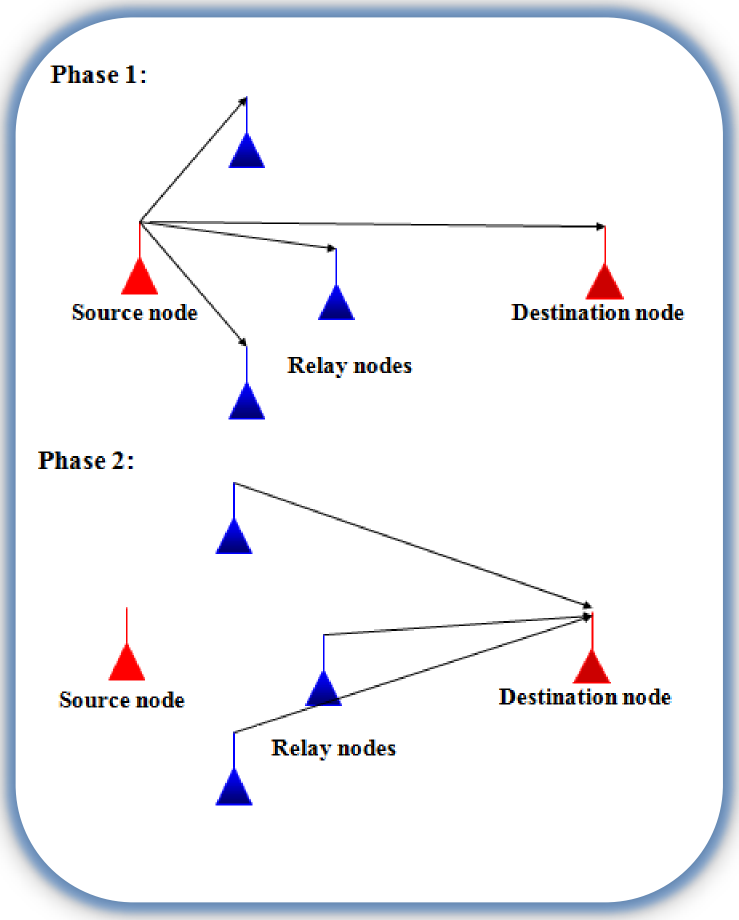

Figure (3.3): Cooperative scheme's transmission phases.

Phase 1: also called Direct Transmission (DT) phase, simply the source transmit their information signal. Both of destination and relay nodes will receive the signal at the same time.

Phase 2: Also called broadcasting phase. The relay nodes will process the signal that received from the source at phase 1 and then retransmit it to the destination.

The processing that's done at the relay nodes is an important factor; it results in different cooperative protocols.

3.3 Cooperative protocols:

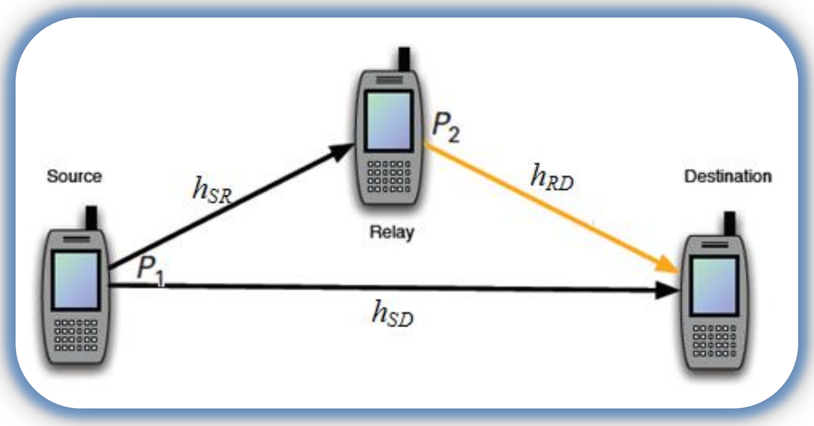

Figure (3.4): Simple cooperative system model.

Generally, the cooperative protocols can be classified in two categorizes, fixed relaying schemes and adaptive relaying schemes [2] [6]. In fixed relaying, the channel resources are divided between the source and the relay in a fixed manner which means that if FDMA are employed then the available bandwidth will be divided in a pre deterministic way between the source and the relay nodes. Adaptive relaying, the other category of cooperation protocols, introduce some adaptive processes try to improve the performance and efficiency of fixed category, in the following sub sections, protocols for each previous category will be illustrated in details.

We will take a simple model, shown in Figure (3.4), as a basis to illustrate the process accomplished in each cooperation protocols .Every symbol defined here will be also used in the reset of this chapter. The system model consists of source (*S*), one relay node (*R*), and destination (*D*).

As shown, P_1 and P_2 are the power of source signal and the power of the relay signal, respectively. In this chapter, we will consider the special case where the source and the relay transmit with equal power *P* and also it at equidistance. Optimal power allocation and moving relay nodes is beyond this research scope.

The received signals y_{SD} and y_{SR} at the destination and the relay from the source, respectively, can be modeled as:

$$y_{SD} = \sqrt{P} h_{SD} S + n_{SD} \quad (3.1)$$

$$y_{SR} = \sqrt{P} h_{SR} S + n_{SR} \quad (3.2)$$

where: S is the transmitted symbol, n_{SD} and n_{SR} are additive noise (modeled as complex Gaussian random variables with zero-mean and variance N_0), h_{SD} and h_{SR} are the channel gains from the source to the destination and the relay, respectively. (Modeled as zero-mean, complex Gaussian random variables with variances σ_{SD}^2 and σ_{SR}^2, respectively).

Whereas the received signal y_{RD} at the destination fromm the relay node can be modeled as:

$$y_{RD} = h_{RD} q(y_{SR}) + n_{RD} \quad (3.3)$$

where: $q(\cdot)$ is a function depends on which processing is implemented at the relay, n_{RD} is additive noise (modeled as complex Gaussian random variable with zero-mean and variance N_0), and h_{RD} is the channel gain from the relay node to the destination (modeled as zero-mean, complex Gaussian random variable with variance σ_{RD}^2).

3.3.1 Fixed cooperation protocols:

In fixed relaying protocols, the channel resources are divided between the source and the relay in a deterministic manner. This category has the advantage of easy implementation due to systematic nature, but it has also disadvantages of low bandwidth efficiency and errors propagation. The low efficiency is due to that the system will divide the channel resources even if the destination correctly detects the transmitted symbols in phase 1, which waste the bandwidth and reduce the overall data rate in the system. Also, this category suffers of errors propagation problem that occurs if the channel between the source and the relay has severe fading so the nodes will relaying distorted copy to the destination.

The processing at the relay differs according to the employed protocols. Here, the most common protocols will be illustrated in details:

1. Fixed Amplify and Forward relaying protocol :

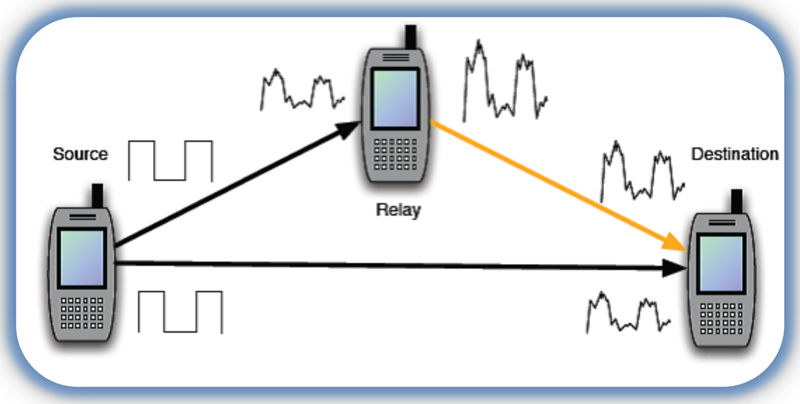

Figure (3.5): Amplify and Forward (AF) relaying protocol.

In this protocol which shown in Figure (3.5), simply called AF protocol, the relay node just amplifies the received signal y_{SR} (written in equation (3.1)) and then it will forward it to the destination [2], [6], [7]. The amplification factor β_m tries to equalize the effect of the channel fading between the source and the relay and it can be written as [2]:

$$\beta_r = \frac{\sqrt{P}}{\sqrt{P|h_{SR}|^2 + N_0}} \quad (3.4)$$

The amplified version of the signal which will be then forwarded to the destination is $\beta_r y_{SR}$ and it has a power P equal to the power transmitted from the source. The received signal at the destination from the relays, y_{RD} , is

$$y_{RD} = \beta_r h_{RD} y_{SR} + n_{RD} \quad (3.5)$$

Substituting (3.2) and (3.4) into (3.5):

$$y_{RD} = \frac{\sqrt{P}}{\sqrt{P|h_{SR}|^2 + N_0}} \sqrt{P} h_{RD} h_{SR} S + n'_{RD} \quad (3.6)$$

where:

$$n_{RD}^{'} = \frac{\sqrt{P}}{\sqrt{P|h_{SR}|^2 + N_0}} h_{RD} n_{SR} + n_{RD}$$

Assuming that n_{SR} and n_{RD} are independent, then the equivalent noise $n_{RD}^{'}$ is a zero-mean, complex Gaussian random variable with variance:

$$N_0^{'} = \left(\frac{P|h_{RD}|^2}{P|h_{SR}|^2 + N_0} + 1\right) N_0 \quad (3.7)$$

Now, there are two copies of the transmitted signal received at the destination, one from the relay node and the other is directly from the source. As mentioned in section (2.2), there are different strategies that can be used to combine these two signals to have better performance, such as SC, SSC, EGC, and MRC. Here, the maximal ratio combiner (MRC), which is the optimal combining technique, will be used to combine the signals.

The MRC output can be written as:

$$y = a_1 y_{RD} + a_2 y_{RD}, \quad (3.8)$$

where a_1 and a_2 are the combining factors.

The value of the combining factors designed to maximize the overall SNR. It is considered as an optimization problem which has different technique to solve. Their values are as the following [2]:

$$a_1 = \frac{\sqrt{P} h_{SD}^*}{N_0}, \qquad a_2 = \frac{\sqrt{\frac{P}{P|h_{SR}|^2 + N_0}} \sqrt{P} h_{SR}^* h_{RD}^*}{\left(\frac{P|h_{RD}|^2}{P|h_{SR}|^2 + N_0} + 1\right) N_0}$$

As mentioned, the MRC maximize the overall SNR and it will be as follow (assuming normalized transmitted symbols energy):

$$SNR_{overall} = SNR_1 + SNR_2, \quad (3.9)$$

where:

$$\mathrm{SNR}_1 = \frac{\left|a_1\sqrt{P}h_{SD}\right|^2}{|a_1|^2 N_0} = \frac{P|h_{SD}|^2}{N_0}$$

and

$$SNR_2 = \frac{\left|a_2 \dfrac{\sqrt{P}}{\sqrt{P|h_{SR}|^2 + N_0}} \sqrt{P} h_{RD} h_{SR}\right|^2}{N_0' |a_2|^2} = \frac{1}{N_0} \frac{P^2 |h_{SR}|^2 |h_{RD}|^2}{P|h_{SR}|^2 + P|h_{RD}|^2 + N_0}$$

Simulation result [8]:

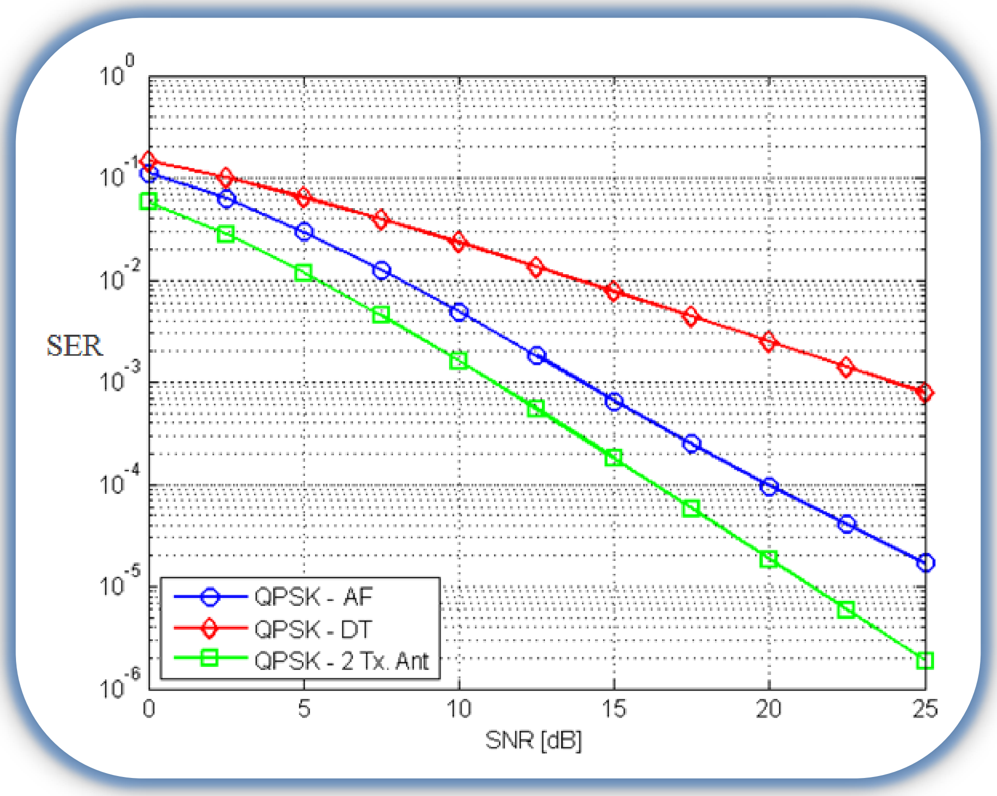

Figure (3.6): The SER performance curve of AF protocol and DT.

Figure (3.6) shows the SER of AF protocol. Also, the performance of direct transmission (DT) included in the same figure as well as the BER of MIMO (2×1). As shown from the figure, there is diversity gain achieved by AF as clear from the curve slope over the (DT) case.

2. Fixed decode and forward relaying protocol:

This protocol, simply called DF protocol, illustrated in Figure (3.7). It processes the data as follow:

the relay node decodes the received signal y_{SR} , re-encodes it, and then the relay forwards the encoded data to the destination [2], [7].

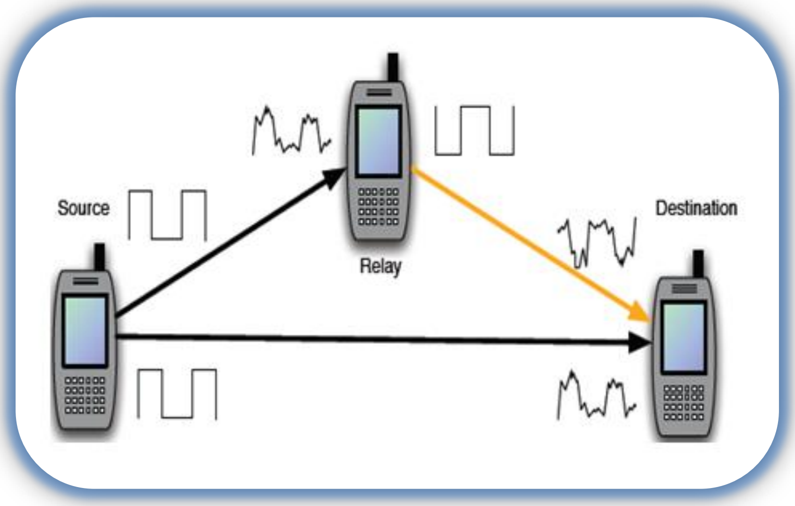

Figure (3.7): Decode and Forward (DF) relaying protocol.

Let the decoded signal of y_{SR} at the relay node is $\hat{S}$, then the transmitted signal will be $\sqrt{P}\hat{S}$. Although this scheme reduces the additive noise at the relay node, it suffers of error-propagation problem that occurs if the channel between the source and the relay has severe fading. In this case, the nodes will detect incorrect symbols and then retransmit the incorrect symbols to the destination which is considered meaningless. We can notice from the simulation result (Figure (3.8)) that for such scheme the diversity achieved is only one. This can be justified as the performance of the system is limited by the worst link from the source–relay and source–destination [2].

Simulation result [8]:

Figure (3.8) shows the SER of DF protocol, direct transmission (DT), and MIMO (2×1) system. As shown, there is a diversity gain achieved by DF as clear from the curve slope over the (DT) case, but it is less than for the case of AF protocol that due to errors propagation.

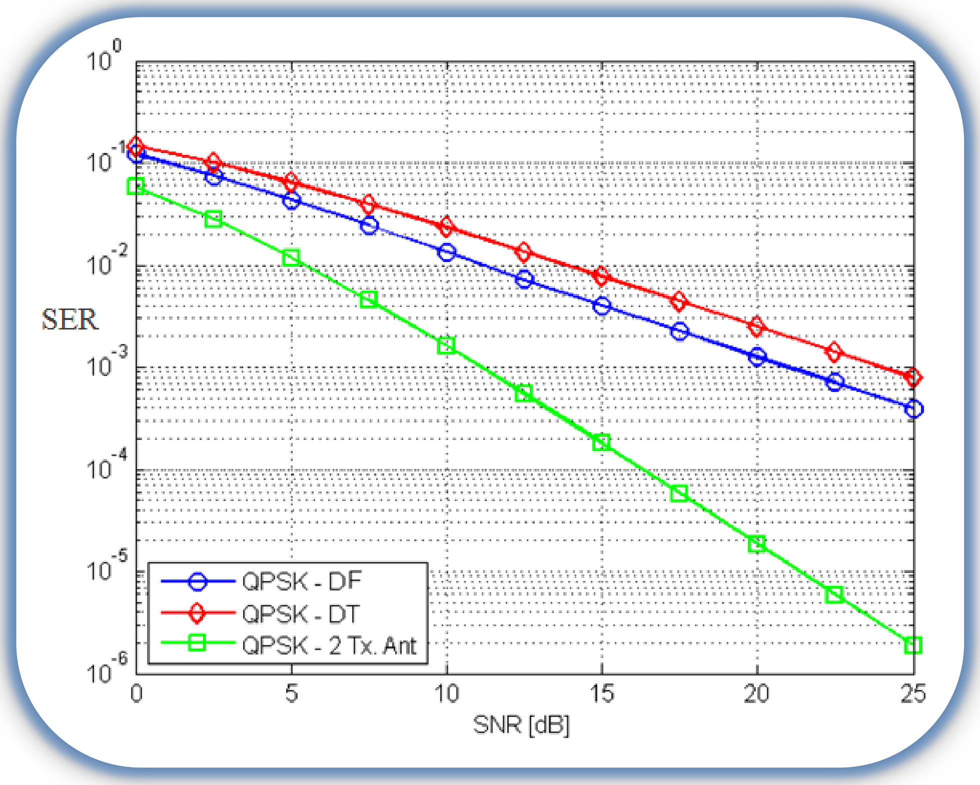

Figure (3.8): SER for DF protocol when QPSK used.

We can notice that the expected performance of DF protocol is not clear here due to propagation error, hence a sufficient level of redundancy should be added to the data at node *S* as a result the relaying will happen only if the relay node correctly detects the symbols, this scheme is termed "selective relaying" in section (3.3.2).

3. Other Fixed protocols:

There are two other strategies classified under fixed category, such as:

Compress-and-forward protocol [2][6]:

As its name indicates, the relay transmits a quantized and compressed version of the received message, this process shown in Figure (3.9). Therefore, the destination node will perform the reception functions by combining the received message from the source node and its quantized and compressed version from the relay node.

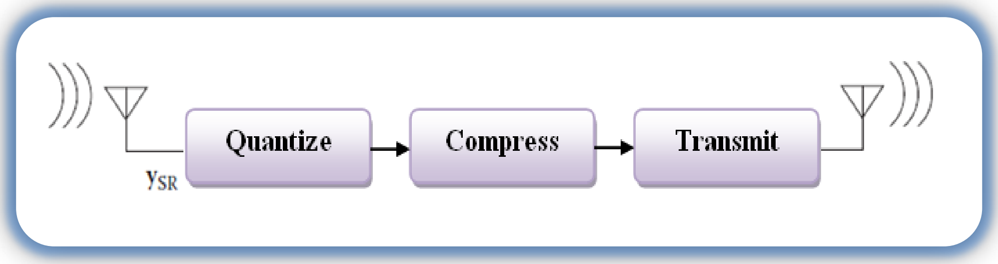

Figure (3.9): Compress and Forward relaying protocol.

Coded cooperation protocol [2][6]:

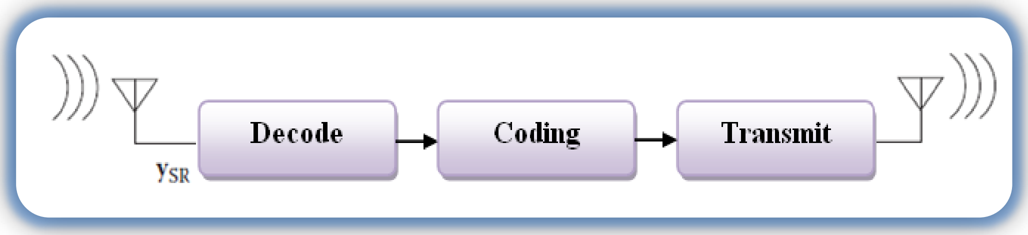

Figure (3.10): Coded relaying protocol.

In this protocol, shown in Figure (3.10), the relay adds redundancy bits to the detected bits that received from the source, and then forward the whole bits to the destination. The redundancy in the codeword is used at the receiver to increase the chances of recovering the original information if errors have been introduced during the transmission process [2].

3.3.2 Adaptive cooperation protocols:

As mentioned in section (3.3.2), the fixed protocols have advantage of easy implementation, but it also has disadvantages which are low spectral efficiency and error propagation. There are different adaptive cooperative protocols that try to overcome the disadvantage of fixed protocols category and increase the overall performance. The main adaptive protocols are selective decode and forward relaying and incremental relaying.

1. Selective decode and forward relaying protocol:

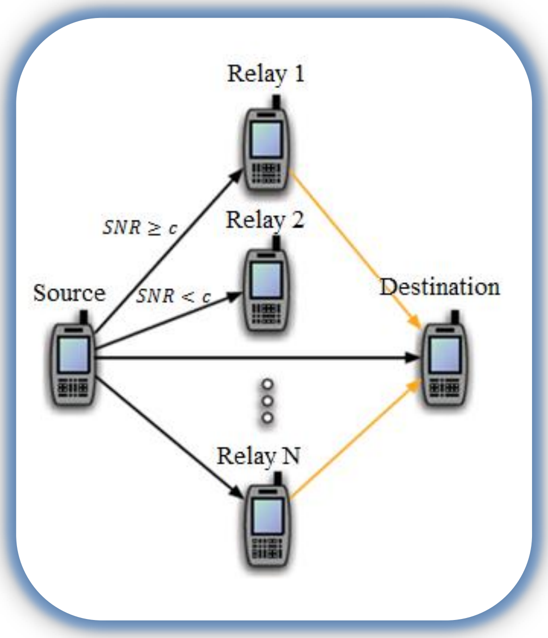

Figure (3.11): Selective decode and forward relaying protocol.

This scheme tries to overcome the problem of fixed DF protocol [2][7]. As mentioned, error propagation problem occurs when the channel between the source and the relay has severe fading so the nodes will detect incorrect symbols and then retransmit these incorrect symbols to the destination. So, the problem will be diminished if a certain value of SNR is introduced at the relay node as threshold such that if the SNR of the received signal at the relay exceeds a certain threshold, the relay decodes the received signal and forwards the decoded information to the destination. Otherwise, if the channel between the source and the relay suffers a severe fading such that the SNR falls below the threshold, the relay idles. To illustrate the idea, suppose there is a system consists of source, destination, and N relay nodes as shown Figure (3.11). If the system uses c as threshold of SNR at each relay node, then the second relay node will be idle since its signal has SNR below the threshold whereas first relay node will be active, since its SNR is greater than the threshold. Another technique that can be used to implement the idea of selective relaying is by adding extra redundancy to the source node symbols, so the relaying done only if the relay detects the symbols correctly.

Simulation result [8]:

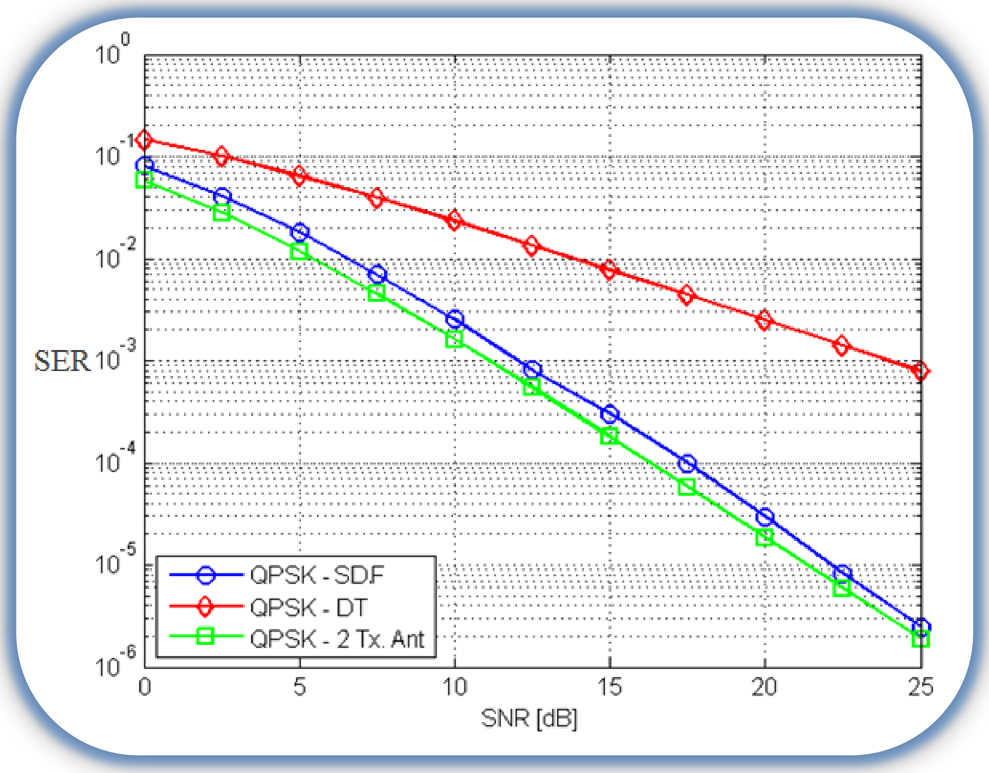

Figure (3.12): The SER performance curve of Selective DF protocol, DT, and MIMO (2×1).

The BER of Selective DF protocol, direct transmission (DT), and MIMO (2×1) system are shown in Figure (3.12). As shown, the value of DF protocol is clear now, there is a great improvement in SER of Selective DF (Figure 3.12) over that one of Fixed DF (Figure (3.9)), that's due to extra redundancy which terminates the error propagation.

2. Incremental relaying :

In fixed protocols category, although if the destination correctly detect the transmitted symbols in phase 1, the channel resources divided between the source and relay node which waste the bandwidth that reduce the overall data rate in the system. This issue can be overcome, if there is feedback channel from the destination to the relay nodes. This called incremental relaying [2] [7].

In incremental relaying, the destination will send an acknowledgment to the relay node through feedback channel if it receives the transmission of the source in phase 1 correctly, so the relay node will be idle. Since, there is no second phase; the source transmits new information in the time slot of this phase. On the other hand, if the source transmission was not successful in the first phase, the relay can use any of the fixed relaying protocols to transmit the source signal from the first phase

3.3.3 Comparison between different protocols:

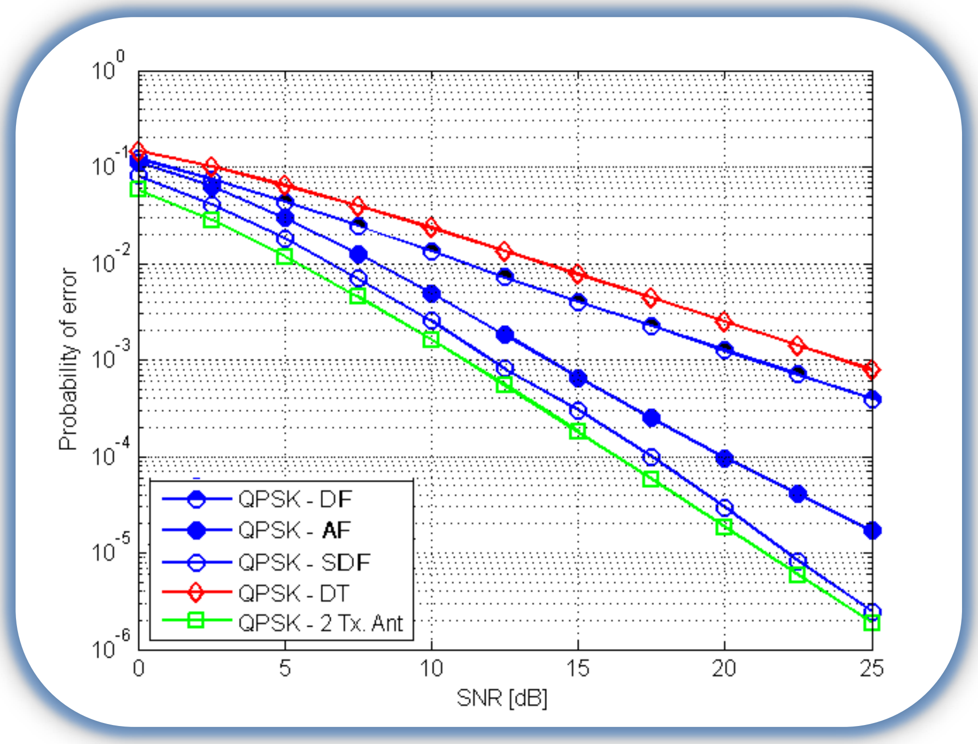

Figure (3.13): The SER performance curve of AF, DF, and SDF protocol when QPSK used

This section try to compare between all different protocols discussed in sections (3.3.1-3.3.2). Figure (3.13) shows the SER performance of these protocols [8], it also show the performance of direct transmission (DT) and transmit diversity of order two.

It can be observed, that the selective relaying scheme is the best, then AF protocol was found to be the second one. Whereas the DF protocol is the worse one, that because the error propagation was occurred.

Figure (3.13) shows the outage probability versus spectral efficiency of all previous protocol [2]. From this figure, you can observe that the DF protocol have the worst spectral efficiency that because of error propagation that has occurred in this protocol. Whereas, the incremental relaying protocol has the best spectral efficiency since it exploits the spectral resource of phase 2 to transmit other data based on the condition that the data is transmitted correctly during phase 1.

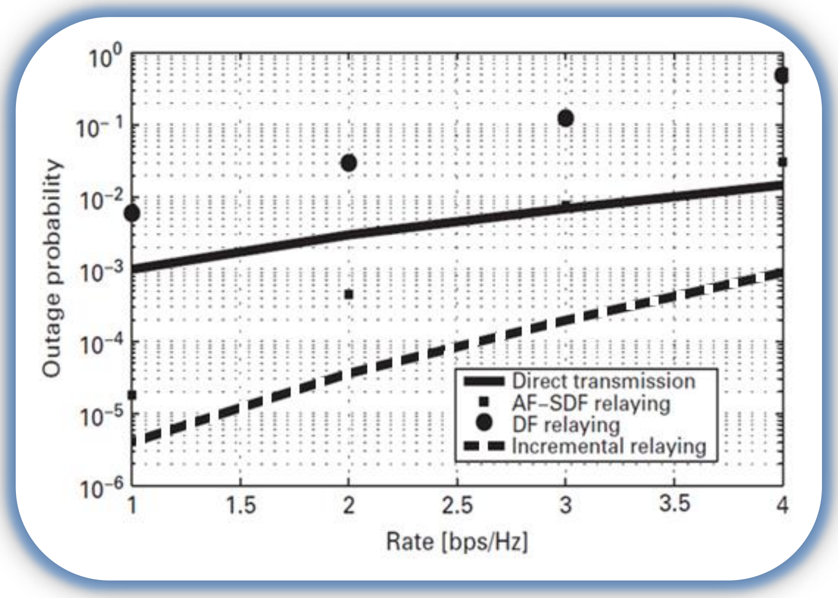

Figure (3.14): AF, DF, SDF, and incremental relaying protocol spectral efficiency.

3.4 Distributed Space time Block Coding:

A mentioned in chapter 1, Space- Time Block Coding (STBC) are used to improve the transmission reliably and spectral efficiency of MIMO systems [9]. Since the cooperative communication techniques can create a virtual MIMO, it can be merged with STBC [10-11-12-13]. When STBC applied to cooperative diversity the system termed as Distributed Space Time Block Code (D-STBC) [4]. The term distributed comes from the fact that the virtual multi-antenna transmitter is distributed between randomly located relay nodes. Here, in this research we limit our scope to selective decode and forward protocol since its performance and we need to restrict our issue in the imperfect synchronization problem.

3.4.1 D-STBC under Alamouti code:

Here, we will illustrate the basics of D-STBC using simple code which is Alamouti [13]. The system model which is analyzed, consists of source (*S*), two relay nodes (R_1 and R_2), and destination (*D*). It is shown in Figure (3.14):

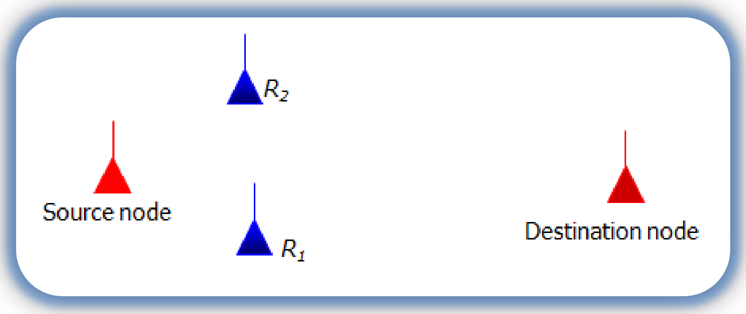

Figure (3.15): The D-STBC (Alamouti code) system model.

As in most cooperative systems, the transmission is done over two phases:

[Phase 1] Node *S* broadcasts their data tuple while R_1, R_2, and *D* are receiving. Each tuple contains two symbols, since Alamouti scheme requires two symbols for each encoding process. This is shown in Figure (3.15); where $h_{SD}, h_{SR_1}, h_{SR_2}$ are the channel gains between *S* and *D*, *S* and R_1, and *S* and R_2, respectively, it modeled as zero-mean, complex Gaussian random variables with variances $\sigma_{SD}^2, \sigma_{SR_1}^2, \sigma_{SR_2}^2$,

At node *D*, the received signal associated with transmitted tuple (*i*) is:

$$r_{SD}(i) = h_{SD}s(i) + n_{SD}(i), \quad (3.10)$$

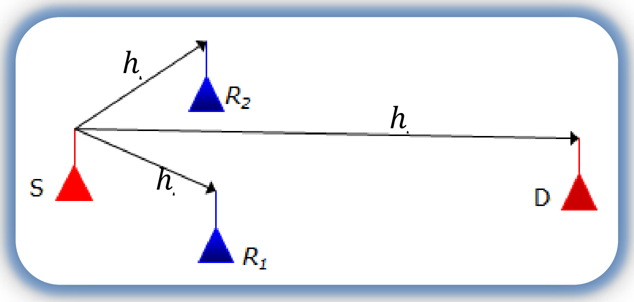

Figure (3.16): Distributed Alamouti code-phase 1.

where:

$s(i) = [s(1,i), s(2,i)]^T$,$r_{SD}(i) = [r_{SD}(1,i), r_{SD}(2,i)]^T$, $n_{SD}(i) = [n_{SD}(1,i), n_{SD}(2,i)]^T$, $n_{SD}(k,i)$ is the AWGN with zero mean and variance of σ_n^2.

Whereas the received signal associated at relay node 1 and 2, is:

$$r_{SR_1}(i) = h_{SR_1} s(i) + n_{SR_1}(i) \quad (3.11)$$

$$r_{SR_2}(i) = h_{SR_2} s(i) + n_{SR_2}(i) \quad (3.12)$$

where:

$r_{SR_1}(i) = [r_{SR_1}(1,i), r_{SR_1}(2,i)]^T$, $r_{SR_2}(i) = [r_{SR_2}(1,i), r_{SR_2}(2,i)]^T$, $n_{SR_1}(i) = [n_{SR_1}(1,i), n_{SR_1}(2,i)]^T$, $n_{SR_2}(i) = [n_{SR_1}(1,i), n_{SR_1}(2,i)]^T$, $n_{SD}(j,i)$ is the AWGN with zero mean and variance of σ_n^2.

[Phase 2] As transmitted data tuple received at R_i, it will be decoded, encoding, then forwarding the symbols to the destination. These steps illustrated as follow:

1. The decoding can be determined using least square (LS) search:

$$\hat{s}_{SR_1}(\ell, i) = arg\left\{\min_{s_i \in S} |h_{SR_1}^* r_{SR_1}(\ell, i) - |h_{SR_1}|^2 s_\ell\right\} \quad (3.13)$$

$$\hat{s}_{SR_2}(\ell, i) = arg\left\{\min_{s_i \in S} |h_{SR_2}^* r_{SR_2}(\ell, i) - |h_{SR_2}|^2 s_\ell\right\} \quad (3.14)$$

for $\ell = 1, 2$. S is the symbol alphabet containing M symbols.

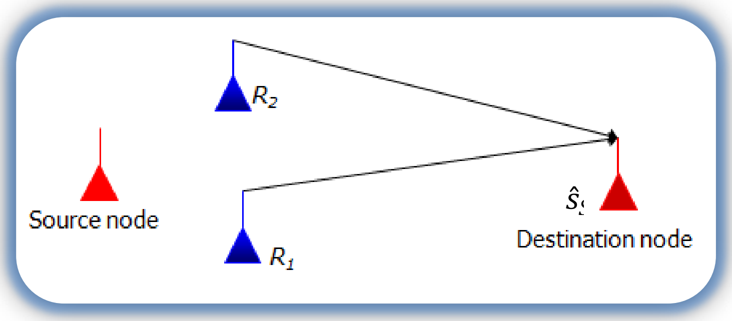

Figure (3.17): Distributed Alamouti code-phase 2.

2. Each relay encodes the detected symbol using Alamouti coding matrix as follow:

   At 1st relay, the result of encoding process is:

$$\begin{bmatrix} \hat{s}_{SR_1}(1,i) & \hat{s}_{SR_1}(1,i) \\ -\hat{s}^*_{SR_1}(2,i) & \hat{s}^*_{SR_1}(1,i) \end{bmatrix}$$

   , and at 2nd relay, the result of encoding process is:

$$\begin{bmatrix} \hat{s}_{SR_2}(1,i) & \hat{s}_{SR_2}(1,i) \\ -\hat{s}^*_{SR_2}(2,i) & \hat{s}^*_{SR_2}(1,i) \end{bmatrix}$$

3. Each relay transmit their sequence :

   The 1st relay transmits:

$$\begin{bmatrix} \hat{s}_{SR_1}(1,i) \\ -\hat{s}^*_{SR_1}(2,i) \end{bmatrix}$$

   , and at 2nd relay transmits:

$$\begin{bmatrix} \hat{s}_{SR_2}(1,i) \\ \hat{s}^*_{SR_2}(1,i) \end{bmatrix}$$

A sufficient level of cyclic redundancy check (CRC) can be added to the data at node S so the relaying will happen only if R_m's are correctly detect the symbols, this scheme is termed "selective relaying" in [7]. This research assumes that the channel gains h_{SR_m} where $m = 1,2$ are such that R_m's can always detect correctly, so$\hat{s}_{SR_1}(\ell,i) = \hat{s}_{SR_2}(\ell,i) = s(\ell,i)$, for $\ell = 1,2$.

Simulation result:

Figure (3.17) shows the BER performance of D-STBC that uses Alamouti code. Same figure also shows the BER performance of direct transmission (DT) without coding or diversity. This simulation assumes that the total transmit power from the two antenna of Alamouti scheme that the receiver has perfect knowledge of the channel. Also it assumes the relay nodes are synchronized with each other, so the destination receives the transmitted symbols from each relay in the same time.

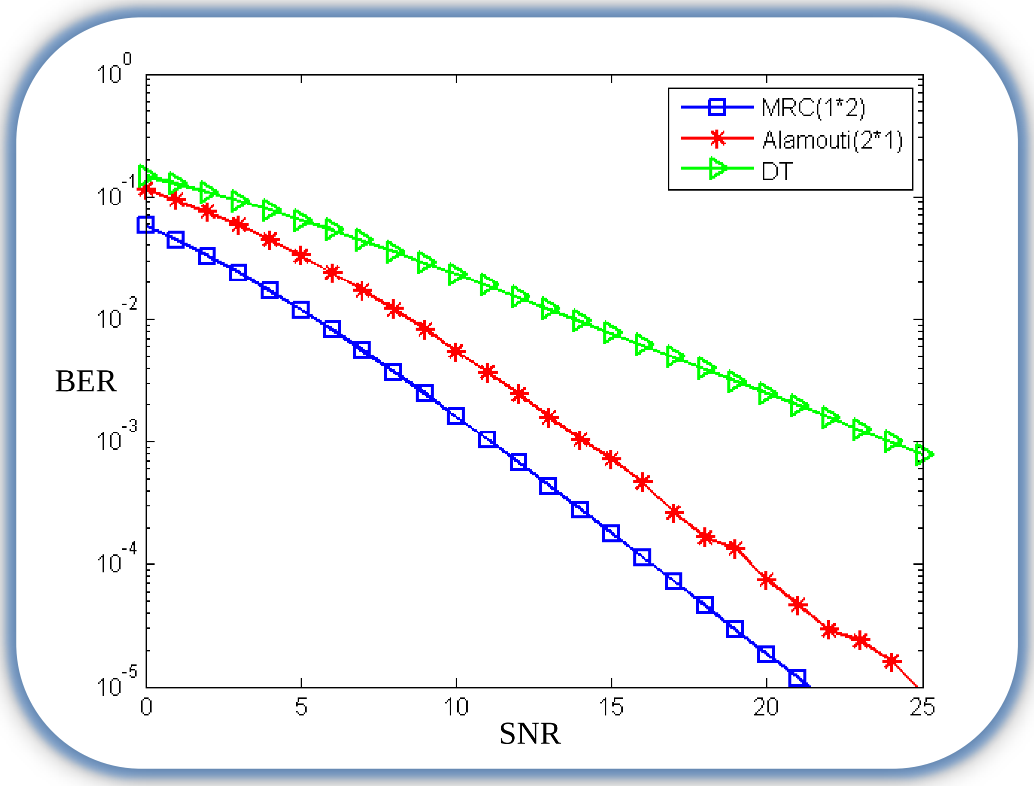

Figure (3.18): The BER curve of Distributed Alamouti system.

Since the relays are assumed to detect the symbols correctly and its transmission receive at the destination at the same time , the performance of D-STBC that using Alamouti code and conventional Alamouti scheme (A) are identical that observed form comparing Figure (3.18) with Figure (2.7).

3.4.2 General D-STBC:

The D-STBC for just two relay nodes is discussed in section (3.4.1), but here we will try to generalize the concept of D-STBC [11-12-13]. The system model which will be analyzed consists of source (S), number m of relay nodes ($R_1 \ldots R_m$), and destination (D). It is shown in Figure (3.18). Following the same steps in section (3.4.1), the transmission is also done in two phases:

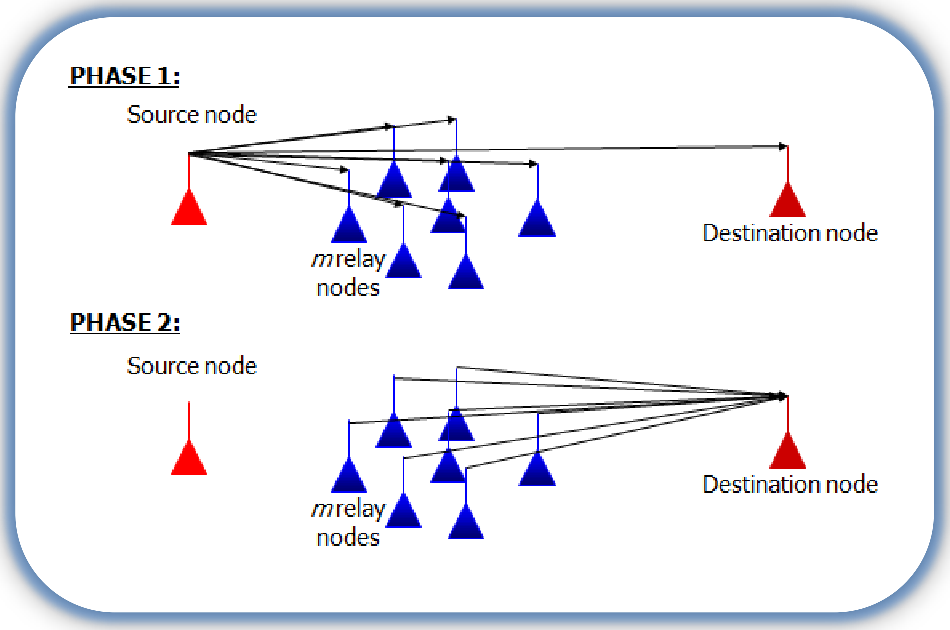

Figure (3.19): The two transmission phases of General D-STBC.

In phase 1, the source transmits their tuple while the relay nodes and the destination are receiving. Each tuple contains k number of symbols, that's according to the coding matrix of the STBC.

In phase 2, each relay node processes its received signal as follow:

- Decode the received and determine the detected symbols $\hat{s}_{SR_1}(\ell, i)$, $\ell = 1, ., k$
- Encode the detected symbols using coding matrix G_m.
- Forward its symbol sequence (each relay transmit its column from the coding matrix)

The performance of General D-STBC is also identical as the performance of conventional STBC, that's true under the following assumption:

1. Each relay node detects the symbols correctly.
2. All relay nodes are synchronized with each other. This means that the destination receives the transmitted symbols from each relay at the same time.

The first assumption can be attained through numerous strategies, such as incremental relaying that mentioned in section (3.3), but the second one is difficult to be employed [15-16]. In this research, we try to analysis and propose solutions for the problem that result from imperfect synchronization between the relay nodes.

3.5 Conclusion:

The MIMO system is one of the most interesting research areas, but it has a big challenge which is the implementation of multiple antennas at the nodes devices. In this chapter, we introduce the cooperative scheme which uses the clients in the communication network to act as distributed antenna to the original transmitter. Many cooperative protocols are studied and simulated here, such as: amplify and forward protocol, decode and forward protocol, and others. Also, Distributed-STBC analyzed and we introduced its big problem which is the lack of perfect synchronization.

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Chapter 4

Imperfect Synchronization: Problem and Solutions

4.1 Introduction:

During the last decade, there has been an intensive work of researches on D-STBC techniques to demonstrate their key role in increasing the channel reliability and improving the spectral efficiency in wireless communication systems without need to implement physical multiple antennas or increasing in spectral resources. Most of the existing research assumes perfect synchronization among cooperative users in D-STBC. This means that all users are assumed to have the identical timing, carrier frequency and propagation delay [1].

Unfortunately, perfect synchronization is almost impossible to be achieved. The lack of common timing reference can badly influence the structure of the code matrix [1]. Therefore, most of the designed space-time codes are no longer valid for cooperative diversity unless they are delay tolerant [2]. There are different research efforts to overcome this problem [3], [4], and [5]; most of which has high decoding complexity [6]. In [3] and [4], a detection scheme for not perfectly synchronized D-

STBC has been proposed which is based on the principle of Parallel Interference Cancellation (PIC).

In this chapter, the effect of imperfect synchronization on the D-STBC system will be analyzed, then an approach in [3] and [4] (PIC approach for 2, 3, and 4 relay nodes) of will be shown and used as a basis to propose a general form of a PIC approach to be suitable for any number of relay nodes in D-STBC system. Finally, we proposed a second approach to mitigate the impact of imperfect synchronization which proves its ssenevitceffe and it depend in successive interference cancellation (SIC) basics [7].

4.2 Problem illustration:

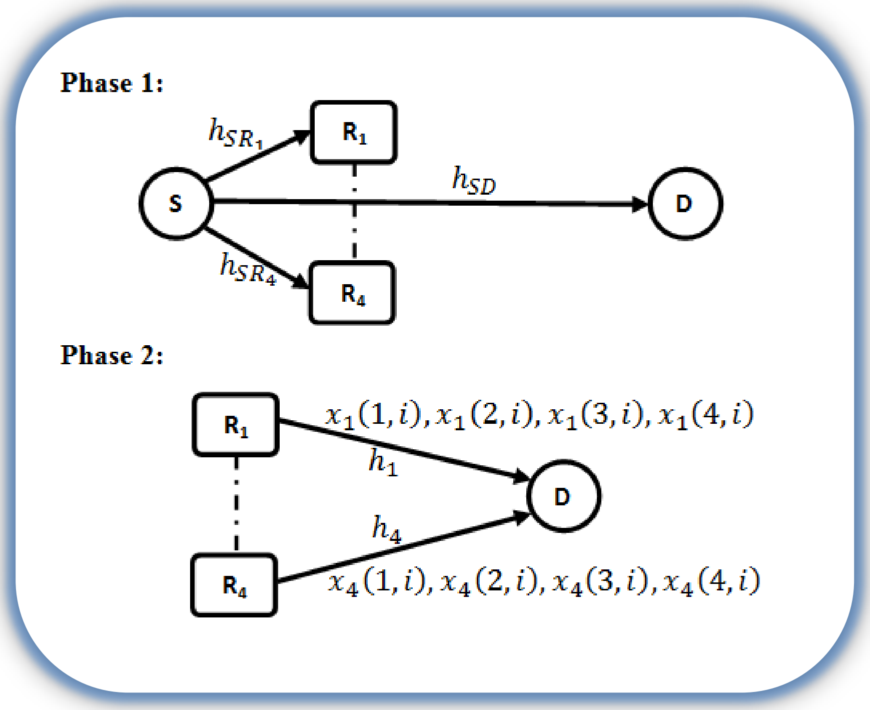

Figure (4.1): The 2-phase of D-STBC system with 4 relay nodes.

To illustrate the problem, a system model shown in Figure (4.1) is considered. The system consists of the source node (S), four relay nodes (R_1 to R_4), and the destination node (D). All of nodes are fixed at random locations for every transmissions period (the case of moving nodes is beyond the scope of this research). All of problem formulation presented here is based on the derivation in [3]. As in most cooperative system, the transmission done through two phases (TDMA or FDMA):

Phase 1: Node *S* broadcasts their data while the relay nodes (R_1, R_2... R_4) and *D* are receiving. The received signal associated with transmitted tuple $S(i)$ assuming a Rayleigh channel model is:

<u>at node D</u>:

$$r_{SD}(i) = h_{SD}s(i) + n_{SD}(i), \tag{4.1}$$

where h_{SD} is the channel gain between *S* and *D*, $s(i) = [s(1,i),..,s(3,i)]$, $r_{SD}(i) = [r_{SD}(1,i),..,r_{SD}(3,i)]$, $n_{SD}(i) = [n_{SD}(1,i),..,n_{SD}(3,i)]^T$, and $n_{SD}(k,i) \in CN(0,\sigma_n^2)$

<u>at relay nodes R_1, R_2... R_4</u>:

$$r_{SR_1}(i) = h_{SR_1}s(i) + n_{SR_1}(i), \tag{4.2-a}$$

$$r_{SR_2}(i) = h_{SR_2}s(i) + n_{SR_2}(i), \tag{4.2-b}$$

$$r_{SR_3}(i) = h_{SR_3}s(i) + n_{SR_3}(i), \tag{4.2-c}$$

$$r_{SR_4}(i) = h_{SR_4}s(i) + n_{SR_4}(i), \tag{4.2-d}$$

where:

$h_{SR_1}, h_{SR_1}, h_{SR_1}$, and h_{SR_1} are the channels gains from *S* to R_1...R_4, respectively. $n_{SR_1}(i), n_{SR_2}(i), n_{SR_2}(i)$, and $n_{SR_2}(i)$ are AWGN noise vectors.

The detection at destination node for the phase 1 transmission can be determined using least square (LS) search:

$$\hat{S}_{SD}(\ell,i) = arg\left\{\min_{s_i \in S} |h_{SD}^* r_{SD}(\ell,i) - |h_{SD}|^2 s_\ell\right\} \tag{4.3}$$

for $\ell = 1,2,3$ and S is the symbol alphabet containing *M* symbols.

Phase 2: As mentioned in chapter 3, there are different relaying protocols can be employed. Here, we use "Incremental Relaying DF" as a relaying mode [8], since it has the best BER performance and the best spectral efficiency. So, only the relays that correctly detect the symbols will be active. The detection at the relay nodes can be determined using least square (LS) search:

$$\hat{s}_{SR_m}(\ell, i) = \arg\left\{\min_{s_i \in S} |h^*_{SR_m} r_{SR_m}(\ell, i) - |h_{SR_m}|^2 s_\ell\right\} \quad (4.4)$$

for $m = 1, .., 4$, $\ell = 1,2,3$, and S is the symbol alphabet containing M symbols.

This work assumes that's the four relay nodes detect the symbols correctly. Since the relays correctly detect the transmitted symbols, the detected symbols at the relay nodes $\hat{s}_{SR_m}(\ell, i)$ is identical as transmitted symbols, $s(i)$. Every relay node will encode its detected symbols $s(i)$ using (4.4) and then each relay transmits its sequence, $x_m(i) = [x_m(1, i), x_m(2, i), x_m(3, i), x_m(4, i)]^T$.

$[x_1(i), x_2(i), x_3(i), x_4(i)] =$

$$\begin{bmatrix} s(1,i) & s(1,i) & s(1,i) & 0 \\ -s^*(1,i) & s^*(1,i) & 0 & -s(1,i) \\ -s^*(1,i) & 0 & s^*(1,i) & s(1,i) \\ 0 & s^*(1,i) & -s^*(1,i) & s(1,i) \end{bmatrix}, \quad (4.4)$$

where $x_1(i), .., x_4(i)$ are the transmitting sequences from R_1,..R_4, respectively.

Because of factors such as different propagation delay, relay's sequences $x_1(i), \ldots, x_4(i)$ will arrive at node D at different time instants. As accurate synchronization is difficult or impossible [9], [10] there is a timing misalignment τ_m between the received sequences at D from the relays, as shown in Figure (4.2). A condition of quasi-synchronization has been assumed: $\tau_m \in [0, 0.5T]$, where T is the symbol period. This assumption is much easier to meet in practice.

The received signal is a superposition of received sequences, and it modeled as:

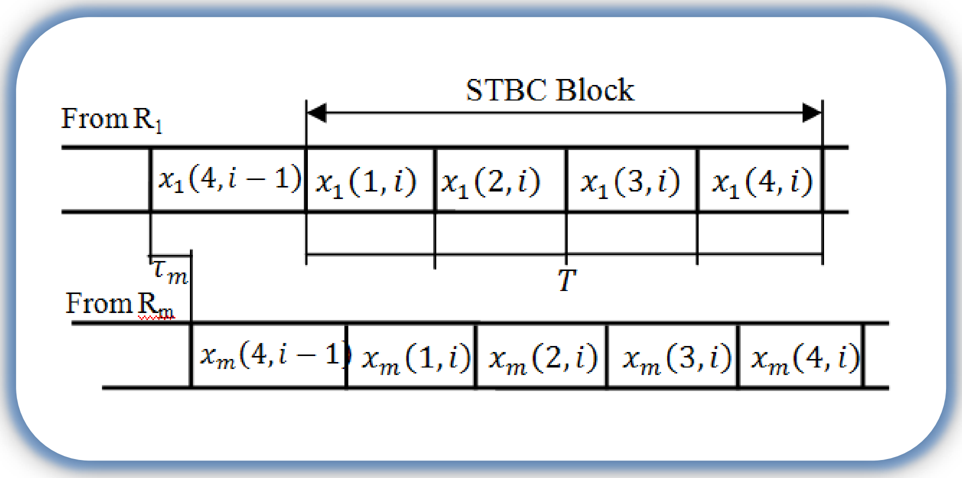

Figure (4.2): The received signals of phase 2 at the destination node of D-STBC system with four relay nodes

$$r(1,i) = \sum_{m=1}^{4} h_m(0)x_m(1,i) + \underbrace{\sum_{m=2}^{4} h_m(1)x_m(4,i-1)}_{interference \quad term} + n_{RD}(1,i), \quad \text{(4.6-a)}$$

and

$$r(k,i) = \sum_{m=1}^{4} h_m(0)x_m(k,i) + \underbrace{\sum_{m=2}^{4} h_m(1)x_m(k-1,i)}_{interference \quad term} + n_{RD}(k,i), \quad \text{(4.6-b)}$$

where k= 2, 3, 4, and $h_m(0)$ denotes to the current time slot channel gain whereas $h_m(1)$ reflect the inter-symbol interference from the previous symbol ($h_m(\ell)$ for $\ell = 2, \dots, \infty$ can be truncated since they are much less dominant [3]).

The strength of $h_m(1)$ depends on the amount of time misalignment and the relation between them is not our issue here because it depends on the PSW used in the system. So we can just use β_m ratio to model the value of time misalignment. β_m ratio is modeled by:

$$\beta_m = \frac{|h_m(1)|^2}{|h_m(0)|^2}$$

The value of β_m depends upon time misalignment and the pulse shaping waveform (PSW) used. Whatever PSW is used, $\beta_m = 0$ for $\tau_m = 0$, and $\beta_m = 1$ $(0\ dB)$ for $\tau_m = 0.5T$ that's due to the symmetry of PSW [3].

Substituting the value of $x_m(j,i)$ from (4.5) into (4.6-a) and (4.6-b), the received sequence can be modeled as follow:

$$r(i) = H_3 s(i) + B_3 s^*(i) + I(i) + n_{RD}(i), \tag{4.8}$$

where

$$r(i) = [r(1,i), r^*(2,i), r^*(3,i), r^*(4,i)]^T,$$

$$H_3 = \begin{bmatrix} h_1(0) & h_2(0) & h_3(0) \\ h_2^*(0) & -h_1^*(0) & 0 \\ h_3^*(0) & 0 & -h_1^*(0) \\ 0 & -h_3^*(0) & h_2^*(0) \end{bmatrix},$$

$$B_3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -h_4^*(0) \\ 0 & h_4^*(0) & 0 \\ h_4^*(0) & 0 & 0 \end{bmatrix},$$

$$I(i) = [I(1,i), I(1,i), I(1,i), I(1,i)]^T,$$

$$n_{RD}(i) = [n_{RD}(1,i), n_{RD}^*(2,i), n_{RD}^*(3,i), n_{RD}^*(4,i)]^T,$$

since

$$I(1,i) = \sum_{m=2}^{4} h_m(1) x_m(4, i-1), \tag{4.9-a}$$

$$I(k,i) = \sum_{m=2}^{4} h_m(1) x_m(k-1, i), k = 2,3,4, \tag{4.9-b}$$

where $n_{RD} \in CN(0, \sigma_n^2)$ is the additive noise, $x_m(j,i)$ is the symbol transmitted from relay *m* and at time slot *j* of tuple *i*.

D-STBC performance under imperfect synchronization:

To carry out the detection based on $r(i)$, we rewrite (4.8) in to the following form (for simplicity, we have dropped the time index i:

$$\begin{bmatrix} r_R \\ r_I \end{bmatrix} = Q \begin{bmatrix} S_R \\ S_I \end{bmatrix} + \begin{bmatrix} I_R \\ I_I \end{bmatrix} + \begin{bmatrix} n_{R,RD} \\ n_{I,RD} \end{bmatrix}, \quad (4.10)$$

where

$$Q = \begin{bmatrix} H_{3R} + B_{3R} & -H_{3I} + B_{3I} \\ H_{3I} + B_{3I} & H_{3R} - B_{3R} \end{bmatrix}.$$

The notation z_R denotes the real part of z, and z_I denotes the imaginary part of z. Now, Q is orthogonal matrix (it is easy to prove that), so

$$\Lambda = Q^T \times Q = diag(\lambda, \dots, \lambda), \quad (4.11)$$

where

$$\lambda = \sum_{k=1}^{4} |h_k|^2$$

The conventional D-STBC detector which assumes perfect synchronization follows the following steps to carry out the detection of transmitted symbols at the receiver:

1. Multiplying the received signals by Q^T (this doesn't change the independence of the additive noise):

$g(i) = [g(1,i),\dots,g(6,i)]^T =$

$$Q^T \begin{bmatrix} r_R \\ r_I \end{bmatrix} = \Lambda \begin{bmatrix} S_R \\ S_I \end{bmatrix} + Q^T \begin{bmatrix} I_R \\ I_I \end{bmatrix} + v \ , \quad (4.12)$$

   where $v = Q^T [n_{RD,R}, n_{RD,I}]^T$ is the post transform additive noise with $E(vv^T) = 0.5\sigma_n^2 \Lambda$

2. Detect the transmitted symbols by using LS search :

$$\hat{s}(\ell,i) = \arg\{\min_{s_\ell \in S} | g(\ell,i) + jg(\ell+3,i) - \lambda s_\ell |^2\} \quad (4.13)$$

,

   where $j = \sqrt{-1}$, $\ell = 1,2,3$, and S as denoted in eq.(2).

Due to the interference component $Q^T \begin{bmatrix} I_R \\ I_I \end{bmatrix}$ in (4.12), the orthogonality of STBC is damaged, a great degradation in the performance occurs, unless $h_m(1) = 0$ (the case of perfect synchronization).

Simulation result:

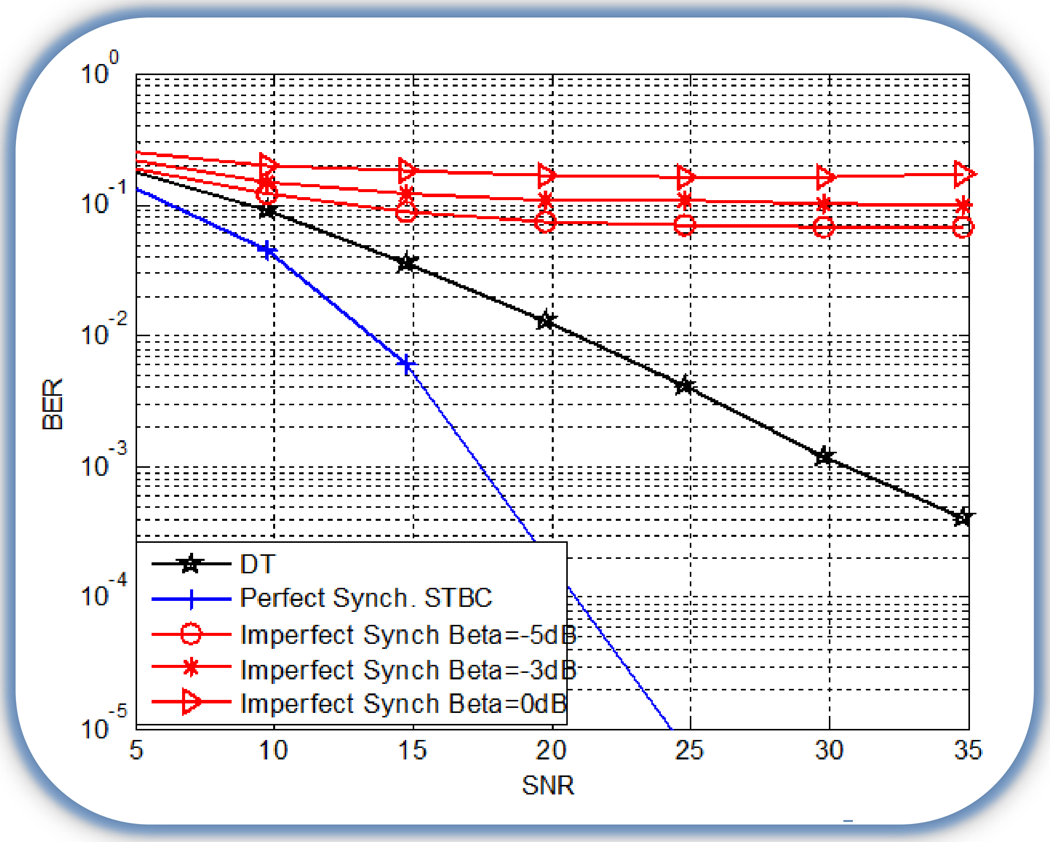

Figure (4.3): The BER of conventional D-STBC detector under imperfect synchronization under different value of β

The BER of the conventional STBC detector have been simulated to show the impact of imperfect synchronization under different values of β_m. Figure (4.3) shows the BER performance of conventional detector when there is perfect synchronization in the D-STBC system, and also when there is imperfect synchronization under $\beta_m = 0, -3, -5$.

The BER of direct transmission is also included in the same figure. From the figure, we can observe that even if the time misalignment is relatively small ($\beta_m =$

$-5\,dB$) the conventional detector fail to mitigate the impact of the imperfect synchronization.

4.3 PIC approach:

Here, an approach to mitigate the impact of imperfect synchronization will be proposed. We can observe from (4.8), that the degradation in the performance is due to the $I(i)$. So, if we can remove as much as possible from it then absolutely the performance will be improved. Parallel Interference Cancellation (PIC) is an effective approach to improve the performance of CDMA scheme under imperfect synchronization [11] and it will be effective in D-STBC as will be shown here.

In section (4.3.1), we present the PIC approach for 4 relay nodes case as in [3], and in section (4.3.2) we try to generalize the concept of PIC approach to be suitable for any number of relay nodes.

4.3.1 Four relay nodes case:

Depending on the derivation in section (4.2), we can notice that $I(1,i)$ in (4.8) is just due to the symbols from previous block. So, if the detection process has been initialized properly (e.g. by using pilot symbols at the start of the packet), $I(1,i)$ in (4.8) can be cancelled. Now, in (4.8) there is interference just from the current block symbols $\{I(2,i), I(3,i), I(4,i)\}$ which can be reduced by using PIC as follow:

Initialization:

1. Set $k = 0$.
2. Let $\hat{s}^k(1,i) = [s(1,i), s(2,i), s(3,i)]$ which is the result of (3), DT process.
3. Remove ISI from $\mathrm{r}(1,\mathrm{i})$ by calculate:

$$r^{'}(1,i) = r(1,i) - I(1,i)$$

Iteration k: $k = 1,\ 2\ldots K$

4. Remove more ISI by calculating

$$r'^{(k)}(i) = \begin{bmatrix} r'(1,i) \\ r^*(2,i) - I^{(k-1)}(2,i) \\ r^*(3,i) - I^{(k-1)}(3,i) \\ r^*(4,i) - I^{(k-1)}(4,i) \end{bmatrix}$$

   use (9-b) and feed it by $\hat{S}^{k-1}$ to calculate $I^{(k-1)}(2,i)$

5. Determine $g^{(k)}(i)$ as follow :

$$g^{(k)}(i) = Q^T \begin{bmatrix} real(r'^{(k)}(i)) \\ imag(r'^{(k)}(i)) \end{bmatrix}$$

6. Apply LS search (4.13) to detect the transmitted symbols.
7. Update the value of the $\hat{S}^k$

Simulation Result:

With an 8-PSK modulation type and assuming imperfect synchronization between the relay nodes, the BER of the conventional detector and PIC detector for k =1, k = 2, and k=3 under the value of $\beta_m = -5, -3,$ and 0 dB will be simulated. Also, the BER of Direct Transmission (DT) and perfect synchronized D-STBC system will be included to compare the results.

Figure (4.4) shows the BER of two iterations of PIC detector (*k =1, k = 2, and k=3*) under $\beta_m = -5\ dB$. The performance of PIC detector (k = 3) relatively approach to that one of perfect synchronized system. We can observe that there is a large improvement on the BER performance over conventional detector. For example, the value of $BER = 10^{-2}$ cannot be achieved by conventional detector whereas by PIC detector you just required a 14.5 dB of SNR when $k = 2$ to achieve it.

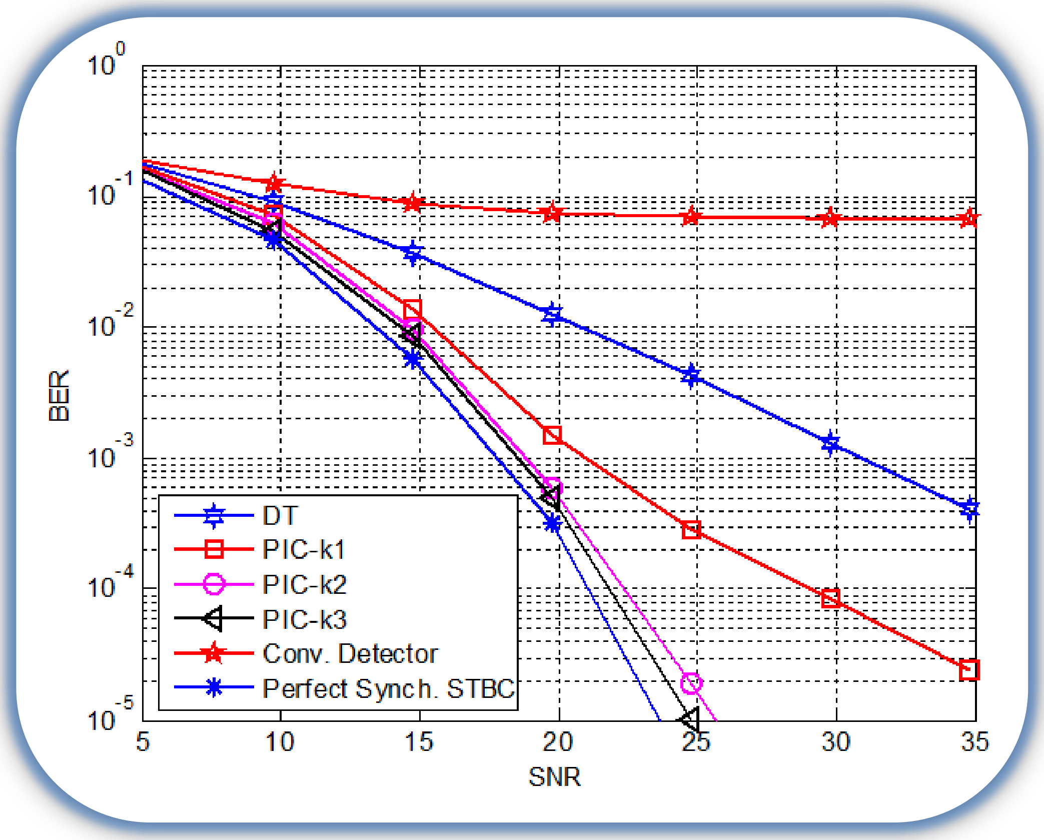

Figure (4.4): Iteration k = 1, 2, and 3 of PIC detector when $\beta_m = -5dB$

Now, the system simulated when $\beta_m = -3\ dB$, which consider relatively large amount of imperfect synchronization. The figure (4.5) shows the performance result, you can observe the PIC detector is still effective and can relatively mitigate the impact of imperfect synchronization, but its affectivity is less than the case of ($\beta_m = -5\ dB$). Also, we simulate the BER of the PIC detector when $\beta_m = 0\ dB$, which consider the largest amount of imperfect synchronization, it is shown in figure (4.6). You can observe the PIC detector is still effective and can relatively mitigate the impact of imperfect synchronization, but its affectivity is less than the case of ($\beta_m = -5\ dB$).

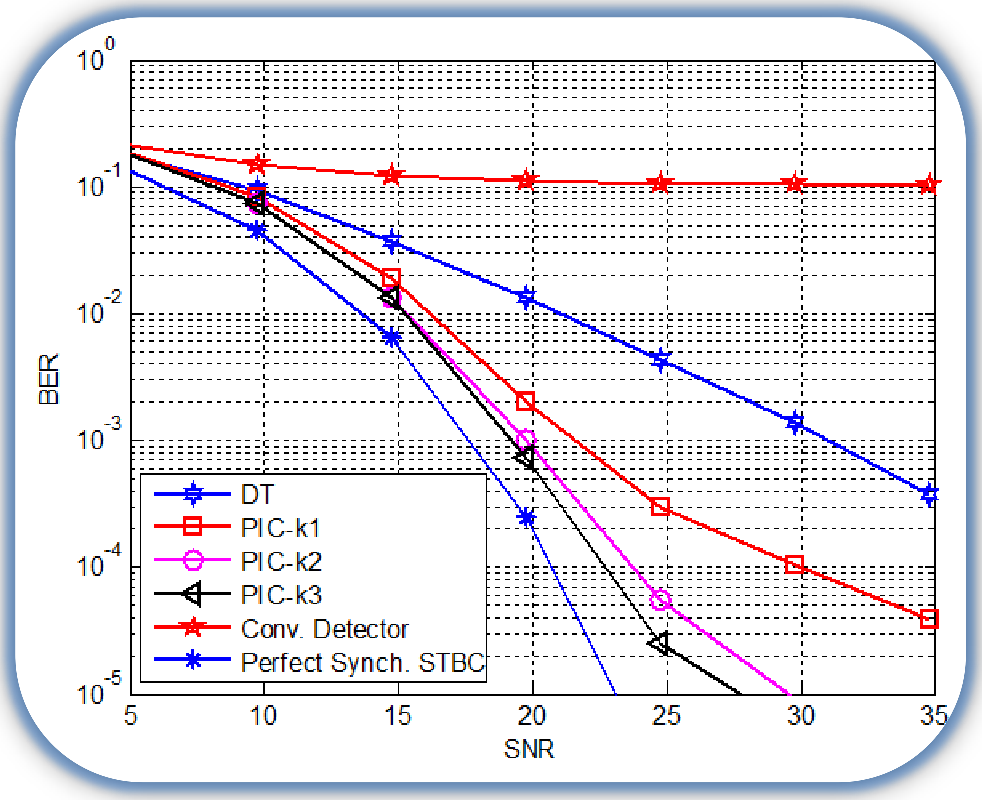

Figure (4.5): The BER of PIC detector (k=1, 2, and 3) when $\beta_m = -3\ dB$

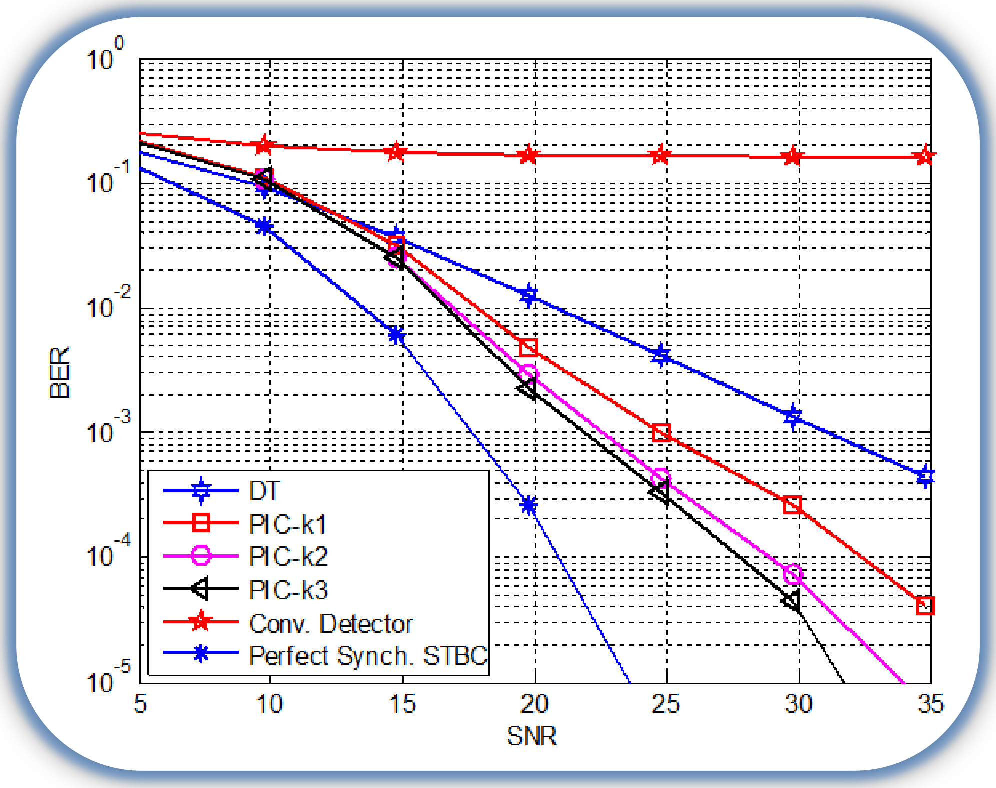

Figure (4.6): The BER of PIC detector (k=1, 2, and 3) when $\beta_m = 0\ dB$

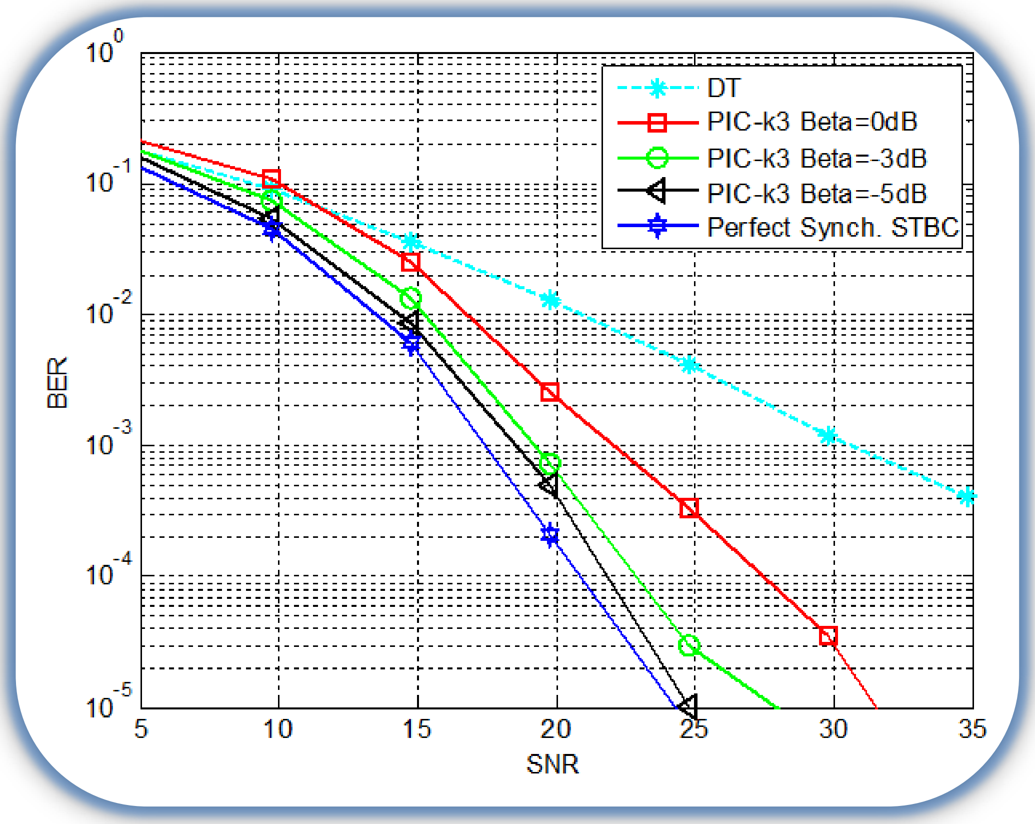

Figure (4.7): The BER of PIC detector (k=2) when $\boldsymbol{\beta_m = -5, -3}$,and 0 $\boldsymbol{dB}$

Finally, we want to compare the performance of PIC approach (k = 2) under different value of time misalignment ($\beta_m = -5, -3$, and 0 dB) in the same figure, it is shown the figure (4.7); you can observe that the efficiency of PIC detector is dramatically affected by the amount of imperfect synchronization. When $\beta_m = -5$ dB, a small amount of time misalignment, the PIC detector has the performance very closely to perfect synchronized D-STBC system, whereas when $\beta_m = -3$ and 0 dB, large amount of time misalignment, the performance of PIC detector has been degraded but the detector is still effective when comparing their performance with the conventional one.

4.3.2 The PIC approach for any number of relay nodes:

The PIC approach in section (4.3.1) has two weak points which are:

1. It was proposed to try to mitigate the impact of the imperfect synchronization when there are just 4 relay nodes in the system model, because it used STBC code support only 4 transmitters.
2. From the step 4 and 5 of the approach, you can observed that the paper assumes the value of $h_m(1)$ and $h_m(0)$ are known and that's mean the receiver have a perfect knowledge about the misalignment time at the receiver , and this is impractical since the relay's sequence will arrive at the destination at a random instances.

We have modified the concept of PIC approach to be suitable for m number of relay nodes. This approach is called as Generalized PIC or GPIC and we will assume there is no perfect knowledge of the delay amount at the receiver. We want to derive a model of the system consisting of source node (*S*), n_{TX} relay nodes ($R_1 ... R_{n_{TX}}$), and destination node (*D*), it shown in Figure (4.6), where h_{SR_m} , h_{SD}, and h_m are the channels gains from *S* to the relay node R_m, from *S* to *D*, from relay node R_m to *D*, respectively.

Since there are n_{TX} relay nodes, we require a STBC code to be compatible with this number of relay nodes. The orthogonal codes generated through systematic steps which list in section (2.8) can be the best choice to be merged with PIC basics to have D-STBC system has ability to face the impact of imperfect synchronization. When these codes used, the received signal model in (4.6) has a little change as follow:

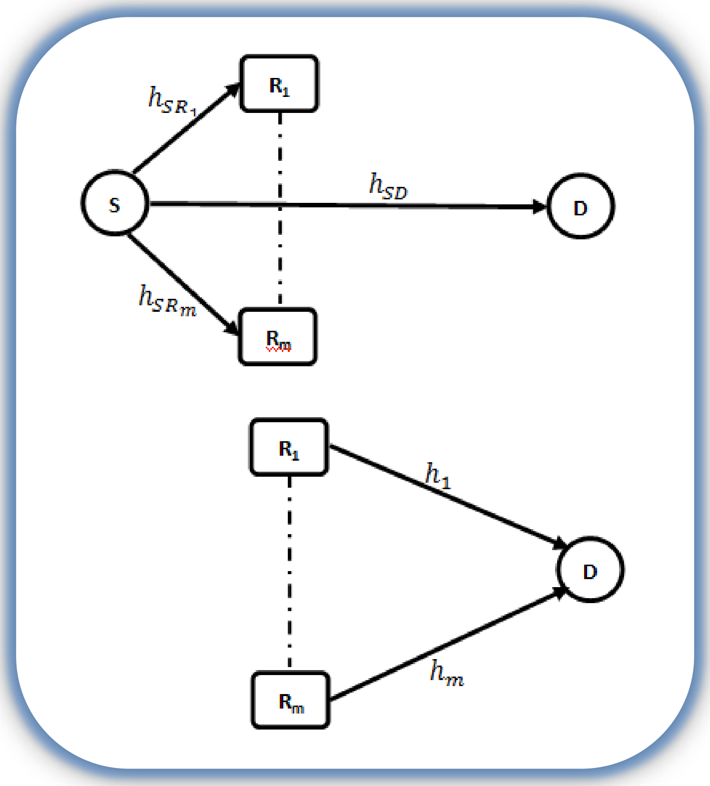

Figure (4.8): The 2-phase of D-STBC system with m relay nodes.

$$r(1,i) = \sum_{m=1}^{n_{TX}} h_m(0)x_m(1,i) + \qquad (4.14\text{-a})$$

$$r(k,i) = \sum_{m=1}^{n_{TX}} h_m(0)x_m(k,i) + \underbrace{\sum_{m=2}^{n_{TX}} h_m(1)x_m(k-1,i)}_{iterference \quad term} + n_{RD}(k,i) \qquad (4.14\text{-b})$$

where $x_m(k,i)$ is the symbol transmitted from antenna m and at the symbol period k for the data tuple i, k = 1,… n_T, m=1,… n_{TX} , n_{TX} is the number of relay nodes, n_T is the number of time period needed to send one block of STBC data.

Now, we want to re-write (4.14) in term of the transmitted symbol which can be determined by substituting the value of $x_m(k,i)$ from the chosen coding matrix generated in section (2.8), and then rewrite it to be as in the following form:

$$r(i) = Hs(i) + I(i) + n_{RD}(i), \tag{4.15}$$

where: $r(i) = [r(1,i), r(2,i), \dots, r(n_T,i)]$, $s(i) = [s(1,i), s(2,i), \dots, s(n_S,i)]$, $I(i) = [I(1,i), I(2,i) \dots, I(n_T,i)]$, and n_{RD} is the AWGN vector

also,

$$I(1,i) = \sum_{m=2}^{n_{TX}} h_m(1) x_m(n_T, i-1), \tag{4.16-a}$$

$$I(k,i) = \sum_{m=2}^{n_{TX}} h_m(1) x_m(k-1, i). \tag{4.16-b}$$

Since the codes that merged with PIC approach are already orthogonal [12], H will be also orthogonal matrix (there is no need to do the matrix manipulation done in section (4.3.1)), that's mean:

$$\Lambda = H^T \times H = diag(\lambda, \dots, \lambda), \tag{4.17}$$

where

$$\lambda = \sum_{k=1}^{n_{TX}} |h_k|^2.$$

Now, we can go directly to the final step which is the detection which can be carried by multiplying the received signal $r(i)$ by H^T, and then carry out the transmitted symbols by LS search.

In our generalization from of PIC detector, we assume that just the average value of time misalignments τ_{avg} (modeled by beta) is known at the receiver instead of knowing all time misalignments of the relay nodes $\tau_1, .., \tau_m$ $(\beta_1, \dots, \beta_m)$. The average value τ_{avg} can be determined using statistical data obtained through transmitting training data from the relay nodes over the channels to the destination.

As mentioned, the interference term will degrade the performance of the system, so we again apply the PIC approach which will be as follow:

Initialization:

1. Set $k = 0$.
2. Let $\hat{S}^k(i) = [\hat{s}(1,i), \dots, \hat{s}(n_s,i)]$ which is the result of LS search of phase *1* transmission.
3. Using β_{avg}, calculate $h_m(0)$ and $h_m(1)$ using (4.7) for all relay nodes.

   Note: $h_1(0) = h_2(0) = \cdots = h_m(0)$ and $h_1(1) = h_2(1) = \cdots = h_m(1)$.
4. Remove ISI from $r(1,i)$ by calculate:

$$r^{'}(1,i) = r(1,i) - I(1,i),$$

where $I(1,i)$ is the interference term in $r(1,i)$, (4.16-a), but use $h_m(1)$of step (3).

Iteration k: $k = 1, \dots, K$

5. Remove more ISI by calculate

$$r^{'(k)}(i) = \begin{bmatrix} r^{'}(1,i) \\ r^{*}(2,i) - I^{(k-1)}(2,i) \\ . \\ . \\ r(n_T,i) - I^{(k-1)}(n_T,i) \end{bmatrix}.$$

   Use the interference term in (4.16-b) to calculate $I^{(k-1)}(j,i)$ but use $h_m(1)$ of step (3) and $\hat{S}^{k-1}$ of step (2).
6. Determine *H* of (4.15), using $h_m(0)$ of step (2).
7. Determine $g^{(k)}(i)$ as follow :

$$g^{(k)}(i) = H^T r^{'(k)}(i)$$

8. Apply LS search to obtain to detect the transmitted symbols via (4.13)
9. Update the value of the $\hat{S}^{k-1}$ using the result of step (6).

Simulation Result:

Firstly, we simulate the BER performance of the case of 4 relay nodes used code generated by the systematic steps in chapter 2, for the iteration k =1, 2, 3 of PIC detector when there is perfect knowledge about the time misalgnment and when there is just the average value of time misalgnment of the channels. The value of β is a random samples from the range of -1 dB to -5 dB with -3dB as an average values. From Figure (4.9), we can observe that the PIC detector is also very effective even when we use just the average value of β instead of using the perfect values of β.

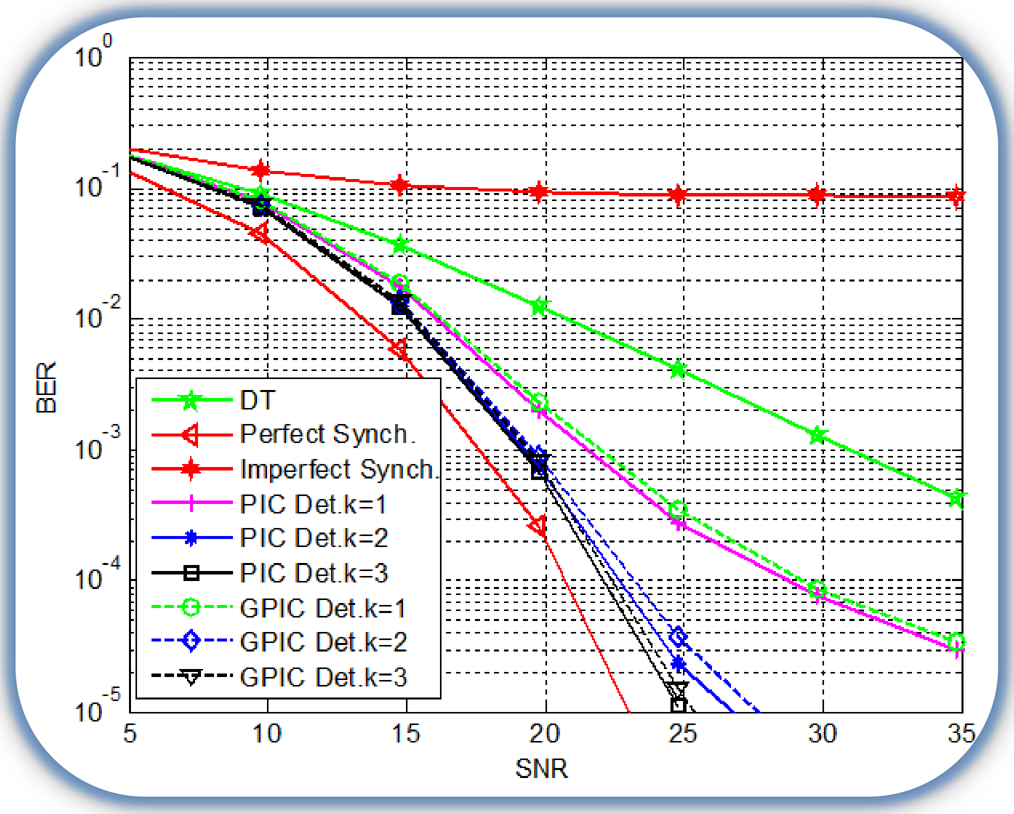

Figure (4.9): The BER of k= 1, 2, and 3 for 4 relay nodes when β=-5 dB for original PIC approach and our modified one.

Here, we want to test the general form of PIC approach, so we simulate the BER when there are six relay nodes that used code generated through the steps of section (2.8). The time misalignment of the relay nodes are generated randomely in the range of

(0 to 0.5T). At the receiver, we assume that only the average value of β and the channels gain under perfect synchronization are known. Figure (4.10) show the BER of the iteration k = 1, 2, 3 of the PIC detector. Because of random delay of the relay nodes (6 random values) and using the average value instead of perfect one, the performance of PIC detector was degraded but it still effective.

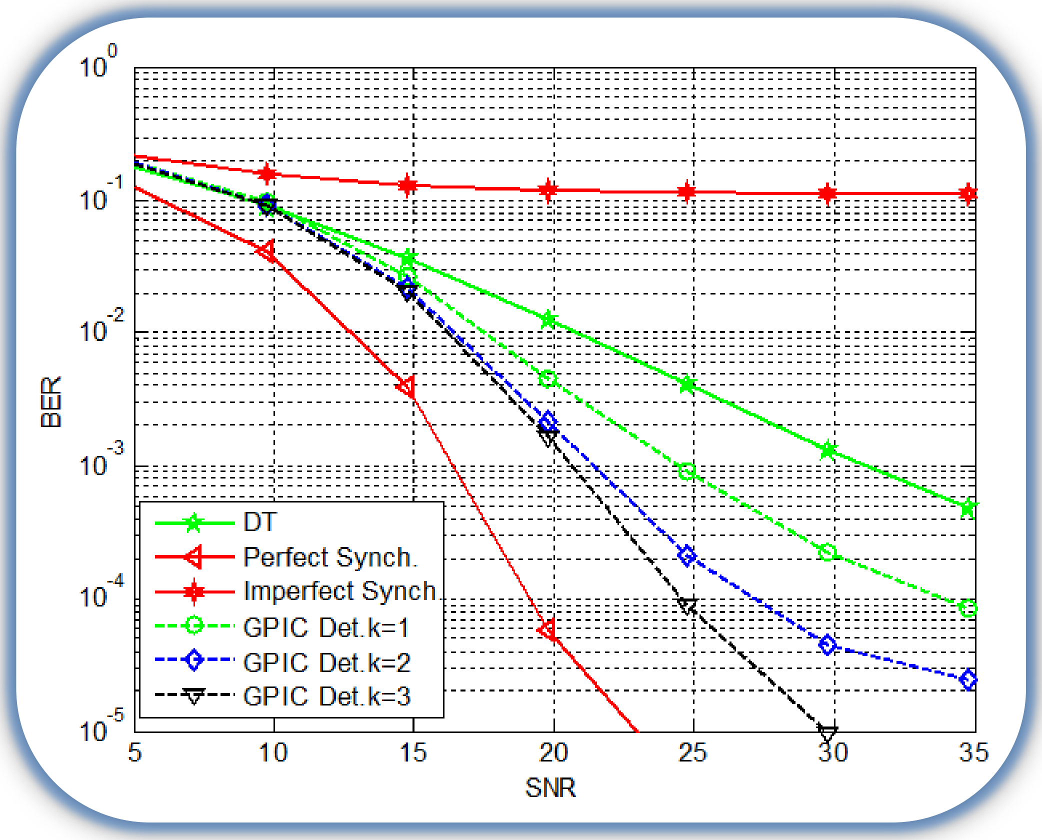

Figure (4.10): The BER of modified PIC approach for D-STBC system when 6 relay nodes

4.4The SIC approach for 4 relay nodes:

It can be noticed that the performance of iteration 1 (k=1) of the PIC approach is basically depend on the result of the detection of DT phase, this is clear at the region of 20 to 35 which shows that the curve of PIC (k=1) follow the curve of DT. Also, it can be observed, that due to the nature of block coding, any symbol error in the DT phase can cause a symbols error for the whole block, so the problem is mainly occured because of two factors: the first is the dependency on the result of DT phase, and the second factor is the block coding. We will try to overcome these problems by using the Successive Interference Cancellation (SIC) [7] which will be proposed here. The main idea to overcome this problem is using the detection of each symbol of phase 2 to cancel their contribution in the interference when the next symbol is detected. In other words., After detecting the first symbol, we model the interference at symbol 2 using both of the result of DT and the detection of first symbol, and we follow the same procedures to the remain symbols. The algorithm steps is explained at the end of this section.

As in PIC approach [3], if the detection process has been initialized properly, $I(1,i)$ in (4.8) can be cancelled (also $I_R(1,i) = I_I(1,i) = 0$ in (4.10)). Now, in (4.8) there is interference just from the current block symbols which will be denoted by I_0, where $I_0 = [I(2,i), I(3,i), I(4,i)]$, so the issue is how you can mitigate this interference. The basic idea is to eliminate the interference from each symbol at the end of iteration instead of deleting the interference from whole received signal vector at the beginning of iteration as in [3]. To adapt the model of [3] which illustrated in section (4.3.1-2) to be suitable with our approach, we rewrite the interference term in (4.8) in term of $S(i)$ by substituting each $x_m(j,i)$ to the corresponding symbol using (4.4):

$$I_0 = H_4 S(i) + B_4 S^*(i),$$

where

$$H_4 = \begin{bmatrix} 0 & 0 & 0 \\ h_2^*(1) & 0 & 0 \\ h_3^*(1) & 0 & 0 \end{bmatrix},$$

$$B_4 = \begin{bmatrix} 0 & h_2^*(1) & h_3^*(1) \\ 0 & 0 & -h_4^*(1) \\ 0 & h_4^*(1) & 0 \end{bmatrix}.$$

Rerewrite (4.18) to be compatible with (4.10) (following same procedure in (4.3.1)).

$$\begin{bmatrix} I_{0R} \\ I_{0I} \end{bmatrix} = Q_{int} \begin{bmatrix} S_R(i) \\ S_I(i) \end{bmatrix}, \tag{4.19}$$

where

$$Q_{int} = \begin{bmatrix} H_{4R} + B_{4R} & -H_{4I} + B_{4I} \\ H_{4I} + B_{4I} & H_{4R} - B_{4R} \end{bmatrix}^T.$$

Substituting (4.19) in to (4.10) yields

$$g^{'}(i) = \begin{bmatrix} g^{'}(1,i) \\ . \\ . \\ g^{'}(6,i) \end{bmatrix}^T = Q^T \begin{bmatrix} r_R^{'} \\ r_I^{'} \end{bmatrix} = \Lambda \begin{bmatrix} S_R \\ S_I \end{bmatrix} + I_0^{'} + Q^T \begin{bmatrix} n_{R,RD} \\ n_{I,RD} \end{bmatrix}, \tag{4.20}$$

where:

$$I_0^{'} = [I_0^{'}(1,i), \dots, I_0^{'}(6,i)]^T = Q^T Q_{int} \begin{bmatrix} S_R \\ S_I \end{bmatrix}, \tag{4.21}$$

and r$^{'}$ is the received signals after remove $I(1,i)$

From (4.21), you can observed that the factor $Q^T Q_{int}$ is a key factor to weight the interference in each symbols, so if it is ordered according to its power and we start our approach to detect the symbol has a lowest interference to be a first symbol then use its result to cancel the interference in the second ordered symbol and follow the same procedure to the last symbol.

Now, the detection process accomplished using the following procedures:

Initialization:

1. Set k = 0.
2. Let $\hat{S}^k(i) = [\hat{s}(1,i), \hat{s}(2,i), \hat{s}(3,i)]$ which is the result of (2), DT process.
3. Remove ISI from $r(1,i)$ by calculate (using (4.9-a)):

$$r^{'}(1,i) = r(1,i) - I(1,i)$$

Iteration k: $k = 1, 2\ldots$ K

4. Determine $g^{'(i)}$ using (4.20).
5. Determine the order of symbols detection process by calculate the power of row component of the factor $Q^T Q_{int}$, let to be [index1, index2, index3]
6. Remove ISI from $g^{'}(index1, i)$ and $g^{'}(index1 + 3, i)$ by calculate :

$$g^{''}(index1, i) = g^{'}(index1, i) - I_0^{'}(index1, i)$$

$$g^{''}(index1 + 3, i) = g^{'}(index1 + 3, i) - I_0^{'}(index1 + 3, i)$$

   use (4.21) and $\hat{S}^{k-1}$ to calculate $I_0^{'}(index1, i)$,and $I_0^{'}(index1 + 3, i)$.

7. Apply LS search to obtain $\hat{s}^k(index1, \mathrm{i})$ via (4.13) and $\ell = index1$.
8. Modify the symbol in $\hat{S}^{k-1}$ at $index1$ to be $\hat{s}^k(index1, \mathrm{i})$
9. Remove ISI from $g^{'}(index2, i)$and $g^{'}(index2 + 3, i)$ by calculate :

$$g^{''}(index2, i) = g^{'}(index2, i) - I_0^{'}(index2, i)$$

$$g^{''}(index2 + 3, i) = g^{'}(index2 + 3, i) - I_0^{'}(index2 + 3, i)$$

   use (4.21) and $\hat{S}^{k-1}$ to calculate $I_0^{'}(index2, i)$,and $I_0^{'}(index2 + 3, i)$.

10. Apply LS search to obtain $\hat{s}^k(index2, i)$ via (4.13) and $\ell = index2$.
11. Modify the symbol in $\hat{S}^{k-1}$ at $index2$ to be $\hat{s}^k(index2, \mathrm{i})$
12. Remove ISI from $g^{'}(index3, i)$ and $g^{'}(index3 + 3, i)$ by calculate :

$$g^{''}(index3, i) = g^{'}(index3, i) - I_0^{'}(index3, i)$$

$$g^{''}(index3 + 3, i) = g^{'}(index3 + 3, i) - I_0^{'}(index3 + 3, i)$$

   use (4.21) and $\hat{S}^{k-1}$ to calculate $I_0^{'}(index3, i)$,and $I_0^{'}(index3 + 3, i)$.

13. Apply LS search to obtain $\hat{s}^k(index3, \mathrm{i})$ via (4.13) and $\ell = index3$.
14. let $\hat{S}^k = [\ \hat{s}^k(1, i)\ ,\ \hat{s}^k(2, i),\ \hat{s}^k(3, i)\ ]$

Simulation result:

Using 8-PSK modulation, the bit error rate (BER) of the proposed detector (SIC) for k = 1, 2 under $\beta = -5, -3,$ and $0\ dB$ are shown in Figure (4.11), Figure (4.12), and in Figure (4.13), respectively. Also, the BER of perfect synchronized model, imperfect synchronization model, and PIC detector of [3] are included in same figures.

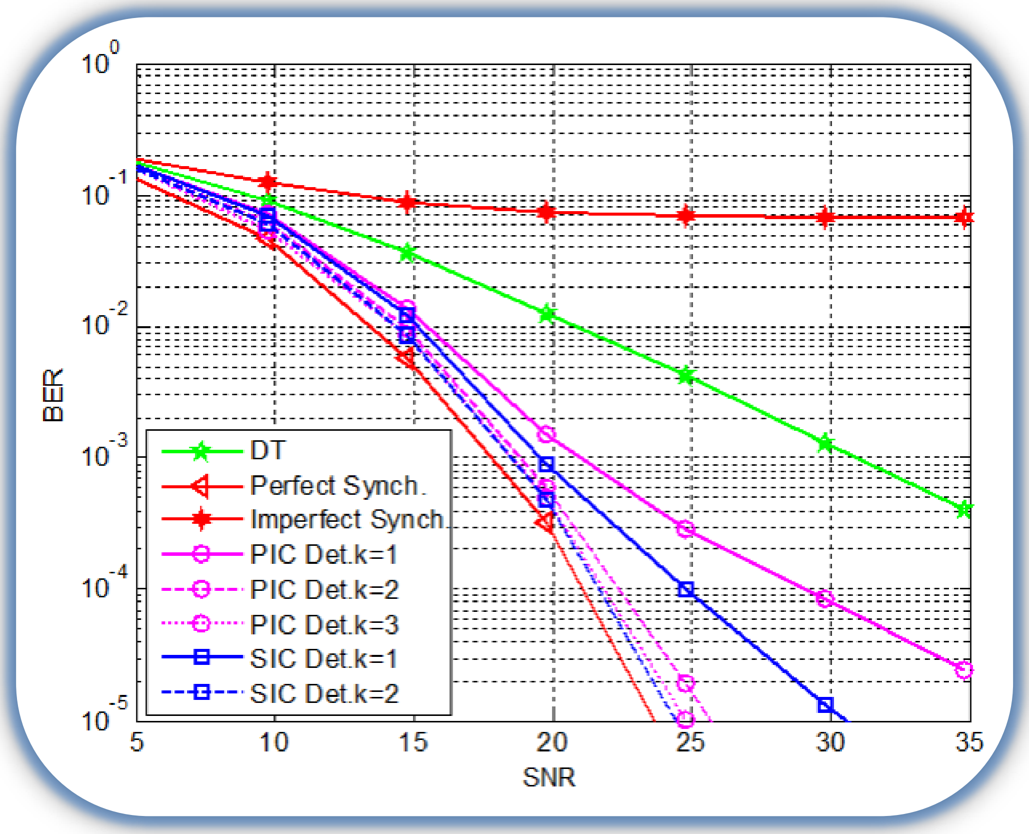

Figure (4.11): The BER of SIC approach for D-STBC system under β=-5

Figure (4.11), (the case of $\beta_m = -5\ dB$), shows that there is a great improvement when SIC is used over that when PIC is used, that's very clear, the SIC detector by just 2 iterations (k = 2) have the same performance of 3 iterations of PIC detector (k = 3). Also, in the first iteration (k = 1), to get BER = 10^{-4} you will require SNR=25 dB when SIC was applied whereas you will require SNR = 29 dB when we used PIC.

Now, we repeat the simulation for the BER of SIC and PIC approach under the value of $\beta_m = -3\,dB$, it is shown in Figure (4.12). Also, you can observe the improvement of SIC approach over that when PIC approach is used. It can be noticed, due to the increasing in the amount of time misalignment ($\beta_m = -3\,dB$), that the performance of the PIC detector was degraded more than the SIC detector, it means that the SIC detector has ability to face the imperfect synchronization more than PIC.

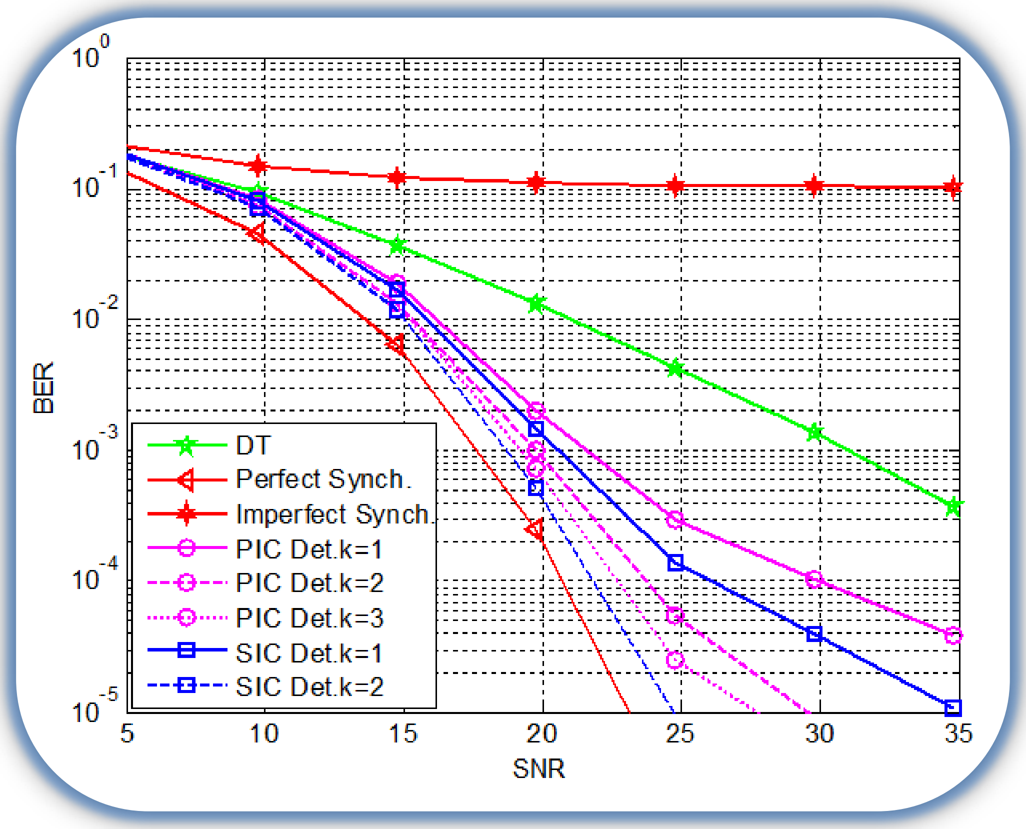

Figure (4.12): The BER of SIC approach for D-STBC system under $\boldsymbol{\beta_m = -3dB}$

To show the efficiency of SIC detector under severe conditions of imperfect synchronization, we repeat the simulation under the value of $\beta_m = 0\,dB$, which consider the largest value in our assumption of the problem formulation in section (4.3.1), the simulation result was shown in Figure (4.13). From Figure (4.13) (the case when there is a large amount of imperfect synchronization ($\tau_m = 0.5T$ ($\beta_m = 0dB$))) you can observed that the SIC approach was keep in its affectivity while a PIC approach does not, this mean that the proposed approach has ability to face a large amount of imperfect synchronization better than PIC detector. Furthermore, our SIC approach gives results close to the perfect synchronization faster than of PIC approach, For example, two iteration (*k* =*2*) of SIC approach gives BER better than three iterations of PIC(*k* = *3*).

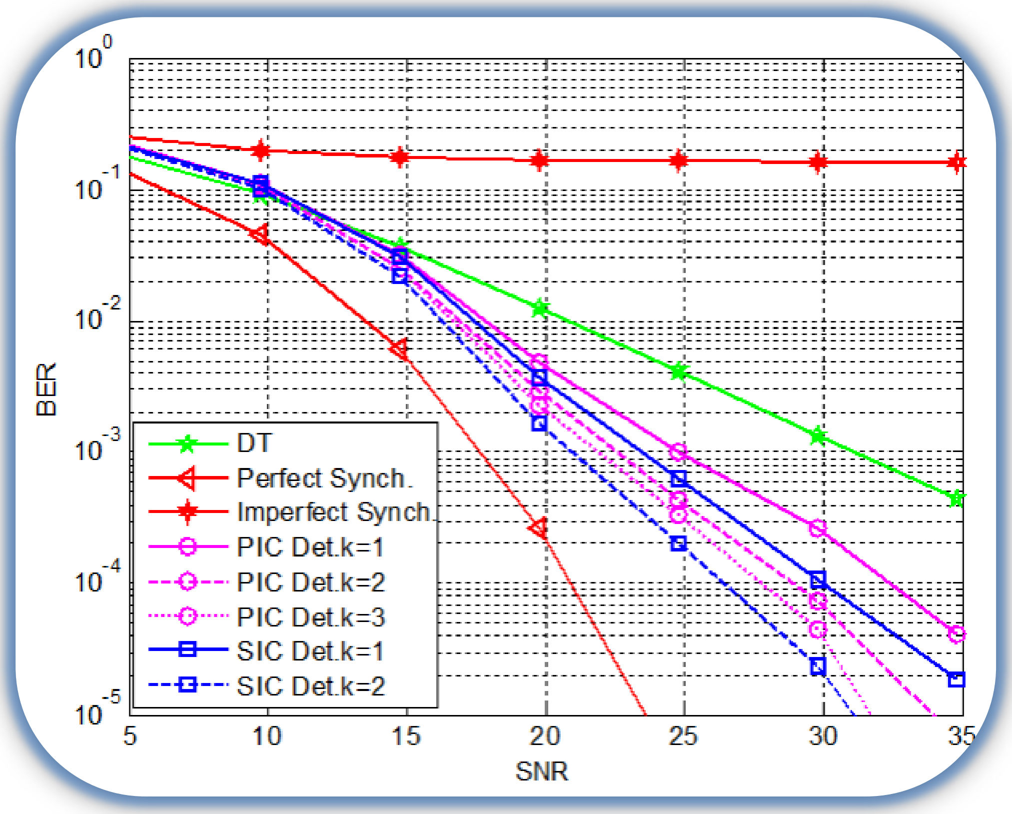

Figure (4.13): The BER of SIC detection for k=1, 2 when $\beta_m = 0$dB.

4.4 Conclusion:

In Distributed-STBC, the features of both cooperative schemes and STBC system were investigated. It requires perfect synchronization between the relay nodes which included in cooperative mechanism. Unfortunately, perfect synchronization is almost impossible to be achieved. Therefore, most of the designed space-time codes are no longer valid for cooperative diversity. In this chapter, a problem of the imperfect synchronization has been illustrated and modeled. A detection scheme of [3] which is based on the principle of Parallel Interference Cancellation (PIC) for Quasi-synchronized D-STBC with 4 relay nodes has been analysis and simulated. Also, this thesis proposed two approaches: generalization form of the PIC approach to be suitable for any number of relay nodes, and new method to mitigate the impact of the imperfect synchronization which based on a successive interference cancellation (SIC) method. The simulation results of SIC approach show that there is great performance improvement over PIC approach and it gain this performance by just two iterations whereas PIC approach require more than three iterations to do that. Also, the SIC approach has proved its efficiency over large amount of time misalignment. Moreover, the proposed approach enjoys a low decoding complexity which is considered as a great advantage in the communication systems. The SIC approach can also be generalized for higher number of relays in the same way explained for PIC.

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Chapter 5

Conclusion and Future Works

5.1 Conclusion:

This thesis is concerned with the implementation of STBC over a cooperative networks under the assumption that the channel gains are known at the receiver. The main concern is to solve the issue of imperfect synchronization between the distributed relay nodes.

The basic concepts of the topic were firstly considered which are the Space Time Block Codes and the Cooperative networks; these are introduced in chapter two and chapter three.

Finally, two low decoding complexity methods are proposed to mitigate the impact of imperfect synchronization between the relay nodes in the D-STBC systems. The first one is based on parallel interference cancellation (PIC) algorithm and the other is based on successive interference cancellation (SIC). The BER performance of the two proposed methods are analyzed and simulated. From the BER performance simulations, it's very clear that they are very effective to mitigate the effects of the issue. In some situations, it is required 5 dB in PIC approach more than the proposed SIC approach which is consider a relatively large improvement.

5.2 Future works:

- Implements the SIC and PIC approach over different cooperative relaying protocols, such as Fixed DF, Fixed AF,..etc, to have a complete system performance.
- Generalize the SIC approach to be suitable for any number of relay nodes as in our proposed modification to PIC approach.
- Modify these methods to the case of moving relay nodes with a given velocity.