IMPLEMENTATION OF COOPERATIVE DIVERSITY IN SPACE FREQUENCY CODED OFDM SYSTEMS

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ABSTRACT

Wireless technology is becoming an important part of our daily life. Although earlier wireless technologies were developed to provide voice transmission which did not require large amount of bandwidth, we are now equipped with intelligent mobiles, PDAs and laptop computers each having various applications connecting us to multimedia services that requires high bandwidth utilization. Technology world is converging to IP based systems where reliability and capacity plays an important role. For example the delay periods which can be neglected in voice transmissions can be crucial in services like on demand TV where data transmission have to be smooth. High performance and high reliability requires the bounds of capacity and coding structures to be increased. In this thesis we consider strong coding algorithms and diversity techniques in broadband channels. Space frequency codes which have been proven to achieve high performance in MIMO systems have been employed to single antenna systems by using cooperative diversity where deployment of multiple antennas is difficult. By constructing such a structure we target to achieve available diversities in the channel to improve the performance.

ÖZET

Kablosuz teknoloji gün geçtikçe yaşamımızda önemli bir yer tutmaktadır. Yakın zamana kadar geniş band gerektirmeyen ses iletimini sağlamak amacıyla kullanılan kablosuz iletişim, günümüzde dizüstü bilgisayar ve yeni nesil cep telefonları üzerinden bizi yüksek band genişliği gerektiren çeşitli multimedya servislere bağlamak için de kullanılmaktadır. Temelde teknoloji dünyası güvenilirliğin ve kapasitenin önemli yer tuttuğu IP bazlı sistemlere yönelmektedir. Örneğin ses transmisyonu sırasında ihmal edilebilen gecikme süreleri IP TV gibi uygulamalar icin kritik olabilmektedir. Buna bağlı olarak yüksek performans ve güvenilirlik ihtiyacı mevcut kapasitenin ve kodlama yapılarının sınırlarını zorlamaktadır. Buradan yola çıkarak bu tezde yüksek band genişliğine sahip kanalların güçlü kodlama algoritmaları ve ceşitlilik yöntemleri üzerinde calışıldı. Çoklu giriş çoklu çıkış sistemler için geliţirilmiş uzay frekans kodlar, ortak çeşitlilik kullanılarak çoklu anten yerleştirilmesi zor olan tek antenli sistemler üzerinden uygulandı. Bu yapı yaratılarak kanallardaki mevcut çeşitlilik kaynakları kullanılarak performansın arttırılması amaçlandı.

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1. Introduction

Recent advances in communication technology have boosted interest for wireless communications. Although earlier technologies were aiming to guarantee high quality voice transmission, new technologies should target not only reliable voice but also high rate data transmission. With explosive growth in wireless Internet and multimedia applications, demand for services utilizing high bandwidth has led researchers to slide their focus to provide high data rates that can compete with that of wire-line communications. This is the main motive behind in development of broadband wireless systems.

Wireless has an indispensable mobility advantage that gives freedom to subscribers to get connected and stay connected to mobile services anytime, anywhere. With increasing number of subscribers wireless communication has also significant advantage in urban areas where new cables should be deployed which increases the costs considerably. In some developing countries wireless infrastructure is more advanced due to the fact mentioned above. Offering such flexibility wireless technology will likely be primary choice for service providers and end-users in the future.

However all these improvements do not come cheap. They should be implemented under some constraints due to nature of wireless medium. In wireless communication transmitted signals have encounter severe attenuation as well as reflection, scattering and shadowing over transmission channel. At the receiver it can be infeasible to detect signal correctly because of constructive and destructive superposition of signals.

Diversity, which is achieved by providing replicas of the transmitted signals at the receiver is a powerful technique used to combat these detrimental effects and improve the performance of wireless system. Commonly used diversity techniques are :

Temporal Diversity : Channel coding in concatenation with time interleaving is used.

Frequency Diversity : Replicas of signal are transmitted at different frequencies to introduce redundancy. Frequency diversity can also be available as multipath diversity where multipath propagation of signal produces replicas of the signal at different frequencies in frequency domain.

Antenna Diversity : Multiple antennas are used at the transmitter and receiver to provide independent processing of transmitted signal at the receiver. Because of spatial separation of antennas it is also referred as spatial diversity. MIMO(Multiple Input Multiple Output) systems utilize antenna diversity efficiently considering the fact that it does not increase transmit power and signal bandwidth. By using multiple antennas at the receiver and transmitter, diversity order is increased by a factor of transmit times receive antennas. In frequency selective channels it is possible to add frequency diversity to the equation which is equal to the number of multipaths available in the channel.

Powerful code structures have been developed to extract maximum gains in a wireless system. Space time codes provided high performance gains in flat fading environment as in [4], [18].However they failed to exploit available gains in a frequency selective channel which led to the design of Space Frequency codes. After derivation of design criteria for Space Frequency codes in [22], various codes has been proposed which have acquired additional multipath gain for a trade-off for complexity.

Although MIMO systems have been proven to offer high performance and capacity gains, it is not feasible to deploy multiple antennas at many wireless transmitters because of the constraints like size and complexity. To overcome these limitations in transmit diversity the idea of cooperation has been proposed which enables mobile users to create virtual antenna arrays [11], [8]. Due to broadcast nature of wireless communication one user is able to hear other users signals and can be designed to have the ability to forward some of partner's information to the receiver. Since the information is transmitted through independent paths from different antennas transmit diversity is achieved.

Remainder of the thesis will consist of the following chapters :

In Chapter 2 we first section will contain benefits and implementation aspects of cooperative diversity. Novel cooperation schemes which constitutes base for ongoing researches on this field will be investigated briefly. Section II will start with introduction of MIMO-OFDM systems which will be followed by definition and design criteria of space frequency codes. Performance of recently proposed codes will also be analyzed.

In Chapter 3 new cooperative space frequency coded designs for MIMO-OFDM systems will be proposed. Signal model and encoding structure will be derived. Our encoding structure will utilize Orthogonal Space Frequency Block Codes and Quasi Orthogonal Space Frequency Block Codes. We will also the discuss the motive behind the this designs.

In Chapter 4 we will summarize our intention and establishments in this thesis and will talk about the possible future extensions to our work.

2. Background and Related Work

2.1. Cooperative Diversity

It has been proven in recent researches that having multiple antennas at transmitter side provides increased capacity and improved performance [2], [18]. For situations where it is not feasible to deploy multiple antennas at the transmitters a new framework was proposed in [8] where different users share their antennas to form a virtual MIMO system.

Cooperative communication has been inspired from the work on relay channel model where relay acts as supportive element for the source node, [1]. In this model both relay and destination node receives the attenuated transmit signal, then relay sends an another signal to the receiver based on what it has received.

In cooperative communication users are able to both transmit their own data and act as relay for the others. When cooperative transmission occurs collaborating users form a virtual array by sharing their antennas to provide spatial diversity. There is no cost in terms of transmit power because of broadcast nature of wireless transmission. However there is a trade-off between the additional power utilized to transmit partners information and amount of diversity gain which can reduced the power consumption.

When cooperation is applied to wireless channel model it has been proven to achieve gains in terms of different performance metrics such as increased capacity and improved reliability in [14], [11], [10], [8], [9].

2.1.1. Fundamental Cooperation Techniques

Various kinds of cooperation techniques have been developed which propose different encoding and detection algorithms at transmitting and receiving nodes. We will present some fundamental algorithms which have been the basis for recent and ongoing researches.

2.1.1.1. System Model : Suppose we have a network consists of m users. Each user has a baseband equivalent discrete signal $x_i[k]$, with average power constraint $\sum_{k=1}^{n} x_i[k] \leq nP_i$. and received signal $y_i[k]$, $i = 1, 2, ..., m$. So the received signal from can be modeled as :

$$y_i[k] = \sum_{j \neq i}^{m} \alpha_{i,j} x_j[k] + w_i[k] \tag{2.1}$$

where $\alpha_{i,j}$ captures the affects of multipath fading, shadowing and path loss between the users, and $w_i[k]$ captures the thermal noise at the user. It is assumed channel coefficients $\alpha_{i,j}$ are fully known at the receivers, and but not known to transmitters. $\alpha_{i,j}$ and $w_i[k]$ are modeled as independent complex valued random variable and independent zero-mean additive white gaussian noise with common variance N_o respectively.

Throughout the analysis of cooperative protocols it is expected that users maintain some degree of synchronization between each other such as block, carrier and symbol synchronization. However we should note that to some level benefits of cooperative diversity is robust to carrier and phase errors.

Now let's reduce our network to three elements,two users(user 1 and user 2) and a destination, before starting analysis.

2.1.1.2. Amplify and Forward : Amplify and forward is the simplest cooperative method in which one user amplifies what it receives from the other. Forwarding is constrained by their power resources. The receiver combines information from user 1 and user 2 and makes a decision on transmitted symbol. The drawback of amplify and forward scheme is that noise at user 2 is also amplified. However since the signal is transmitted through independently faded channels, still better decision likely to be

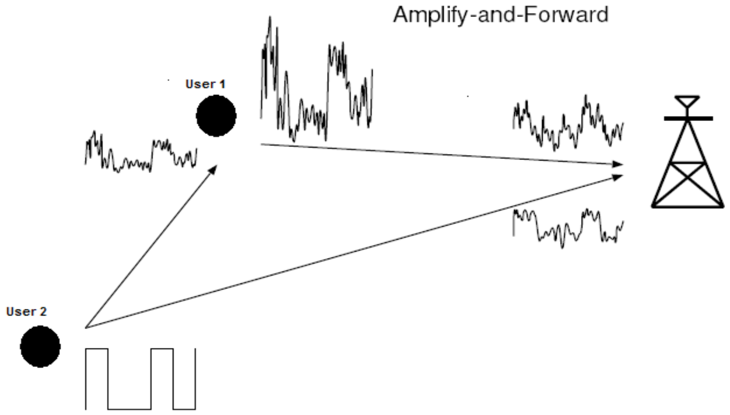

Figure 2.1. Illustration of Amplify and Forward

realized at the receiver. Let's suppose that user 1 transmits $x_1[k]$ for $k = 1, 2, ..., n$. User 2 processes received signal $y_2[k]$ for $k = 1, 2, ..., n$, and relays the information by corresponding transmit signal

$$x_2[k] = \beta_2 y_2[n-k], \qquad k = n+1, n+2, ..., 2n. \tag{2.2}$$

and to obey the power constraint, partner utilize the gain ;

$$\beta_2 \leq \sqrt{\frac{P_1}{|\alpha_{2,1}|^2 P_2 + N_o}} \tag{2.3}$$

where $\alpha_{r,s}$ is the fading coefficient between users. Then received signal $y_2[k]$ is processed at the receiver for $k = 1, 2, ..., 2n$ for successive blocks of length n. When extended to multiple relay case each node either transmits within the allocated sub-block period so that interference is minimized, or transmits simultaneously to maximize the interference to get better diversity benefit for a bandwidth inefficiency tradeoff.

2.1.1.3. Decode and Forward : In detect and forward user 2 applies some decoding algorithms to the received signal and forwards it after encoding. Although effect of noise is diminished, performance can be effected dramatically by channel conditions. Consider a system where user 1 transmits $x_1[k]$ for $k = 1, 2, ..., n$. User 2 decodes the

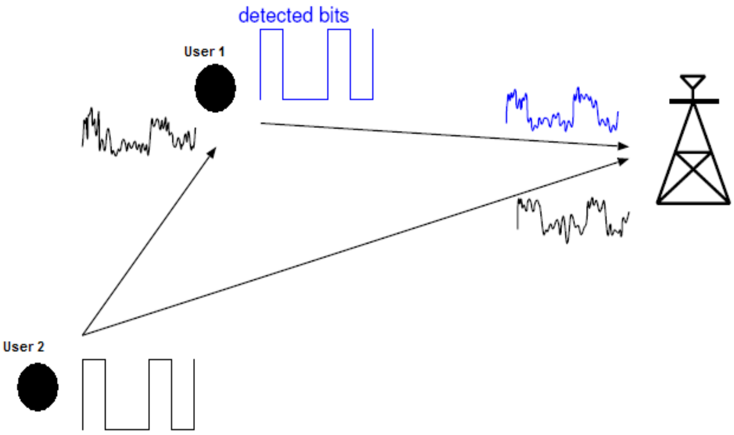

Figure 2.2. Illustration of Decode and Forward

received signal $y_2[k]$ to form an estimate $\hat{x_1}[k]$ which is re-encoded at partner before being transmitted. Encoding of transmitted signal can be implemented by repetition coding;

$$x_2[k] = \sqrt{\frac{P_2}{P_1}}\hat{x_1}[k-n], \qquad k = n+1, n+2, ..., 2n \tag{2.4}$$

Received signal $y_d[k]$ at the destination can be processed for $k = 1, 2, ..., 2n$ by combining blocks from partner and source. Encoding at partner may be implemented such that transmitted codeword is correlated to the source codeword instead of repetition coding which can be also considered as form of parallel channel coding. In multiple relay case, partners may utilize repetition coding or space time coding to transmit jointly to the destination. Although having low complexity repetition coding has drawbacks like low bandwidth efficiency and scheduling.

2.1.1.4. Selection relaying : Performance of fixed decode and forward strongly depends on channel characteristics between users. When inter-user channel is bad, performance of the cooperative system drops dramatically. Since fading coefficients are known to the receivers $\alpha_{2,1}$ can be measured by the transmitters. By using these measurements cooperating users can adopt their transmission scheme. If measured $|\alpha_{2,1}|^2$ falls below a certain threshold, source continues to transmit its data to the destination. If $|\alpha_{2,1}|^2$ is above certain threshold, user 2 contributes to transmission by utilizing either amplify and forward or decode and forward.

Selection relaying likely to offer diversity because information is lost only if two of the channel coefficients should lie below certain threshold. Suppose $|\alpha_{2,1}|^2$ is small, then $|\alpha_{d,1}|^2$ should also be small for faulty transmission. If $|\alpha_{2,1}|^2$ is above the threshold, both $|\alpha_{d,1}|^2$ and $|\alpha_{d,2}|^2$ should be small to lose information since nodes are to cooperate in this case. In dynamic decode and forward which is an extension to regular decode and forward, partner does not start transmitting until it successfully decodes received source data [14].

2.1.1.5. Incremental Relaying : In incremental relaying destination node sends a feedback message such as an acknowledgement bit indicating whether the transmission is successful of not. This proposition aims to limit bandwidth inefficiency in previous protocols because the partner repeats continuously. The partner retransmits only it receives a negative feedback from destination indicating an unsuccessful transmission based on SNR measurements. This approach provides better use of degrees of freedom available in the channel since repetition occurs only when necessary.

2.1.1.6. Coded Cooperation : Apart from the perviously proposed cooperative algorithms which are based on a partner repeating the information in some form, coded cooperation utilizes cooperative signaling in conjunction with channel coding [6], [7]. Coded cooperation uses the idea of incremental relaying, but by employing appropriate coding need for feedback from destination is cleared away. The main characteristics of this code are codeword is divided into two groups, one to be transmitted by the source and the other to be transmitted by the partner by appropriate decoding, and since partner uses error correction error propagation is avoided.

Consider a system with two users and a base station, where users divide their data into blocks of K bits. Each block is encoded with appropriate algorithm. Each codeword has

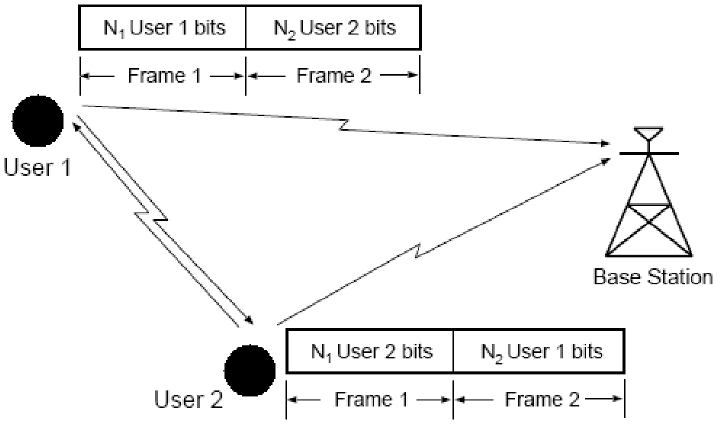

Figure 2.3. Distribution of data bits in coded cooperation

$N = K/R$ bits where R is the overall code rate. Codewords are partitioned according to rates R_1 and R_2 with bit rates $N_1 = K/R_1$ and $N_2 = K/R_2$ respectively.

Both users transmit first portion N_1 bits of the codeword in the first frame. If the user decodes partner's information successfully, second portion N_2 bits of the partner is transmitted. If decoding is unsuccessful user's own second portion is sent. Each user always transmit N bits over two frames. In the second frame the users transmit independently of the knowledge whether the partner successfully decoded their first frame.

In this scheme the base station must know which frames are successfully decoded by which user for correct detection of received bits.

2.2. MIMO-OFDM Systems

2.2.1. OFDM

OFDM(Orthogonal Frequency Division Multiplexing) is a special case of multicarrier transmission, in which data stream is carried over a number of low-rate subcarriers. OFDM can be considered as modulation and multiplexing technique. Traditional multicarrier transmissions divide total bandwidth into frequency subchannels, having a guard band between each subchannel which leads to inefficient use of available spectrum. OFDM subcarriers are chosen such that they are orthogonal to each other allowing subchannels to overlap. This provides a better use of available spectrum. Since bandwidth of each subchannel is much smaller that the coherence bandwidth of the channel, intersymbol interference is limited. In OFDM system input bitstream is mapped to modulation symbols according to a scheme such as QPSK(Quadrature phase-shift keying) or QAM(Quadrature Amplitude Modulation). After mapping serial data stream is divided into parallel blocks of length N where N is number of the tones. Each block is processed by IFFT(Inverse Fast Fourier Transform) and transformed into an OFDM signal. Discrete representation of an OFDM signal is shown below;

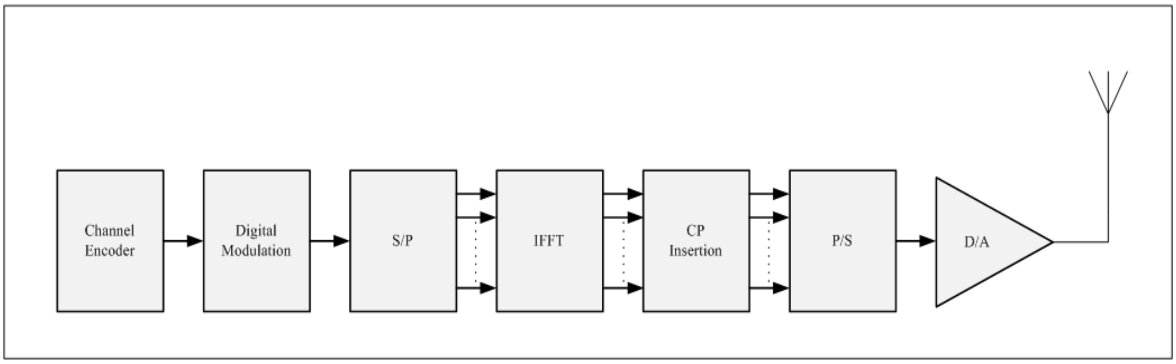

Figure 2.4. OFDM system

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j2\pi \frac{k}{N} n} \tag{2.5}$$

Before transmission cyclic prefix(CP) is appended to top of OFDM block to eliminate ISI(Intersymbol Interference) which is chosen longer than multipath delay spread of the channel. After parallel to serial conversion the signal is transmitted. When the signal is received at the receiver data stream is converted to parallel and CP is removed. After FFT(Fast Fourier Transform) processing on the received signal;

$$X[k] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} x[n] e^{-j2\pi \frac{n}{N} k} \tag{2.6}$$

modulated symbols are demodulated and transmitted data stream is recovered. OFDM is prone to timing and synchronization errors since symbol period is large for subcarriers. However offering numerous advantages like bandwidth efficiency, easy implementation, robustness to multipath fading and resource allocation makes OFDM widely used technique in wireless communications.

2.2.2. MIMO-OFDM

MIMO(Multiple Input Multiple Output) technology has the potential to provide high data rates and high reliability that the future wireless communication systems require. However due to nature of the wireless medium it can be challenging to reach the target rates and performance. Fading and interference from other users may effect overall rate dramatically. MIMO systems will be implemented in broadband systems where channels suffer from frequency-selectivity, therefore, ISI. Combination OFDM with MIMO ensures significant performance increase since OFDM turns frequency-selective channels into set of parallel flat fading channels

In single-antenna OFDM systems, frequency diversity is obtained by coding and interleaving across frequency bins. In frequency selective MIMO channels, available diversity sources are spatial and frequency diversity. Different coding techniques has been proposed to use these sources concurrently.

2.2.2.1. System Model : A general model for MIMO-OFDM systems consisting of M_t transmit, M_r receive antennas and N OFDM tones is shown in figure 2.5. Incoming bit stream is mapped to data symbols according to a modulation scheme. Then data symbols $S = [s_1, s_2, ..., s_{N_s}]$ are encoded into a codeword matrix $\mathbf{C}$ of size NT_xM_t. Codeword matrix is transmitted through M_t antennas in T OFDM block each consisting of N subchannels. c_j^n denoting a vector of length N, for $j = 1, 2, ..., M_t$ and $n{-}1, 2, ..., T$, the codeword matrix becomes

$$\mathbf{C} = \begin{bmatrix} c_1^1 & \dots & c_{M_t}^1 \\ \vdots & \ddots & \vdots \\ c_1^T & \dots & c_{M_t}^T \end{bmatrix} \tag{2.7}$$

After CP insertion in OFDM blocks, c_j^n will be transmitted from jth transmit antenna in the nth OFDM block. The receiver will perform reverse OFDM processing and will send to decoder for optimal detection.

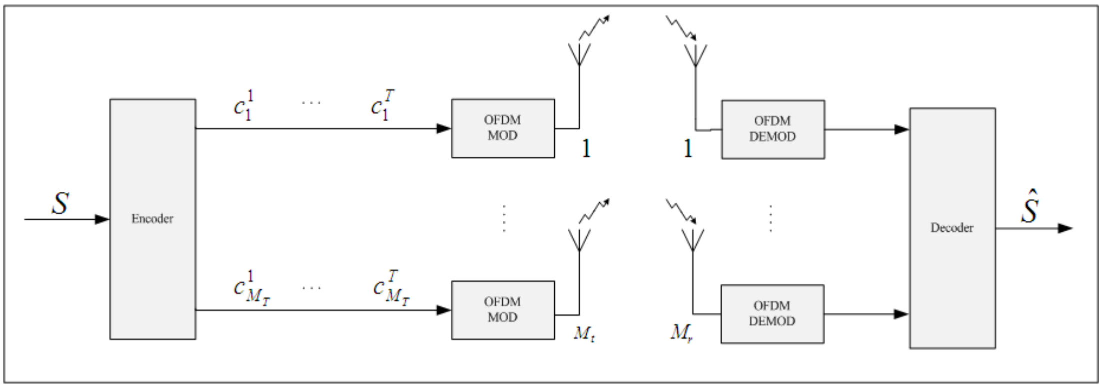

Figure 2.5. MIMO-OFDM system, where $S = [s_1, s_2, ..., s_{N_s}]$ is the input symbol vector and $\hat{S}$ is corresponding detected symbol vector.

As we previously noted it is possible to decrease fading effects of the channel by using different diversity techniques such as time, frequency and space diversity. Diversity diminishes the probability that a signal fades by providing replicas of the transmitted signal at the receiver. The reception performance of communication system is measured by bit-error-rate(BER) or symbol-error-rate(SER) versus signal-to-noise(SNR) ratio.The average error probability over a fading channel is characterized as

$$P_e \sim (G_c \cdot SNR)^{G_d}$$

where G_c is called *coding gain* and G_d is called *diversity gain*. In a flat fading MIMO channel maximum diversity gain is equal to $M_t M_r$ which is equal to number of antennas. ST coding can be utilized to maximize the gain In frequency selective channels there is an additional gain L which is the number of multipaths available in the channel making maximum achievable diversity M_tM_rL. Coding across OFDM tones, OFDM antennas and transmit antennas is needed to achieve maximum diversity We will investigate methods for increasing diversity gains in detail in the following sections.

2.2.3. Coding for MIMO-OFDM Systems

2.2.3.1. Space Time Coding : Space Time coding for fading channels is a powerful technique that achieves high performance using the diversity benefits of multiple antennas. By simultaneous coding across space and time ST codes provides high performance improvement without sacrificing bandwidth. ST codes were first proposed by [18], where the authors derived the performance criteria, quantifying diversity by the rank of certain matrices and the coding advantage by determinants of these matrices. Then they constructed ST trellis codes for different fading channels. The main disadvantage of ST trellis codes is decoding complexity which increases exponentially with level of diversity and rate of transmission chosen. ST block codes from orthogonal designs which was proposed by [4], has numerous advantages in terms of diversity level, transmission rate and low-complexity. For two antennas this code can achieve a diversity of 2 and code rate of 1. Generator matrix for Alamouti code is

$$\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{2.8}$$

where rows correspond to timeslots and columns correspond to antennas. This OSTBC(Orthogonal Space Time Block Code) introduces single symbol ML decoding at the receiver thanks to orthogonality of the code matrix. Futher analysis [20]has shown that OSTBC has failed to achieve a rate larger than 3/4 for more than 2 transmit antennas.To address this issue Quasi Orthogonal Space Time codes were proposed in [21] by relaxing single symbol decoding. This code is simply constructed by mapping two OSTBC into codeword matrix with the Alamouti approach. Generator matrix of QOSTBC can be shown as

$$\mathbf{G} = \begin{pmatrix} G(s_1, s_2) & G(s_3, s_4) \\ -G^*(s_1, s_2) & G^*(s_1, s_2) \end{pmatrix} = \begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & -s_4^* & s_1^* & s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{pmatrix} \tag{2.9}$$

It can be seen that this code achieves full rate it transmits four symbols in four timeslots. However this matrix may fail to achieve full diversity since the rank of the difference matrix(between transmitted and decoded codeword) could be two. And it is impossible to achieve full diversity if the symbols are chosen from the same constellation. Instead symbols s_3 and s_4 may be rotated before transmission to obtain $\tilde{s_3}$ and $\tilde{s_4}$ respectively to use signal space diversity [3]. The resulting code is very powerful providing full diversity, rate one and simple pairwise decoding.

First ST coded MIMO-OFDM systems was proposed in [19] ,where ST trellis coded symbols are interleaved across OFDM subchannels which leads to large decoding complexity. In [24] OSTBC were applied accepting each subchannel as a virtual antenna. ST encoded information symbols s_1 and $-s_2^*$ are sent through OFDM blocks n and n+1 for antenna 1, and s_2 and $-s_1^*$ are sent through OFDM blocks n and n+1 for antenna 2. This approach fails to obtain additional multipath diversity while providing spatial diversity. In [28] by using mapping technique it was shown that it is possible to achieve both spatial and multipath diversity. Although this code maintains simple ML decoding because of mapping, which is simply repeating transmission on different subchannels, the code rate is reduced by $1/L$.

2.2.3.2. Space Frequency Coding : The idea of Space Frequency coding is to implement coding across antennas and OFDM subchannels. Design criteria for SF coding in broadband wireless systems was initially proposed in [22]. Authors showed that using existing space time codes in broadband channels does not exploit full available diversity. They referenced code structure in [25] where simple mapping of Alamouti code to OFDM subchannels for two antennas was proposed. Two symbols s_1 and $-s_2^*$ are sent from subchannels k and $k+1$ of the same OFDM block for antenna 1, and s_2 and s_1^* are sent from antenna 2 with the same manner. This code as implied in [22] fails to achieve available diversity $M_t M_r L$ in frequency selective channels. By repeating each row of ST code matrix on k different subchannels within the same OFDM block in [28], a SF code structure obtaining available multipath diversity in addition to spatial diversity. However this code has a limited code rate which cannot be larger than $1/L$. In [29] a powerful SFBC for MIMO OFDM systems was proposed which achieves rate-1 and full diversity for any number of transmit antennas. To obtain full diversity and rate-1, symbol vector is multiplied by a algebraic rotation matrix ψ before being send to OFDM subchannels and transmit antennas. Then coded symbols are spread over subcarriers in a way that code matrix is orthogonal. Following code structure for 2 antennas is an example from this design.

$$\mathbf{G} = \sqrt{2}\begin{bmatrix} x_1 & x_2 & 0 & 0 & x_5 & x_6 & \dots \\ 0 & 0 & x_3 & x_4 & 0 & 0 & \dots \end{bmatrix}^T \tag{2.10}$$

where $[x_1 \quad x_2 \quad x_3 \quad x_4] = [s_1 \quad s_2 \quad s_3 \quad s_4]\frac{1}{2}V(\phi, -\phi, j\phi, -j\phi)$. V is Vandermonde matrix utilized to precode information symbols and rotate the signal constellation for rate-1 and full diversity. And finally decoding is performed by using sphere decoding per four symbols and a multipath diversity of two is obtained as well as rate-1 for the code above.

Recently rate-1 and full diversity QOSTBC for MIMO-OFDM channels has been proposed in [33]. The code design is based on quasi orthogonal space time block codes which is also presented in [33]. Set of combined symbols are used to achieve full rate and rotated symbols in combined symbols are used to achieve full diversity in QOSTBC design. SF code is derived from QOSTBC for two antennas and to achieve full rate and multipath diversity of two. Following structure shows the codeword of the design:

$$\mathbf{G} = \begin{bmatrix} x_1^1 & x_2^1 \\ -{x_1}^1* & {x_2}^1* \\ x_3^1 & x_4^1 \\ -{x_3}^1* & {x_4}^1* \\ x_1^2 & x_2^2 \\ -{x_1}^2* & {x_2}^2* \\ x_3^2 & x_4^2 \\ -{x_3}^2* & {x_4}^2 \\ \vdots & \vdots \end{bmatrix} \quad \left.\begin{matrix} \\ \\ \\ \\ \end{matrix}\right\} \quad \begin{matrix} x_1 = s_1 + \tilde{s_2} \\ x_2 = s_3 - \tilde{s_4} \\ x_3 = s_1 + \tilde{s_2} \\ x_4 = s_3 - \tilde{s_4} \end{matrix} \tag{2.11}$$

This code is full rate since it transmits four symbols for four subcarriers and enjoys a multipath diversity of two. Decoding of this code is done for per 4 symbols and under specific channel conditions, complexity is 1/2 of the code in [29].

2.2.3.3. Space-Time-Frequency Coding : STF codes as the name implies uses three dimensions when generating the codeword. Most of the work on STF codes have considered quasi static channels, where path gain remain constant throughout the codeword. In [27] design criteria for full diversity STF codes has been derived. Although code structure achieve multipath diversity when time dimension is set to unity (STF becomes SF code), it is indispensable for decreasing complexity by subcarrier grouping in their design. Recently QOSFBC were proposed by [33] where coding across time significantly decreases complexity if the code. This code also achieved full multipath diversity as well as spatial diversity. However this codes are not able to obtain any gain from temporal domain, coding across time only reduces decoding complexity since channels are assumed to be quasi static. In [30] it has been proven that maximum available in a block fading channel equals to M_tM_rLT where T is the rank of temporal correlation matrix. There are recently proposed codes by [35] to offer maximum diversity and high rate, which we will not review in detail.

2.2.4. Multiuser Space-Frequency Coding

Researches for Space Frequency coding in MIMO systems have primarily focused on point-to-point links. However upcoming wireless technologies which will likely integrate MIMO are not proven to give optimal performance within a network consisting of base stations, mobile nodes or access points equipped with multiple antennas. In point-to-point links it is possible to encode data across transmit antennas, since all antennas are fed by the same encoder. In multiuser case different users should coordinate their transmission which introduces a completely different problem for code design. In [32] regions for joint code design has been derived depending on the users transmission rates. Determining the dominant error event regions it has been demonstrated that joint code design is only beneficial when both of users transmit at high rates concurrently. This work is limited to two antennas and does not give any systematic code design. The basic idea of multiuser SF coding is to allow users to choose their unique codebooks so that error rate of concurrent transmission is minimized.

Another extension to multiuser SF coding may be cooperative diversity where it is not possible to deploy multiple antennas at transmitters. When the channel quality between users and destination is below certain threshold, users can encode their own and partners data according to a SF algorithm and transmit concurrently SF coded vectors to form MIMO-SF codeword. At the receiver assuming carrier and phase synchronization, decoding can be performed similar to point-to-point MIMO communication. However performance of this structure is strongly dependent on the quality of interuser channel since the symbol vectors are formed in conjunction with decoded symbols of the partner.

3. Cooperative SF coded MIMO-OFDM systems

3.1. Introduction

Diversity increases the performance of a broadband wireless channel by providing redundant copies of a transmitted signal at the receiver. Cooperative Diversity and MIMO are two different techniques that enjoys the benefits of spatial diversity while frequency selectivity of broadband channel introduces multipath diversity.

Cooperative communication can be considered as a choice where spatial separation is important since nodes are likely placed apart from each other and it is not feasible to deploy multiple antennas at transmitting nodes. However it does not offer dedicated collaboration with high performance because cooperation depends on the quality of the channel between nodes. MIMO has recently attracted attention after new developments enabled deployment of multiple antennas in various devices. Having the capability of providing high data rates and reliability that broadband wireless systems demands for, MIMO will likely keep the focus on. From a cellular perspective where handsets should be small and have low-complexity it does not seem possible to deploy multiple antennas at mobile nodes yet.

OFDM is a powerful technique to combat detrimental effects of broadband channels transforming frequency selective channels into flat fading channels. By combining OFDM with MIMO systems it is possible to achieve spatial and frequency diversity available in the channel if powerful space frequency codes are used. In SF coding symbols are distributed over different antennas and OFDM symbols.

If the transmitting nodes are limited to have one antenna, we may consider to create virtual MIMO systems by using cooperative diversity. Space time protocols for exploiting cooperative diversity in flat fading channels has been studied in [10], where transmission period is divided into two phases. Source nodes transmitted in the first phase, relays transmitted what they have decoded in the second phase according to a space time algorithm which enabled relays to transmit on the same subchannel. In [12] multiuser OFDM system with space time cooperation was proposed. Their system followed amplify and forward method and used linear precoders to utilize multipath diversity available in a frequency selective channel. The authors of [13] designed a OFDM system which used space time codes in cooperation phase. They employed traditional Alamouti codes on OFDM blocks to achieve spatial diversity and let channel encoders to deal with frequency diversity. Recently in [15], high rate space-frequency codes were used in OFDM system for cooperative communications. They assumed that relay nodes successfully decoded information from source and developed a system from there taking arbitrary delay profiles into account.

In this chapter we propose two SF coded cooperative diversity system. We use the idea of virtual MIMO-OFDM systems to achieve spatial and multipath diversity available in the channel to improve the performance of single antenna OFDM systems. In our system users use OSFBC and QOSFBC structure proposed in to form symbol vectors by using their own and other user's decoded information to create virtual MIMO codeword matrix.

In Section II we define the system model, giving the components of out cooperative system. Based on the system model we construct signal model and cooperative code structures in Section III. We will discuss the metrics that effect the behavior and the performance of our system in last section.

3.2. System Model

Our cooperative system consists of two users and a destination. Users use OFDM modulation and are assumed to be able transmit and receive simultaneously. OFDM transmitter structure used is shown in figure 3.1. Space frequency encoder is operational when the users are in cooperative mode. Users have N OFDM subcarriers and at Phase I they transmit over $N/2$ subcarriers while listening over remaining $N/2$ subcar-

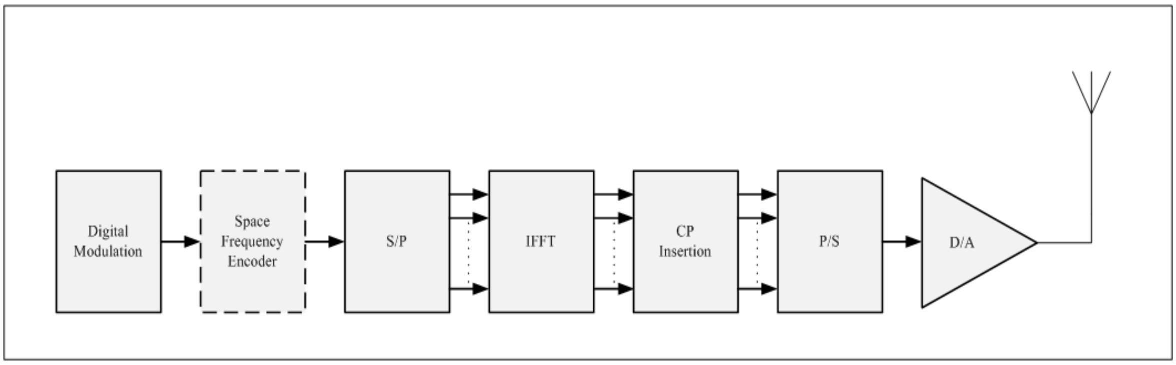

Figure 3.1. OFDM system with Space Frequency Encoder

riers. When users encounter severe fading in transmission to the receiver they switch into cooperating mode and employ space frequency encoding. At phase II detected symbols from non-cooperative mode are encoded to form symbol vectors according to SF algorithm. Next new combined symbols are parsed into blocks of N and IFFT transform is applied to form an OFDM symbol and transmitted after CP(cyclic prefix) is appended on top of OFDM symbol.At the receiver after CP removal, received symbols are FFT transformed and symbols are used for detection. We should note that throughout the chapter we expect some level of synchronization and assume that nodes are block, carrier and symbol synchronous to be more focused on the scope of the chapter.

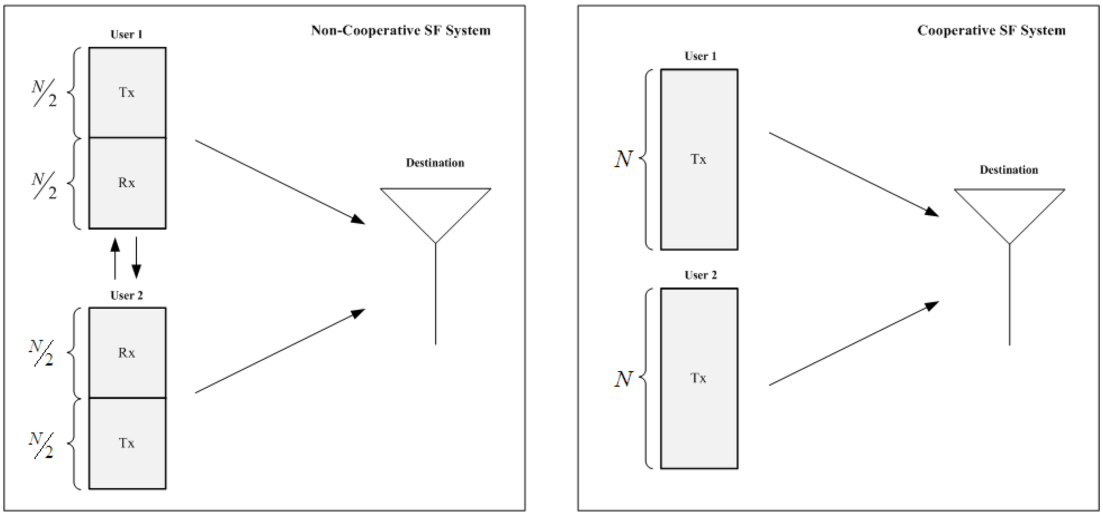

Figure 3.2. Non-cooperative and Cooperative Transmission respectively

3.3. Channel and Signal Model

Elements in our system operates in broadband channels which suffer frequency selectivity. As mentioned before in phase I users do not transmit cooperative information and continue regular transmission. Channel impulse response of channel between users 1, 2 and destination(will be identified as 3 in equations) is given by

$$h_{i,j} = \sum_{l=0}^{L-1} \alpha_{i.j}(l)\delta(\tau - \tau_j(l)) \quad i \neq j \tag{3.1}$$

The complex amplitude and delay for the lth path between nodes are $\alpha_{i,j}$ and $\tau_j(l)$ are respectively.The $\alpha_{i,j}$'s are modeled as zero-mean complex Gaussian random variables with variances $E|\alpha_{i.j}|^2 = \sigma^2(l)$, where E stands for expectation. The total power is normalized such that $\sum_{l=0}^{L_j-1} \alpha_{i.j}^2 = 1$. And the frequency response of the channel is given by

$$H_{i.j} = Fh_{i,j} \tag{3.2}$$

where

$$\begin{aligned} h_{i,j} &= [\alpha_{i,j}(0) \quad \alpha_{i,j}(1) \quad \ldots \quad \alpha_{i,j}(L-1)]^T & (3.3)\\ H_{i,j} &= [H_{i,j}(0) \quad H_{i,j}(1) \quad \ldots \quad H_{i,j}(N-1)]^T & (3.4)\\ F &= [f^{\tau_0} \quad f^{\tau_1} \quad \ldots \quad f^{\tau_{L-1}}] & (3.5) \end{aligned}$$

f is given by $f = [1 \quad \xi \quad \ldots \quad \xi^{N-1}]^T$ where $\xi = \exp(-j(2\pi/T))$. T corresponds to OFDM symbol period. Let us define subcarriers $\varepsilon_1 = \{0, 1, ..., N/2 - 1\}$, $\varepsilon_2 = \{N/2, ..., N-1\}$ and $\varepsilon_3 = \{0, ..., N-1\}$. At the first phase user 1 transmits over subcarriers ε_1 receives over subcarriers ε_2, while user 2 transmits over subcarriers ε_2 and receives over ε_1. Destination listens over ε_3 in both phases.

Phase I:

Before transmission IFFT is applied to symbol vector

$$X = F^h S \tag{3.6}$$

where F^h is a NxN diagonal IFFT matrix and $S = [s(0) \quad s(1) \quad (2) \quad \ldots \quad s(N-1)]^T$. After IFFT processing CP, which is simply last P samples for OFDM block, is appended on top of OFDM block to obtain resultant transmission vector, which is $X = [x(N-1-P) \quad x(N-1) \quad x(0) \quad x(1) \quad \ldots \quad X(N-1)]^T$. After cyclic prefix(CP) is removed and FFT is applied, received signals at the nth subcarrier for user 1, user 2 and destination in the first phase are

$$y_1(n) = \quad H_{21}(n)s_2(n) + w_1(n) \qquad \text{over} \qquad \varepsilon_2 \tag{3.7}$$

$$y_2(n) = \quad H_{12}(n)s_1(n) + w_2(n) \qquad \text{over} \qquad \varepsilon_1 \tag{3.8}$$

$$y_3(n) = \quad \begin{cases} H_{13}(n)s_1(n) + w_3(n) & \text{over} \qquad \varepsilon_1 \\ H_{23}(n)s_2(n) + w_3(n) & \text{over} \qquad \varepsilon_2 \end{cases} \tag{3.9}$$

Users can use ML decoding to obtain symbols that are going to be utilized in the second phase. Decoded symbol vector at each user can be defined as ;

$$\hat{S}_1 = \text{argmin} \sum_{n=N/2-1}^{N-1} ||y_1(n) - H_{21}s_2(n)||^2 \quad \text{at} \quad \text{user1} \tag{3.10}$$

$$\hat{S}_2 = \text{argmin} \sum_{n=0}^{N/2-1} ||y_2(n) - H_{12}s_1(n)||^2 \quad \text{at} \quad \text{user2} \tag{3.11}$$

where $||\cdot||$ denotes the Frobenius norm. Actually ML decoder for pure OFDM systems is nothing but a ZF(zero forcing) equalizer followed by a threshold detector. Basically ZF algoritm multiplies received signal vector with H^H which is conjugate transpose of channel matrix.

Phase II:

In phase II both users transit over ε_3. At destination received signal at the nth subcarrier is given by;

$$y_3(n) = \sum_{i=1}^{2} H_{i3}(n)s_i(n) + w_3(n) \qquad \text{over} \quad \varepsilon_3, \quad \text{where} \quad i = 1,2 \tag{3.12}$$

Destination will also use ML decoding algorithm for to decode transmitted codewords which is given as;

$$\hat{S}_3 = \text{argmin}||Y_3 - HS||^2 \quad \text{at} \quad \text{destination} \tag{3.13}$$

where H and S are combined channel matrix and symbol vector respectively which are derived by algebraic operations. Structure of these components will be given in detail in the following . We are going to review three cases for cooperative transmission which takes place in phase II.

- Regular Decode and Forward : Users will retransmit their information and will forward detected symbols of other user without applying any space frequency algoritm
- Orhogonal Space Frequency Block Coded Copperation : Users will encode their own symbols and decoded symbols to according to well known Alamouti algoritm to form vectors of MIMO cahnnel matrix
- Quasi Orthogonal Space Frequency Block Coded Cooperation : To take multipath diversity into account, users will apply encoding according to the codes structure based on Quasi Orthogonal Space Frequency Block Codes.

3.3.1. Regular Decode and Forward

In regular decode and forward users will forward decoded symbols directly to destination without employing a encoding algorithm by allocating listening subcarriers for transmission of other user's decoded data.Now let the user 1 transmit symbols $s_{1,0}, s_{1,1}, \dots s_{1,N/2-1}$ over ε_1 and user 2 transmits symbols $s_{2,N/2}, s_{2,N/2+1}, \dots s_{2,N-1}$ over ε_2 in phase I. Corresponding decoded symbols over ε_2 at user 1 are $\hat{s}_{2,N/2}, \hat{s}_{2,N/2+1}, \dots$, $\hat{s}_{2,N-1}$, while decoded symbols over ε_1 at user 2 are $\hat{s}_{1,0}, \hat{s}_{1,1}, \dots, \hat{s}_{1,N/2-1}$. When users switch to cooperative transmission mode they retransmit their own data and the other user's decoded data to the destination. Since no special space frequency coding algorithm is applied, transmitting decoded data over listening subcarriers forms a channel a matrix where columns represent data transmitted from each antenna.

$$C = \begin{bmatrix} s_{1,0} & s_{2,N/2} \\ s_{1,1} & s_{2,N/2+1} \\ \vdots & \vdots \\ s_{1,N/2-2} & s_{2,N-2} \\ s_{1,N/2-1} & s_{2,N-1} \\ -\hat{s}_{2,N/2} & \hat{s}_{1,0} \\ -\hat{s}_{2,N/2+1} & \hat{s}_{1,1} \\ \vdots & \vdots \\ -\hat{s}_{2,N-2} & \hat{s}_{1,N/2-2} \\ -\hat{s}_{2,N-1} & \hat{s}_{1,N/2-1} \end{bmatrix} \tag{3.14}$$

Since this structure has no interesting property than being a repetition code, decoding at the destination can be performed by analyzing the columns independently and use simple OFDM ML detection for each column and decide on favor of the symbol which has a high SNR. Decoding formulas for each column per subcarrier are;

$$\hat{S}_1 = \text{argmin} \sum_{n=0}^{N-1} ||y(n) - H_{13}s_1(n)||^2 \quad \text{for} \quad \text{user1} \tag{3.15}$$

$$\hat{S}_2 = \text{argmin} \sum_{n=0}^{N-1} ||y(n) - H_{23}s_2(n)||^2 \quad \text{for} \quad \text{user2} \tag{3.16}$$

3.3.2. Orthogonal Space Frequency Block Coded Cooperation

Now let the user 1 transmit symbols $s_{1,0}, s_{1,1}, \ldots s_{1,N/2-1}$ over ε_1 and user 2 transmits symbols $s_{2,N/2}, s_{2,N/2+1}, \ldots .s_{2,N-1}$ over ε_2 in phase I. Corresponding decoded symbols over ε_2 at user 1 are $\hat{s}_{2,N/2}, \hat{s}_{2,N/2+1}, \ldots, \hat{s}_{2,N-1}$, while decoded symbols over ε_1 at user 2 are $\hat{s}_{1,0}, \hat{s}_{1,1}, \ldots, \hat{s}_{1,N/2-1}$. When necessary conditions for cooperative transmission occurs users allocate N subcarriers for transmission and turn space frequency encoders on to form symbol vectors according to the following algorithm to form columns of virtual MIMO matrix. User 1 transmits

$$S_1 = [s_{1,0} \quad -\hat{s}^*_{2,N/2} \quad s_{1,1} \quad -\hat{s}^*_{2,N/2+1} \quad \ldots \quad s_{1,N/2-2} \quad -\hat{s}^*_{2,N-2} \quad s_{1,N/2-1} \quad -\hat{s}^*_{2,N-1}]^T$$

, while user 2 transmits

$$S_2 = [s_{2,N/2} \quad \hat{s}^*_{1,0} \quad s_{2,N/2+1} \quad \hat{s}^*_{1,1} \quad \ldots \quad s_{2,N-2} \quad \hat{s}^*_{1,N/2-2} \quad s_{2,N-1} \quad \hat{s}^*_{1,N/2-1}]^T$$

to form

$$C = \begin{bmatrix} s_{1,0} & s_{2,N/2} \\ -\hat{s}^*_{2,N/2} & \hat{s}^*_{1,0} \\ s_{1,1} & s_{2,N/2+1} \\ -\hat{s}^*_{2,N/2+1} & \hat{s}^*_{1,1} \\ \vdots & \vdots \\ s_{1,N/2-2} & s_{2,N-2} \\ -\hat{s}^*_{2,N-2} & \hat{s}^*_{1,N/2-2} \\ s_{1,N/2-1} & s_{2,N-1} \\ -\hat{s}^*_{2,N-1} & \hat{s}^*_{1,N/2-1} \end{bmatrix} \tag{3.17}$$

Decoding will be performed for 2 symbols at a time. If we generalize the received signal at destination at each subcarrier;

$$\begin{aligned} y[2m] &= s_{1,m}H_{13}[2m] + s_{2,N/2+m}H_{23}[2m] + w_3[2m] \\ y[2m+1] &= -\hat{s}^*_{2,N/2+m}H_{13}[2m+1] + \hat{s}^*_{1,m}H_{23}[2m+1] + w_3[2m+1] \end{aligned} \quad (3.18)$$

where $m = 0, \ldots, N/2 - 1$. If we rearrange the equations

$$\begin{aligned} y[2m] &= H_{13}[2m]s_{1,m} + H_{23}[2m]s_{2,N/2+m} + w_3[2m] \\ y[2m+1]^* &= -H_{13}[2m+1]^*\hat{s}_{2,N/2+m} + H_{23}[2m+1]^*\hat{s}_{1,m} + w_3[2m+1]^* \end{aligned} \quad (3.19)$$

If receiver assumes that users decode the symbols of each other successfully in phase I the equation becomes:

$$\begin{bmatrix} y[2m] \\ y[2m+1]^* \end{bmatrix} = \begin{bmatrix} H_{13}[2m] & H_{23}[2m] \\ H_{23}[2m+1]^* & -H_{13}[2m+1]^* \end{bmatrix} \begin{bmatrix} s_{1,m} \\ s_{2,N/2+m} \end{bmatrix} + \begin{bmatrix} w_3[2m] \\ w_3[2m+1]^* \end{bmatrix} \quad (3.20)$$

We can observe that we have 4 unknowns in channel matrix. For the sake of simplicity we assume that adjacent subcarriers are subject to same fading which converts the channel matrix into well known Alamouti code channel matrix. Then simple maximum likelihood(ML) decoding can be applied to detect transmitted symbols. Maximum likelihood decoding rule results in

$$\begin{bmatrix} \hat{s}_{1,m} \\ \hat{s}_{2,N/2+m} \end{bmatrix} = \frac{1}{|H_{13}[2m]|^2 + |H_{23}[2m]|^2} \begin{bmatrix} H_{13}[2m]^* & H_{23}[2m] \\ H_{23}[2m]^* & -H_{13}[2m] \end{bmatrix} \begin{bmatrix} y[2m] \\ y[2m+1]^* \end{bmatrix} \quad (3.21)$$

3.3.3. Quasi Orthogonal Space Frequency Block Coded Cooperation

Although we are able to achieve spatial diversity by using OSTBC in cooperative transmission, it is not possible to exploit multipath diversity available in frequency selective channels. To use all the available diversity we employ QOSTBC in cooperative transmission.

As indicated before we use the design in [33] for our cooperative QOSFBC algorithm.First we briefly review code structure, then we can look at implementation method to our cooperative system. Since we have two users having one antenna each we use QOSTBC for $M_t = 2k$ antennas in [33]. General SF codeword based on aforementioned design can be given as

$$C = [\quad G^{1T} \quad G^{2T} \quad \ldots \quad G^{bT} \quad \ldots \quad]^T \tag{3.22}$$

where,

$$G^b = [A(X_1^b, X_2^b) A(X_3^b, X_4^b) \ldots A(X_{2k-1}^b, X_{2k}^b)] \tag{3.23}$$

$b \in \{1, ..., \frac{N}{2\Delta}\}$ denotes the block number and N is assumed to be a integer multiple of block length 2Δ We use the code structure that provides a multipath diversity of two($\Delta = 2$) for our cooperative scheme. Suppose in non-cooperative mode, user 1 transmits symbols $s_{1,0}, s_{1,1}, \ldots . s_{1,N/2-1}$ over ε_1 and user 2 transmits symbols $s_{2,N/2}, s_{2,N/2+1}, \ldots . s_{2,N-1}$ over ε_2. Corresponding decoded symbols over ε_2 T user 1 are $\hat{s}_{2,N/2}, \hat{s}_{2,N/2+1}, \ldots, \hat{s}_{2,N-1}$, while decoded symbols over ε_1 at user 2 are $\hat{s}_{1,0}$,$\hat{s}_{1,1}$,$\ldots$, $\hat{s}_{1,N/2-1}$. Having obtained the decoded symbols we can form new set of information vectors based on QOSFBC design. We can define new combined symbols consisting of decoded symbols and to be retransmitted symbols. If new symbol vectors are joined together to form the codeword matrix we get the following design:

$$C = \begin{bmatrix} X_1^1 & X_2^1 \\ -\hat{X}_2^1* & \hat{X}_1^1* \\ X_3^1 & X_4^1 \\ -\hat{X}_4^1* & \hat{X}_3^1* \\ X_1^2 & X_2^2 \\ -\hat{X}_2^2* & \hat{X}_1^2* \\ X_3^2 & X_4^2 \\ -\hat{X}_4^2* & \hat{X}_3^2* \\ \vdots & \vdots \end{bmatrix} \qquad \begin{array}{ll} X_1^1 = s_{1,0} + \underline{s}_{1,1} & X_2^1 = s_{2,N/2} + \underline{s}_{2,N/2+1} \\ \hat{X}_1^1 = \hat{s}_{1,0} + \hat{\underline{s}}_{1,1} & \hat{X}_2^1 = \hat{s}_{2,N/2} + \hat{\underline{s}}_{2,N/2+1} \\ X_3^1 = s_{1,0} - \underline{s}_{1,1} & X_4^1 = s_{2,N/2} - \underline{s}_{2,N/2+1} \\ \hat{X}_3^1 = \hat{s}_{1,0} - \hat{\underline{s}}_{1,1} & \hat{X}_4^1 = \hat{s}_{2,N/2} - \hat{\underline{s}}_{2,N+2+1} \\ & \vdots \\ & \vdots \end{array} \tag{3.24}$$

Note that each column in C corresponds to SF vector of each user. And $\underline{s} = se^{j\theta}$ is rotated version of s to achieve full diversity by signal constellation rotation. This code structure is rate 1 and achieves full multipath and spatial diversity. Since the design is to provide multipath diversity of two, minimum rank of difference matrix between transmitted codeword and received codeword is four from $M_T L M_r$. So, decoding is performed for four symbols at a time. The received signal at each subcarrier can be shown as;

$$\begin{aligned} y[4m] =& (s_{1,2m} + \underline{s}_{1,2m+1})H_{13}[4m] \\ &+ (s_{2,N/2+2m} + \underline{s}_{2,N/2+2m+1})H_{23}[4m] + w_3[4m] \\ y[4m+1] =& -(\hat{s}_{2,N/2+2m} + \hat{\underline{s}}_{N/2+2m+1})^* H_{13}[4m+1] \\ &+ (\hat{s}_{1,2m} + \hat{\underline{s}}_{2m+1})^* H_{23}[4m+1] + w_3[4m+1] \\ y[4m+2] =& (s_{1,2m} - \underline{s}_{1,2m+1})H_{13}[4m+2] \\ &+ (s_{2,N/2+2m} - \underline{s}_{2,N/2+2m+1})H_{23}[4m+2] + w_3[4m+2] \\ y[4m+3] =& -(\hat{s}_{2,N/2+2m} - \hat{\underline{s}}_{N/2+2m+1})^* H_{13}[4m+3] \\ &+ (\hat{s}_{1,2m} - \hat{\underline{s}}_{2m+1})^* H_{23}[4m+3] + w_3[4m+3] \end{aligned} \tag{3.25}$$

where $m = 0, \ldots, N/4 - 1$. After rearranging the terms knowing that destination assumes that users decoded each others data successfully in phase I, equation becomes;

$$\begin{bmatrix} y[4m] \\ y[4m+1]^* \\ y[4m+2] \\ y[4m+3]^* \end{bmatrix} = \begin{bmatrix} H_{13}[4m] & H_{23}[4m] & 0 & 0 \\ H_{23}[4m+1]^* & -H_{13}[4m+1]^* & 0 & 0 \\ 0 & 0 & H_{13}[4m+2] & H_{23}[4m+2] \\ 0 & 0 & H_{23}[4m+3]^* & -H_{13}[4m+3]^* \end{bmatrix}$$

$$\times \begin{bmatrix} s_{1,2m} + s_{1,2m+1} \\ s_{2,N/2+2m} + s_{2,N/2+2m+1} \\ s_{1,2m} - s_{1,2m+1} \\ s_{2,N/2+2m} - s_{2,N/2+2m+1} \end{bmatrix} + \begin{bmatrix} w_3[4m] \\ w_3[4m+1]^* \\ w_3[4m+2] \\ w_3[4m+3]^* \end{bmatrix} \tag{3.26}$$

At the receiver ML decoding is performed to obtain symbols from the codeword. If we assume that adjacent subcarriers undergo same fading we can use pairwise decoding where we can group decoding formulas into two functions containing pair of symbols. This reduces the complexity significantly. Maximum likelihood decoding formula for QOSTBC ;

$$\min_{s_1,s_2,s_3,s_4} H^H \cdot C^H \cdot C \cdot H - H^H \cdot C^H \cdot y - y^H \cdot C \cdot H \tag{3.27}$$

yields following pairwise decoding formulas after some algebraic manipulation. Decoding formula for the first two symbols of the block code can be written as;

$$\begin{aligned} & f_{min}(s_{1,2m}, \underline{\mathrm{s}}_{1,2m+1}) = \\ & |s_{1,2m} + \underline{\mathrm{s}}_{1,2m+1}|^2 (|H_{13}[4m]|^2 + |H_{23}[4m+1]|^2) \\ & + |s_{1,2m} - \underline{\mathrm{s}}_{1,2m+1}|^2 (|H_{13}[4m+2]|^2 + |H_{23}[4m+3]|^2) \\ & + 2\Re\Big[(s_{1,2m} + \underline{\mathrm{s}}_{1,2m+1})(y[4m]H_{13}[4m]^* + y[4m+1]^* H_{23}[4m+1]) \\ & + (s_{1,2m} - \underline{\mathrm{s}}_{1,2m+1})(y[4m+2]H_{13}[4m+2]^* + y[4m+3]^* H_{23}[4m+3]) \Big] \end{aligned} \tag{3.28}$$

while formula of the second pair is

$$\begin{aligned}
&f_{min}(s_{2,N/2+2m}, \underline{s}_{2,N/2+2m+1}) = \\
&|s_{2,N/2+2m} + \underline{s}_{2,N/2+2m+1}|^2(|H_{13}[4m+1]|^2 + |H_{23}[4m]|^2 \\
&+ |s_{2,N/2+2m} - \underline{s}_{2,N/2+2m+1}|^2(|H_{13}[4m+3]|^2 + |H_{23}[4m+2]|^2) \\
&+ 2\Re\Big[(s_{2,N/2+2m} + \underline{s}_{2,N/2+2m+1})(y[4m]H_{23}[4m]^* - y[4m+1]^*H_{13}[4m+1]) \\
&+ (s_{2,N/2+2m} - \underline{s}_{2,N/2+2m+1})(y[4m+2]H_{23}[4m+2]^* - y[4m+3]^*H_{13}[4m+3])\Big]
\end{aligned} \tag{3.29}$$

3.4. Simulation Results

Our system consists of two users and a destination. Users and receiver are equipped with one antenna and have 128 subcarriers. In first phase user 1 allocates first 64 of total subcarriers while user 2 allocates last 64 subcarriers for transmission. Remaining subcarriers are allocated for listening other users' data. In phase II both users allocate all of 128 subcarriers for transmission. We assume that the receivers has perfect channel knowledge while transmitters do not know the channel. User- to-user and users-to-destination channel between users are 2 ray multipath channel. For phase II we use a delay spread of $20 * 10^{-6}$ seconds for second path arriving at destination. We performed 8000 iterations for each SNR value in our simulations. We compare OSFBC cooperation and QOSFBC cooperation in our simulations for which we use BPSK modulation and rotation angle of $\pi/2$ for QOSFBC. Destination assumes that users decode each others information successfully and constitutes ML decoding formulas according to this assumptions. In decoding process we use the formulas 3.18 and 3.25 to obtain received signals for OSFBC and QOSFBC respectively. Then we embed these received signal values to the corresponding ML decoding formulas 3.21 for OSFBC and 3.28-3.29 for QOSFBC. In figure 3.4 the performance of the codes in the second phase are shown if perfect decoding occurs at each user in the first phase. We can see that QOSFBC performs better than OSFBC especially in high SNR as expected. Figure 3.4 shows the performance of the system in phase II where interuser channel is not ideal. We can see that both code structures behaves identical which means that QOSFBC are more vulnerable to decoding errors. Errors affect QOSFBC in a way that this code structure is not able to enjoy available multipath diversity.So considering low decoding complexity of OSFBC it is fair to say that it would be convenient to use OSFBC in systems where cooperative transmission method is fixed decode and forward.

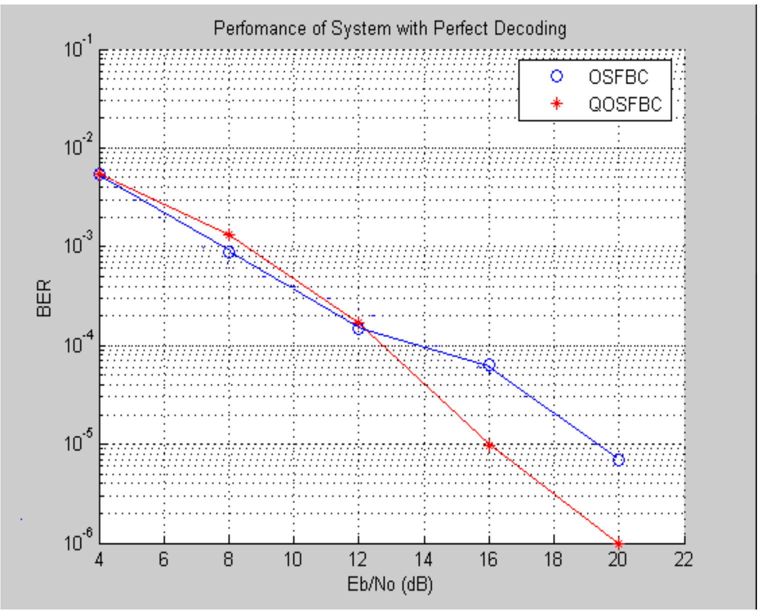

Figure 3.3. Performance with Perfect Decoding

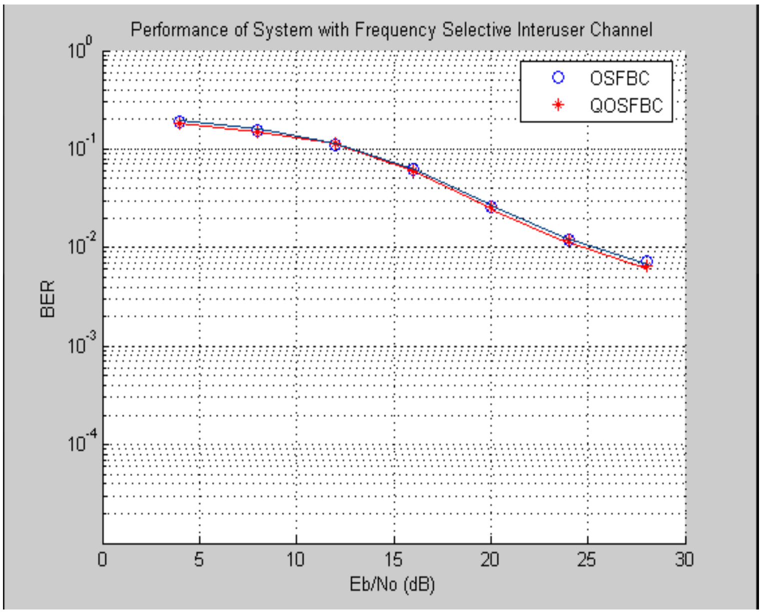

Figure 3.4. Performance with Frequency Selective Interuser Channel

4. Conclusion and Future Work

Throughout this thesis we provided a strong literature survey regarding cooperative diversity and space frequency coding in MIMO-OFDM systems. For broadband wireless channels SF coding have the potential to achieve available multipath diversity in frequency-selective channels when used in conjunction with MIMO systems which are already known to provide spatial diversity. Those systems enjoys the orthogonal subcarriers of OFDM which eliminates interschool interference and simple IFFT-FFT algorithms at transmitter and receiver which reduces complexity significantly. Another important proposed diversity antenna technique, cooperative diversity, is promising candidate where it is not feasible to deploy multiple antennas at transmitting nodes. The idea is to form virtual antenna arrays by using other nodes' antennas as a relay. By choosing an adaptive cooperation algorithm that functions according the quality of interuser channel it is possible to achieve maximum spatial gain available.

We considered scenarios where users are limited to have a single antenna and provided algorithms for cooperative systems to design virtual MIMO-OFDM systems combined with SF codes that will be able to improve the performance of a fading channel.

Our network consisted of two users and a destination node where users are transmitting over 1/2 of available carriers and receive over remaining subcarriers in phase I. When appropriate conditions occur for cooperative transmission users allocate all available subcarriers for transmission and SF encoding takes place before transmission. After OFDM processing SF encoded symbol vectors are transmitted to form a virtual Space frequency coded MIMO-OFDM system.

Our results show fixed decode and froward degrades the performance of QOSFBC. Adaptive cooperative transmission methods such as selection relaying where cooperation depend on channel quality can be considered as an option. When the channel quality falls below a certain threshold, users may continue regular transmission or use

OSFBC in cooperative transmission. Observing that the channel quality is increasing users may start encoding according to QOSFBC algorithm to use the available multipath diversity in frequency selective channel.

Another open subject is whether the information from the first phase should be included in decoding process of the second phase. One option is to use the probability of detecting a signal from phase I as prior information for phase II.However the drawback of this approach is that decoding complexity increases significantly. So this trade-off should be examined carefully.

As a result this work can be extended to form a better performance cooperative system which is able to utilize all the available diversity in a frequency selective broadband channel.

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APPENDIX A: Matlab Code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%  SYSTEM WITH FREQUENCY SELECTIVE %%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%  INTERUSER CHANNEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% FOR PERFECT DECODING SKIP PHASE I AND MAKE %%%%%%%%
%%%%%% USER1 TRANSMIT DATA = USER2 DECODED DATA %%%%%%%%%%
%%%%%% USER2 DATA = USER1 DECODED DATA %%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc;
clear all;
M=2;     %parameter for bpsk
%dstream = 1024;     %data stream
dstream = 64;
Nc = 64; %no, of carriers
dNc= Nc*2;
cp = 8; %cyclic prefix
L=2; %number of taps
column_number = dstream/Nc;
%SNR = 0:1:15;
iter=80;
error1=[];
error2=[];
error3=[];
BER11=[];
BER22=[];
for SNR=4:4:28
    for packetid=1:iter
    %%%%%%%%%%transmitter%%%%%%%%%%%%
%pre-assign transmission vectors
vx_total=[];
vx_total2=[];
```

```
v_data =randint(1,dstream,1:0);   %random data stream user 1
v_data2 = randint(1,dstream,1:0);    %random data stream user 2

v_data3 = [v_data v_data2];

mod_v_data = pskmod(v_data,M);  %modulate data using bpsk
mod_v_data2 = pskmod(v_data2,M); %modulate data using bpsk for user 2
%mod_v_data3 = [mod_v_data mod_v_data2];

%convert serial stream to parallel for each user
m_pre_ifft = reshape(mod_v_data,Nc,[]);
m_pre_ifft2 = reshape(mod_v_data2,Nc,[]);

for i=1:column_number;      %loop for ifft of each column
   v_ifft=ifft(m_pre_ifft(:,i));
   v_ifft2=ifft(m_pre_ifft2(:,i));

   v_cp=v_ifft(Nc-cp+1:end,:);      %determine cyclic prefix
   v_cp2=v_ifft2(Nc-cp+1:end,:);

   v_tx_col=[v_cp; v_ifft];       %add cyclic prefix to each column
   v_tx_col2=[v_cp2; v_ifft2];

   vx_total = [vx_total v_tx_col];%total transmission matrix user 1
   vx_total2 = [vx_total2 v_tx_col2];%total transmission matrix user 2
end
%prepare data for serial transmission
tx_serial = reshape(vx_total,1,[]);
tx_serial2 = reshape(vx_total2,1,[]);

%%%%%%%%%%%%channel%%%%%%%%%%%%%%%%%%%
%predefined rx serial signal vectors
rx_serial=[]; %received serial data user1
rx_serial2=[]; %received serial data user2

rx_serial3=[]; %received serial data at destination
rx_serial13=[];
```

```
rx_serial23=[];

h_all=[]; % overall channel matrix between users
h13_all=[]; % overall channel matrix between user 1 and destination
h23_all=[]; % overall channel matrix between user 2 and destination

% For each datastream per ofdm symbol we generate a new channel
for k=1:Nc+cp:length(tx_serial-Nc-cp+1);  %detemine length of OFDM symbols

    tx_ofdm_symbol = tx_serial(k:k+Nc+cp-1);  %serial ofdm symbol
    tx_ofdm_symbol2 = tx_serial2(k:k+Nc+cp-1);

%since we assume that the interuser is reciprocal we generate commnon random
%channel
h=1/sqrt(2)*(randn(1,2)+j*randn(1,2));
h_all = [h_all;h];  %total channel info to be used for ifft at receiver

%channel between user 1 and destination
h13=1/sqrt(2)*(randn(1,2)+j*randn(1,2));
h13_all = [h13_all;h13];

%channel between user 2 and destination
h23=1/sqrt(2)*(randn(1,2)+j*randn(1,2));
h23_all = [h23_all;h23];

%convolve each serial ofdm data with corresponding channel coeff.
%between users
rx_ofdm_symbol=conv(tx_ofdm_symbol,h);
rx_ofdm_symbol2=conv(tx_ofdm_symbol2,h);

%convolve serial data of users with channel to the destination
rx_ofdm_symbol13=conv(tx_ofdm_symbol,h13);
rx_ofdm_symbol23=conv(tx_ofdm_symbol2,h23);

%total serial data per user
rx_serial=[rx_serial rx_ofdm_symbol];
rx_serial2=[rx_serial2 rx_ofdm_symbol2];
```

```
%serial data arriving at destination
rx_serial13=[rx_serial13 rx_ofdm_symbol13];
rx_serial23=[rx_serial23 rx_ofdm_symbol23];

%rx_serial3 = [ rx_serial13 rx_serial23];
end

%add noise to each receved symbol per user and destination
for k = 1:1:length(rx_serial)
    rx_serial_noise(1,k)=awgn(rx_serial(1,k),SNR);
    rx_serial_noise2(1,k)=awgn(rx_serial2(1,k),SNR);
end

for k = 1:1:length(rx_serial)
    rx_serial_noise13(1,k)=awgn(rx_serial13(1,k),SNR);
    rx_serial_noise23(1,k)=awgn(rx_serial23(1,k),SNR);
end
%%%%%%%%%%%%%receiver%%%%%%%%%%%%%%%%%%%

%convert serial data to parallel for each user and destination
m_rx_total = reshape(rx_serial_noise,Nc+cp+1,[]);
m_rx_total2 = reshape(rx_serial_noise2,Nc+cp+1,[]);

m_rx_total13 = reshape(rx_serial_noise13,Nc+cp+1,[]);
m_rx_total23 = reshape(rx_serial_noise23,Nc+cp+1,[]);
%m_rx_total3 = reshape(rx_serial_noise3,Nc+cp+1,[]);

%determine number of parallel channels
column_num = length(rx_serial_noise)/length(m_rx_total);
%remove cyclic prefix from each column
pre_fft = m_rx_total(cp+1:Nc+cp,:);
pre_fft2 = m_rx_total2(cp+1:Nc+cp,:);
pre_fft13 = m_rx_total13(cp+1:Nc+cp,:);
pre_fft23 = m_rx_total23(cp+1:Nc+cp,:);

%take the fft of received signal for each user
```

```
y = fft(pre_fft);
y2 = fft(pre_fft2);
y13 = fft(pre_fft13);
y23 = fft(pre_fft23);

%take the transpose of total channel coefficient matrix
h_all = transpose(h_all);
%combine two channel coefficients for joint detection
h13_all = transpose(h13_all);
h23_all = transpose(h23_all);

%h3_all = [h13_all h23_all];
%h3_all = transpose(h3_all);
%determine the fft matrix to find frequency response of channel
Ww = zeros(Nc,L);
for v = 1:1:L;
for k = 1:1:Nc;
Ww(k,v)=exp(-2*j*pi*k/Nc*(v-1));
end;
end;
%find the freq response of channel for each user (we just rename the
%channel matrix since we assume that channel between users is reciprocal)
fft_h = Ww*h_all;
fft_h2 = Ww*h_all;

%freq. response of the channels between users and destinaton
fft_h13 = Ww*h13_all;
fft_h23 = Ww*h23_all;
%%%%%%%%%%%%%%%%%%%%%%%%Preparation for receiver processing%%%%%%%%%%5
%initialize vectors for detecion for each user
d_v_data=zeros(Nc,1);
d_v_data2=zeros(Nc,1);

%vectors for destination
d_v_data13=zeros(Nc,1);     %from User 1
d_v_data23=zeros(Nc,1);     %from user 2
d_v_data3=zeros(dNc,1);     %joint
```

```
demod_data = zeros(Nc,column_num);
demod_data2 = zeros(Nc,column_num);
demod_data3 = zeros(dNc,column_num);

%operate columnwise ,decode symbols per subcarrier
%%%%%%%%%%%%%%User 1%%%%%%%%%%%%%%%%%%
for m=1:1:column_num
       for n=1:1:Nc
   %fft_hd(n,m) = fft_h(n,m);    %map channel matix
   %rec_sig(n,m) = y(n,m);   %map received signal
        d_v_data(n,m) = y(n,m)/fft_h(n,m);
         if real(d_v_data(n,m)) > 0
             dv_data(n,m)= 1;
         else
             dv_data(n,m)= -1;
         end
       demod_data(n,m)=dv_data(n,m);
       end
end
%%%%%%%%%%%%%%%%%User 2%%%%%%%%%%%%%%%
for m=1:1:column_num
       for n=1:1:Nc
   %fft_hd2(n,m) = fft_h2(n,m);    %map channel matix
   %rec_sig2(n,m) = y2(n,m);   %map received signal
        d_v_data2(n,m) = y2(n,m)/fft_h2(n,m);
         if real(d_v_data2(n,m)) > 0
             dv_data2(n,m)= 1;
         else
             dv_data2(n,m)= -1;
         end
       demod_data2(n,m)=dv_data2(n,m);
       end
end

demod_data;
demod_data2;
s_demod_data =reshape(demod_data,1,[]); %at user 2
```

```
s_demod_data2=reshape(demod_data2,1,[]); %at user 1
v_demod_fft = pskdemod(s_demod_data,M);
v_demod_fft2 = pskdemod(s_demod_data2,M);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%   PHASEII    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%clear all
keep demod_data demod_data2 m_pre_ifft m_pre_ifft2 v_data3 SNR iter  ...
packetid error1 error2 BER11  BER22 ...
%errors12 ber12 errors21 ber21 v_demod_fft3 ...
M=2;     %parameter for bpsk
%dstream = 1024;     %data stream
dstream = 64;
Nc = 64; %no, of carriers
dNc= Nc*2;
cp = 8; %cyclic prefix
L=2; %number of taps
column_number = dstream/Nc;
Es=1;
BW=dNc*iter;
T=dNc/BW;
tau=[0 2e-0005];
h = gcf; grid on; hold on;
set(gca, 'yscale', 'log', 'xlim', [0 30], 'ylim', [1e-5 1]);
xlabel('Eb/No (dB)'); ylabel('BER');
set(h,'NumberTitle','off');set(h, 'renderer', 'zbuffer');
title('Performance of System with Frequency Selective Interuser Channel');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  OSFBC  %%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
m_u1_data = zeros(dNc,column_number);
m_u2_data = zeros(dNc,column_number);
%[m_pre_ifft demod_data]
%[m_pre_ifft2 demod_data2]
```

```
%User 1 encoding process
m_re_data = m_pre_ifft; % retransmit symbols
m_dec_data = demod_data2; %decoded symbols

%Generate symbol vectors for phase II
for n=1:column_number;
    for m=1:1:Nc
        m_u1_data(2*m-1,n) =  m_re_data(m,n);
        m_u1_data(2*m,n) =  -conj(m_dec_data(m,n));

        m_u1_X1(2*m-1,n)= m_re_data(m,n);
        m_u1_X1(2*m,n)= m_dec_data(m,n) ;
    end
end

X1=m_u1_X1;

%User 2 encoding process
m_re_data2 = m_pre_ifft2; % retransmit symbols
m_dec_data2 = demod_data; %decoded symbols

%Generate symbol vectors for phase II
for n=1:column_number;
    for m=1:1:Nc
        m_u2_data(2*m-1,n) =  m_re_data2(m,n);
        m_u2_data(2*m,n) =  -conj(m_dec_data2(m,n));

        m_u2_X2(2*m-1,n)= m_re_data2(m,n);
        m_u2_X2(2*m,n)= m_dec_data2(m,n) ;
    end
end

X2=m_u2_X2;

%Generate channel coefficients
    h1s_all=[];
```

```
    h2s_all=[];
    for k=1:1:column_number

   %channel between user 1 and destination
    h1s=1/sqrt(2)*(randn(1,2)+j*randn(1,2));
    h1s_all = [h1s_all;h1s];
    %channel between user 2 and destination
    h2s=1/sqrt(2)*(randn(1,2)+j*randn(1,2));
    h2s_all = [h2s_all;h2s];
    h1s_all=h1s_all';
    h2s_all=h2s_all';

    %Find the frequency response of the channel
    WS = zeros(dNc,L);
    for v = 1:1:L;
    for n = 1:2:dNc-1;
    %WS(n,v)=exp(-2*j*pi*n/Nc*(v-1));
    %WS(n+1,v)=exp(-2*j*pi*n/Nc*(v-1));
    WS(n,v)=exp(-2*j*pi*n/T*tau(L));
    WS(n+1,v)=exp(-2*j*pi*n/T*tau(L));
    end;
    end;
    H1s = WS*h1s_all;
    H2s = WS*h2s_all;
    end

%Determine received signals
 for k=1:1:column_number
   for p=1:1:dNc/2


       Z=0;
       No=Es/10^(SNR/10);
       Z=sqrt(No/2)*(randn(2,1)+j*randn(2,1));
       R1(2*p-1,k)=X1(2*p-1,k)*H1s(2*p-1,k)+X2(2*p-1,k)*H2s(2*p-1,k) + Z(1);
       R1(2*p,k)=conj(X2(2*p,k))*H2s(2*p,k)-conj(X1(2*p,k))*H1s(2*p,k) + Z(2);

       %Add noise
```

```
        %R1(2*p-1,k)=awgn(R1(2*p-1,k),SNR);
        %R1(2*p,k)=awgn(R1(2*p,k),SNR);
   end
 end
%Decoding will be done per two symbols
%du=[];
%du2=[];
for k=1:1:column_number
    for l=1:1:Nc
        du =1/(abs(H1s(2*l-1,k))^2+ abs(H2s(2*l-1,k))^2)\\
        *[conj(H1s(2*l-1,k)) H2s(2*l-1,k);conj(H2s(2*l-1,k))\\
        -H1s(2*l-1,k)]*[R1(2*l-1,k);conj(R1(2*l,k))];
        if real(du(1))> 0
            du1(l)=0;
        else
            du1(l)=1;
        end;
        if real(du(2))> 0
            du2(l)=0;
        else;
            du2(l)=1;
        end;
    end
end
dec_all = [du1 du2];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% QOSFBC %%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
m_u1_pre_ifft = zeros(dNc,column_number);
m_u2_pre_ifft = zeros(dNc,column_number);
%[m_pre_ifft demod_data]
%[m_pre_ifft2 demod_data2]

%User 1 encoding process
m_re_pre_ifft = m_pre_ifft; % retransmit symbols
m_dec_pre_ifft = demod_data2; %decoded symbols
```

```
%rotate symbols at even subcarriers for both decoded and to be
%retransmitted symbols
for n=1:column_number;
    for m=2:2:Nc
        m_re_pre_ifft(m,n)= m_re_pre_ifft(m,n)*exp(j*pi/2);
        m_dec_pre_ifft(m,n)= m_dec_pre_ifft(m,n)*exp(j*pi/2);

    end
end
%Generate symbol vectors for phase II
for n=1:column_number;
    for m=1:2:Nc-1
        m_u1_pre_ifft(2*m-1,n) =  m_re_pre_ifft(m,n)+ m_re_pre_ifft(m+1,n);
        m_u1_pre_ifft(2*m,n) =  -conj(m_dec_pre_ifft(m,n) + m_dec_pre_ifft(m+1,n));
        m_u1_pre_ifft(2*m+1,n) =  m_re_pre_ifft(m,n) - m_re_pre_ifft(m+1,n);
        m_u1_pre_ifft(2*m+2,n) =  -conj(m_dec_pre_ifft(m,n) - m_dec_pre_ifft(m+1,n));

        m_u1_S1(2*m-1,n)= m_re_pre_ifft(m,n)+ m_re_pre_ifft(m+1,n);
        m_u1_S1(2*m,n)= m_dec_pre_ifft(m,n) + m_dec_pre_ifft(m+1,n);
        m_u1_S1(2*m+1,n)= m_re_pre_ifft(m,n)- m_re_pre_ifft(m+1,n);
        m_u1_S1(2*m+2,n)= m_dec_pre_ifft(m,n) - m_dec_pre_ifft(m+1,n);
    end
end
S1=m_u1_S1;
%User 2 encoding process
m_re_pre_ifft2 = m_pre_ifft2;
m_dec_pre_ifft2 = demod_data;

%rotate symbols at even subcarriers for both decoded and to be
%retransmitted symbols
for n=1:column_number;
    for m=2:2:Nc
        m_re_pre_ifft2(m,n)= m_re_pre_ifft2(m,n)*exp(j*pi/2);
        m_dec_pre_ifft2(m,n)= m_dec_pre_ifft2(m,n)*exp(j*pi/2);
    end
end
```

```
%Generate symbol vectors for phase II
for n=1:column_number;
    for m=1:2:Nc-1
        m_u2_pre_ifft(2*m-1,n)=m_re_pre_ifft2(m,n)+m_re_pre_ifft2(m+1,n);
        m_u2_pre_ifft(2*m,n)=conj(m_dec_pre_ifft2(m,n)+m_dec_pre_ifft2(m+1,n));
        m_u2_pre_ifft(2*m+1,n)=m_re_pre_ifft2(m,n)-m_re_pre_ifft2(m+1,n);
        m_u2_pre_ifft(2*m+2,n)=conj(m_dec_pre_ifft2(m,n)-m_dec_pre_ifft2(m+1,n));

        m_u2_S2(2*m-1,n)= m_re_pre_ifft2(m,n)+m_re_pre_ifft2(m+1,n);
        m_u2_S2(2*m,n)= m_dec_pre_ifft2(m,n)+m_dec_pre_ifft2(m+1,n);
        m_u2_S2(2*m+1,n)= m_re_pre_ifft2(m,n)-m_re_pre_ifft2(m+1,n);
        m_u2_S2(2*m+2,n)= m_dec_pre_ifft2(m,n)-m_dec_pre_ifft2(m+1,n);
    end
end

S2=m_u2_S2;

%Generate channel coefficients
    h1p_all=[];
    h2p_all=[];

    for k=1:1:column_number

   %channel between user 1 and destination
    h1p=1/sqrt(2)*(randn(1,2)+j*randn(1,2));
    h1p_all = [h1p_all;h1p];
    %channel between user 2 and destination
    h2p=1/sqrt(2)*(randn(1,2)+j*randn(1,2));
    h2p_all = [h2p_all;h2p];

    h1p_all=h1p_all';
    h2p_all=h2p_all';
%Find the frequency response of the channel
    WW = zeros(dNc,L);
    for v = 1:1:L;
    for n = 1:2:dNc-1;
    %WW(n,v)=exp(-2*j*pi*n/Nc*(v-1));
```

```
    %WW(n+1,v)=exp(-2*j*pi*n/Nc*(v-1));
    WW(n,v)=exp(-2*j*pi*n/T*tau(L));
    WW(n+1,v)=exp(-2*j*pi*n/T*tau(L));
    end;
    end;
    H1p = WW*h1p_all;
    H2p = WW*h2p_all;
    end

%Determine received signals
 for k=1:1:column_number
   for p=1:1:dNc/4
      % HH=[H1p(4*p-3,k) H2p(4*p-3,k) 0 0;
      %     conj(H2p(4*p-2,k)) -conj(H1p(4*p-2,k)) 0 0;
      %     0 0       H1p(4*p-1,k)       H2p(4*p-1,k);
      %     0 0  conj(H2p(4*p,k))  -conj(H1p(4*p,k))]
      % C=[ S1(4*p-3,k);
      %     S1(4*p-2,k);
      %     S1(4*p-1,k);
      %     S1(4*p,k)]
      % R2=HH*C
      % for k=1;
      %  R3(k,1)=R2(k,1);
      %  R3(k+1,1)=conj(R2(k+1,1));
      %  R3(k+2,1)=R2(k+2,1);
      %  R3(k+3,1)=conj(R2(k+3,1));
      %  end;
      %  R1=[R1;R3]
        N=0;
        NNo=2*(Es/10^(SNR/10));
        N=sqrt(NNo/2)*(randn(4,1)+j*randn(4,1));

        R(4*p-3,k)=S1(4*p-3,k)*H1p(4*p-3,k)+S2(4*p-3,k)*H2p(4*p-3,k)+N(1) ;
        R(4*p-2,k)=conj(S2(4*p-2,k))*H2p(4*p-2,k)-conj(S1(4*p-2,k))*H1p(4*p-2,k)+N(2);
        R(4*p-1,k)=S1(4*p-1,k)*H1p(4*p-1,k)+S2(4*p-1,k)*H2p(4*p-1,k)+N(3);
        R(4*p,k)=conj(S2(4*p,k))*H2p(4*p,k)-conj(S1(4*p,k))*H1p(4*p,k)+N(4);
```

```
        %Add noise
        %R(4*p-3,k)=awgn(R(4*p-3,k),SNR);
        %R(4*p-2,k)=awgn(R(4*p-2,k),SNR);
        %R(4*p-1,k)=awgn(R(4*p-1,k),SNR);
        %R(4*p,k)=awgn(R(4*p,k),SNR);

        %R(4*p-3,k)=R(4*p-3,k);
        %R(4*p-2,k)=conj(R(4*p-2,k));
        %R(4*p-1,k)=R(4*p-1,k);
        %R(4*p,k)=conj(R(4*p,k));
   end
 end

 %Generate possible vector spaces
x_q=[1 -1];
y_q=[0 0];
BPSK_s=x_q+y_q*i;

x_r=[0 0];
y_r=[1 -1];
BPSK_r=x_r+y_r*i;

vector_c=combvec(BPSK_s,BPSK_r).';
bpsk_space=vector_c(:,1);
rotated_space=vector_c(:,2);

%Decoding will be performed per 4 symbols in each ofdm symbol
%dec_bits=zeros(dNc,k)
dec_bits=0;
dec_bits_user1=0;
dec_bits_user2=0;

for k=1:1:column_number
    for l=1:4:dNc-3

      %cost function for s1 and s2
      f_12=(abs(bpsk_space+rotated_space).^2)*(abs(H1p(l,k)).^2\\
```

```
   +abs(H2p(l+1,k)).^2)+(abs(bpsk_space-rotated_space).^2)*(abs(H1p(l+2,k)).^2\\
   +abs(H2p(l+3,k)).^2)-2*real((bpsk_space+rotated_space)\\
   *(conj(R(l,k))*H1p(l,k)+R(l+1,k)*conj(H2p(l+1,k)))\\
   +(bpsk_space-rotated_space)\\
   *(conj(R(l+2,k))*H1p(l+2,k)+R(l+3,k)*conj(H2p(l+3,k))));
   %choose the symbol pair that minimizes the cost function
 [Hmin,I]=min(f_12);
  if vector_c(I,1) == 1
  dec_bits(l,k) = 0;
  else
  dec_bits(l,k) = 1;
  end

%[Hmin,I]=min(f_12);
  if vector_c(I,2) == i
  dec_bits(l+1,k) = 0;
  else
  dec_bits(l+1,k) = 1;
  end

 %cost function for s3 and s4
 f_34=(abs(bpsk_space+rotated_space).^2)*(abs(H2p(l+1,k)).^2\\
 +abs(H1p(l,k)).^2)+(abs(bpsk_space-rotated_space).^2)*(abs(H2p(l+3,k)).^2\\
 +abs(H1p(l+2,k)).^2)-2*real((bpsk_space+rotated_space)\\
 *(conj(R(l,k))*H2p(l+1,k)-R(l+1,k)*conj(H1p(l,k)))\\
 +(bpsk_space-rotated_space)\\
 *(conj(R(l+2,k))*H2p(l+3,k)-R(l+3,k)*conj(H1p(l+2,k))));

 %choose the symbol pair that minimizes the cost function
 [Hmin,I]=min(f_34);
 if vector_c(I,1) == 1
 dec_bits(l+2,k) = 0;
 else
 dec_bits(l+2,k) = 1;
 end

%[Hmin,I]=min(f_34);
```

```
    if vector_c(I,2) == i
    dec_bits(l+3,k) = 0;
    else
    dec_bits(l+3,k) = 1;
    end
  end
%Make the format of input bit stream and the decoded bit stream the same
%for k=1:column_number
for m=1:2:dNc/2-1
decoded_bits_user1(m,k) = dec_bits(2*m-1,k);
decoded_bits_user1(m+1,k) = dec_bits(2*m,k);
end

%for k=1:column_number
for m=2:2:dNc/2
decoded_bits_user2(m-1,k) = dec_bits(2*m-1,k);
decoded_bits_user2(m,k) = dec_bits(2*m,k);
end

dec_bits=[decoded_bits_user1;decoded_bits_user2];
end

dec_bits=reshape(dec_bits,1,[]);

error1(packetid)=biterr(v_data3,dec_all);
error2(packetid)=biterr(v_data3,dec_bits);
    end
   BER1= sum(error1)/(iter*dNc)
   BER2= sum(error2)/(iter*dNc)

semilogy(SNR,BER1,'bo')
semilogy(SNR,BER2,'r*')
legend('OSFBC','QOSFBC' );
drawnow;

BER11=[BER11 BER1];
BER22=[BER22 BER2];
```

```
end
fitBER1 = berfit(SNR,BER11);
fitBER2 = berfit(SNR,BER22);
semilogy(SNR, fitBER1, ’b’, SNR, fitBER2, ’r’);
hold off;
```

VITA

Can Yiğit was born on 26 July 1980, in Istanbul. He received his BS degree in 2003 in Electronics Engineering from Işi k University where he is now pursuing his MS degree in Electronics Engineering. He worked as project engineer in Turcom Technologies from September 2003 to May 2004. In June 2004 he started to work as a system administrator in Netaş-Servisnet where he is responsible for providing maintenance to the management network of digital switches consisting of unix, linux, windows servers, online databases and various data equipments such as routers and firewalls. His research interests include space time and space frequency processing, broadband wireless communication and cooperative diversity.