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WIRELESS COOPERATIVE COMMUNICATIONS WITH OFDM

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APPROVAL PAGE

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ABSTRACT

Relay-based wireless cooperative communication is a promising technique to meet the high demand and quality of service required for recent wireless technologies. Orthogonal frequency division multiplexing (OFDM) has been accepted in the wide area of communication including wireless communication due to its high spectral efficiency and the capability to convert frequency selective channel to flat fading. The optimum use of orthogonal frequency division multiplexing in cooperative relaying depends on resource allocation in general. This resource allocation includes relay selection, sub-carrier matching and assignment, power allocation as well. In this research, we examined different resource allocation for well-known relaying protocols namely amplify-forward and decode-forward with orthogonal frequency division multiplexing and proposed some techniques with computational efficiency. In general, we aim to provide efficient resource allocation to increase the system throughput. The main objective of this research is to increase efficiency of one-way and two-way relaying based on orthogonal frequency division multiplexing. In particular we have provided some adaptive relaying strategies which are simulated for different relaying.

Keywords: Amplify and Forward, Cooperative Relaying, Decode and Forward, OFDM, One-way Relaying, Two-way Relaying.

OFDM TABANLI İŞBİRLİKÇİ TELSİZ KOMÜNİKASYON

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ÖZ

Röle tabanlı işbirlikçi telsiz haberleşme telsiz teknolojilerinin gereksimi olan yüksek talebi ve servis kalitesini sağlayabilecek bir tekniktir. OFDM specturum kullanımında ve frekansa göre değişkenlik gösteren kanallarda göstermiş olduğu verimlilikten dolayı telsiz haberleşmeyide kapsayan çok geniş bir haberleşme alanında kabul görmüştür. OFDM teknolojisinin işbirlikçi sistemlerde etkin kullanımı genel anlamda sistemlerin sahip olduğu kaynakları verimli kullanmasına bağlıdır. Bu kaynaklar genelde rölelerin seçimi, alttaşıyıcıların eşleştirilmesi, güçün dağıtımı kapsamaktadır. Bu araştırmada biz bu kaynakların etkin kullanımı işbirliçi OFDM sisteminde iyi bilinen yükselt-ilet ve kodla-ilet röleme yöntemlerini dikkate alarak inceledik ve hesaplama verimliliği iyileştirilmiş yeni teknik önerileri sunduk. Geneldeki amacımız haberleşme sisteminin başarısını artıracak verimli kaynak kullanımını sağlamaktır. Esas hedefimiz ise tek yönlü ve çift yönlü OFDM röle sistemlerinin etkin kaynak kullanımı ile verimliliğini artırmaktır. Özelde ise yeni uyumlu röle sistemleri önerilerek simülasyonları yapıldı.

Anahtar Kelimeler: Yükselt ve ilet, İşbirlikçi röle, Kodla ve ilet, OFDM, Tek-yön röle, İki-yön röle

To my family

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SYMBOL/ABBREVIATION	
AF	Amplify and forward
BER	Bit error rate
BPSK	Binary phase shift keying
CC	Cooperative communication
CS	Cooperative system
CO-OFDM	Cooperative orthogonal frequency division multiplexing
DF	Decode and forward
FDM	Frequency division multiplexing
FFT	Fast fourier transform
IFFT	Inverse Fast fourier transform
LAR	Link adaptive relaying
MIMO	Multi input multi output
MISO	Multi input single output
MMSE	Minimum mean square error
MRC	Maximum ratio combiner
OW-CC	One-way cooperative communication
OFDM	Orthogonal frequency division multiplexing
PA	Power allocation
SIMO	Single input multi output
SNR	Signal to noise ratio
TW-CC	Two-way cooperative communication

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

As being fastest growing part of communication industry, wireless communication has become very popular in the view of public. It includes satellite communication, wide area local network (WLAN) such as WiMAX, local area network (LAN), cellular network, ultra wide band network (UWB), Bluetooth, ZigBee. To mention the size of the industry, it is enough to remember that almost three billion people uses cellular phone today. The rapidly advanced technology enables the transmissions over larger distances with better quality, less power, and smaller and cheap devices thereby public and private use radio communications, television, and wireless networking extensively. The recent technology became based on digital transmission as opposed to initially analog system.

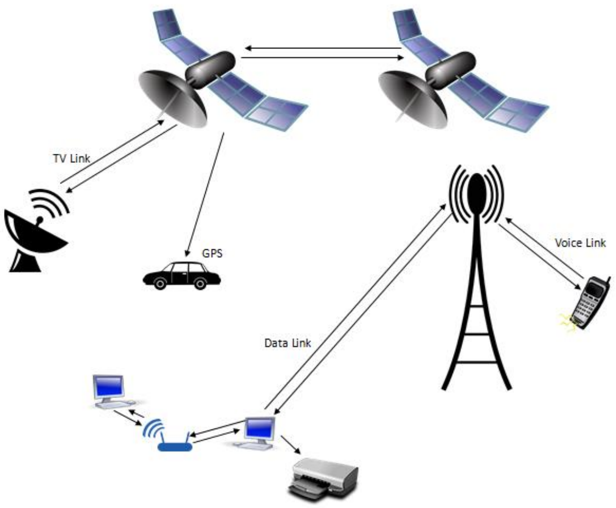

Figure 1.1 Wireless communications.

At the early beginning (around 1970), being as an expensive and slow communication (around 10 Kbps) tool compared to wire communication, the wireless was not preferred. With the introduction of IEEE 802.11 standard it became more popular since it provided cable free installation with relatively high speed date rates (around a few 100 Mbps) which was enough for much application other than video sharing.

The cellular network is the most successful application of wireless communication. It becomes more popular day by day as it introduces faster data communication. With the appearance of 3G communication the data rates reached to around 100Mbps. It seems that there is no alternative to cellular system in terms of providing data communication on mobile. The fact that the power of transmitted signals attenuated with distance became a key concept to increase the capacity of cellular network for it allows two users to operate on the same frequency at spatially-separate locations with minimal interference between them. This allows very efficient use of cellular spectrum; hence a large number of users can be accommodated.

The last decay wireless vision has already become reality. Today's wireless vision is much larger than the past thanks to developments in the related areas. It includes many fantastic application such as sharing multimedia anywhere anytime with small devices, establishing connection among all electronics devices to create intelligent systems, improving disabled people lives, instant emergency response, patient monitoring, teleconference, remote teaching, monitoring forest, stress and strains in buildings, spread of disaster and as military applications, tracking of enemies and counter-terrorism. These varieties of applications make it difficult to have a standard since expectation various too. A good voice wireless communication must have at most 30msec delay with 20Kbps speed while being relatively more flexibility to bit error rate (BER) as around 10^-3. A good data channel requires 10^-6 BER with 100Mbps bit rate but more flexibility delay. This actually makes it difficult to build a system which meets all requirements.

Wireless communication has great technical issues to overcome. It is easy do any kind of process on a signal on computers. But there is need to have light, cheap, less power consuming chips to have such processing on small electronic devices which requires development in circuit design. Another big challenge is the use of limited spectrum efficiently which results in more signal processing. The wireless communications channel itself is too challenging due to its random behavior. It is frequency selective and open to interference always. These mentioned problems as well as non-mentioned ones require wireless nodes to cooperate. The cooperation of wireless nodes introduces many research fields to researchers.

1.2 LITERATURE SURVEY ON CO-OFDM

Cooperative OFDM communication is called CO-OFDM when the sub-carriers of OFDM system are used only for a wireless node and not shared with other nodes. In the case the sub-carriers can be assigned to different nodes in a network it is named CO-OFDMA (Orthogonal Frequency-Division Multiple Access). The studies generally examine ; resource allocation such as relay selection, bit loading, power allocation, sub-carrier matching, channel and timing offset and application of various protocols into CO-OFDM. The early studies appear on this CO-OFDM dates back to 2007.Among these studies we will touch the most favorite ones. In particular we mention following articles.

In (An and Song 2007), the authors consider cooperative relaying with OFDM where half of sub-carriers are allocated for the relay link and the other half is allocated for the direct link. Therefore it is called orthogonal frequency division multiple access (OFDMA). In this study the destination node is modeled as multiple antennas receiver hence maximum ratio combiner is used to combine received copies on different antennas. The paper considered both amplify-forward and decode-forward protocols and suggest that decode-and forward based cooperation performs better when the source-destination link has higher quality than relay link.

In (Shin, et al. 2007), the combination of OFDM with cooperative relaying is examined. In the paper, the authors try to develop practical timing and frequency synchronization algorithms and a channel estimation algorithm for their proposed system since it was claimed that synchronization technique which is for only OFDM but not CO-OFDM will not be very efficient for cooperative relaying. The authors stated that their proposal of frequency synchronization algorithm makes use of the underlying two phase cooperation protocol, and the proposed channel estimation algorithm is based on a pairwise orthogonal construction of two sequences. The study considers only one-way relaying and each wireless node is equipped with one antenna.

The study of (Li, Ng and Han 2008) basically examines carrier frequency and timing offset in cooperative systems. It states that the synchronization becomes more critical in cooperative system since there are many transmitters in the system. It offers that OFDM can be employed to help the synchronization by simple increasing cyclic prefix, yet it indicates that OFDM itself suffers from carrier frequency synchronization where the CFO incurs inter-carrier interference. The solution to this problem relates to some feedback operation to transmitters which is considered non-applicable for cooperative system where relays may change the position opposite direction. The author comes up with an idea of utilizing the redundancy of the long CP for CFO mitigation or cancellation.

In (Kim, Wang and Madihian 2008), the authors investigates optimal power and rate control in OFDMA cooperative system where there is a centralized network controller in which first the frequency-selective channel gains are obtained and the optimization algorithm is run to get the optimal solutions.

In (Pischella and Belfiore 2008), the authors studied about controlling power in distributed cooperative OFDMA cellular network in downlink by prepossessing Radio Resource Management strategy for downlink cooperation which consists of relayed users identification, resource allocation, and power control.

In (Ho, Zhang and Liang 2008), the author considers amplify-forward two way relaying over OFDM. The main objective of the paper to allocate the power for relay, source and destination nodes to maximize the system's sum capacity by using dual decomposition by assuming that full channel knowledge is available and at relay the greedy approach is used for tone permutation.

In (Siriwongpairat, Sadek and Liu 2008), it is stated that an OFDM cooperative protocol improves spectral efficiency over those based on fixed relaying protocols while achieving the same performance of full diversity. This is done by exploiting limited feedback from the destination node. The proposed protocol allows each relay to help forward information of multiple sources in one OFDM symbol. The study also provides a practical relay-assignment scheme for implementing the proposed cooperative protocol in OFDM based networks.

In (Jitvanichphaibool, Zhang and Liang 2009), the two-way relaying technology, based on the principle of network coding, is applied to MUs (Mobile Users) in relay for decode-forward (DF) and amplify-forward (AF) protocols. Furthermore convex optimizations techniques are used to develop efficient algorithms for optimal allocation of transmit resources such as power levels, bit rates, and OFDM sub-carriers at the BS, RSs, and MUs.

In (Zhang, Zhang and Tellambura 2009), a two-time-slot cooperative channel estimation protocol is proposed and optimal channel estimation is developed for a cooperative AF or DF OFDM system with frequency offsets. The author used a training sequence which was sent to the relays and the destination (first time slot), and the relays retransmit the training sequence (second time slot). Based on this, pilot designs for AF and DF relays are derived.

In (Dogukan 2009), the author proposed channel estimation for OFDM cooperative systems with amplify-forward protocol.

In (Gao, Zhang and Liang 2009), the authors focus on the half-duplex AF/ANC (amplify-forward with analog network coding) -based TWRN (two-way relay network) adopting OFDM modulation. It is stated that the channels from the two sources to the relay can be directly obtained at each source terminal, which eliminates the need of the feedback from relay to sources. In the paper they introduced cascade channel estimation which estimates source to source channel from which they extract the sources to the relay channels which is named de-noising.

In (Ding and Uysal 2009), amplify-forward cooperative OFDM with multiple-relays is considered and performance analysis and relay selection methods are studied. The PEP (pairwise error probability) for the cooperative OFDM system is derived and two relay selection methods proposed which are named per-sub-carrier basis and an all-sub-carrier basis selection.

In (Huang, et al. 2010), the timing and carrier frequency offset (CFO) synchronization in decode-forward cooperative systems in frequency selective channels is examined. A block of orthogonal frequency-division multiplexing (OFDM) having a tile structure in the frequency domain is proposed to perform synchronization.

In (Duval, et al. 2010), sub-carrier selection and power allocation for amplify-forward relaying over OFDM is studied and the system's end to end capacity is examined. The objective of the paper was to allocate the power used at base and relay station to maximize the system overall capacity which is done with complex optimization formulations and an iterative algorithm.

In (Dang, et al. 2010), joint relay selection, sub-carrier assignment and power control problem for a two-hop multi-relay OFDM system using amplify-and-forward (AF) protocol is studied with the objective of maximizing the transmission rate subject to an individual power constraint of each transmit node or a total network power constraint.

In (Song, Kim and Im 2010), the channel estimation for OFDM cooperative system with amplify-forward protocol is studied and linear interpolation is used for estimation. The poor performance of linear interpolation in cascade channel estimation is improved at the expense of feedback information.

In (Wang, Li and Wang 2012),a new zero-padding (ZP) and cyclic-prefix (CP) transmission protocols suggested for joint estimation of the carrier frequency offset (CFO) and the channel for a two-way relay network (TWRN) with *amplify- forward* (AF) CO-OFDM.

In (Amin and Uysal, Optimal bit and power loading for amplify-and-forward cooperative OFDM systems 2011), three adaptive algorithms are proposed which are optimal power loading (OPL), optimal bit loading (OBL), and optimal joint bit and power loading (OBPL) for amplify-and-forward relaying while the bit error rate (BER) is considered performance measure with the aim of optimizing the BER under total power constraint and for a given average data rate.

In (Yang, et al. 2011), optimal power control in OFDM two-way relaying is studied with the aim of enhancing the achievable sum rate of the terminals under a constrained total transmits power by using convex optimization. It is shown that the proposed method outperforms fixed power scheme.

In (He, et al. 2012), joint channel estimation and data detection in orthogonal frequency division multiplexing (OFDM) amplify-and-forward (AF) cooperative systems under high mobility is investigated where partial data-dependent superimposed training (PDDST) is considered to preserving the spectral efficiency.

In (Liu and Chen 2012), joint optimization is studied in a wireless network where multi-users communicate over multi-relays based on OFDM. The joint optimization includes channel and relay assignment, sub-carrier pairing, sub-carrier allocation as well as relay selection.

In (Wang, Li and Wang 2012), adaptive sub-carrier assignment and fair power control at relay in cooperative OFDM wireless network is studied.

In (Amin and Uysal, Adaptive power loading for multi-relay OFDM regenerative networks with relay selection 2012), the authors studied relay selection with different strategies and an adaptive power loading algorithm for sub-carriers both at relay and sources to minimize the BER.

In (Lu, et al. 2012), the author’s considered cooperative OFDM for opportunistic spectrum sharing in one-way communication where relay is allocated sub-carriers depending on rate of transmission over direct link. In the case the rate is below certain levels, the relay can access more sub-carriers.

In (Liu and Chen 2012), one-way cooperative OFDM system with decode-forward relaying is considered. Depending on whether the relay is helpful, sub-carrier-pairs (a pairs mean a sub-carrier at the source-relay link matches with a sub-carrier at the relay-destination link) can work or stay in idle mode. The relay is considered helpful when the minimum signal to noise ratio the relay link is greater than SNR in the direct link. By using the feedback from both the relay and the destination the source optimally allocate the power.

The relay selection for both sub-carrier and OFDM block based system is examined in (Leithon, Sun and Yuen 2012) with analog network coding. The sub-carrier based system selects multi-relay while OFDM block based system select only one relay. The study also derives asymptotic symbol error rate and shows full diversity order can be achieved for both the systems.

A decode-forward two-way CO-OFDM is considered in (Vu and Kong 2012). The authors' aim is to allocate power for sub-carriers by using water filling algorithm and compare it to the sub-carrier matching system.

The study of (Yao and Dong 2012) considers carrier frequency offset synchronization at source, relay, and destination terminal in cooperative OFDM system.

In (Sun, Cen and Yang 2013), half-duplex amplify-forward CO-OFDM is studied with the objective of energy maximization. The authors considered both transmit and circuit energy consumption.

In (He, et al. 2013), the author claimed that decode-forward CO-OFDM becomes suboptimal when each sub-carrier is treated as a separate channel and instead a cross-sub-carrier channel coding is adopted to achieve larger rate region.

Apart from cited studies above we like to mention the following recent studies which examine different aspect of cooperative OFDM relaying in wireless communication.

In (Zhang, Shen and Xie 2014), LTE-advanced cooperative cellular network is considered to help the cell-edge throughput and extend the coverage area .The paper proposes joint OFDM sub-carrier allocation and power allocation scheme to optimize downlink multi-user capacity.

In (Wang, et al. 2014) the authors' proposes a class of low-complexity multi-antenna relaying scheme with OFDM for both one-way and two-way cooperative communication. In this study relay is used to receive combining, power scaling, and transmit diversity.

Definitely, the given studies above show the varieties of studies in the field. The studies may be grouped as;

The studies related to resources allocation such as power, relay selection.

The studies related to channel estimation, synchronization.

The studies related to different protocols design such as amplify-forward, decode-forward.

CHAPTER 2

COOPERATIVE COMMUNICATIONS AND OFDM

2.1 COOPERATIVE COMMUNICATIONS

In this section we will look at the cooperative communications from its development perspective. Later, the system will be introduced to give overall picture of the topic which will be followed with types of cooperative communications and protocols used in the relaying.

2.1.1 Development of Cooperative Communications

The relaying strategy to improve the quality of service in communication is an idea studied in 1970's. The studies of Van der Meulen (Meulen, 1971) and Cover El Gamal (Cover & Gamal, 1979) are considered earliest papers in the literature. This relaying was different than contemporary one in many respects. The early relaying strategies aim to provide better communication by employing a relay link as shown in Fig.2.1. This changed in modern relaying such that each link can be both relay and main link as shown in Fig.2.2. This means that there is no link for only relaying purpose. A link acts as a relay link if there is a need. The other difference is diversity. The recent studies consider diversity to combat fading while the analysis of Cover El Gamal was done for additive white Gaussian noise (AWGN) channel since diversity was not known concept then.

The other very important concept which is assumed a big achievement in cooperative relaying is two-way communication which became possible with network coding. The breaking point to make the cooperative communication an attractive topic was the study of Sendonaris (Sendonaris, Erkip, & Aazhang, 2003) which was about application of cooperative communication to the cellular network. The work states that whenever the inter-user channel is in good condition between paired users, more power will be allocated to cooperation and when the condition of the channel is bad, the cooperation will be reduced. The study of Laneman (Laneman, Tse, & Wornell, 2004) is also considered very important and it is related to ad-hoc networks.

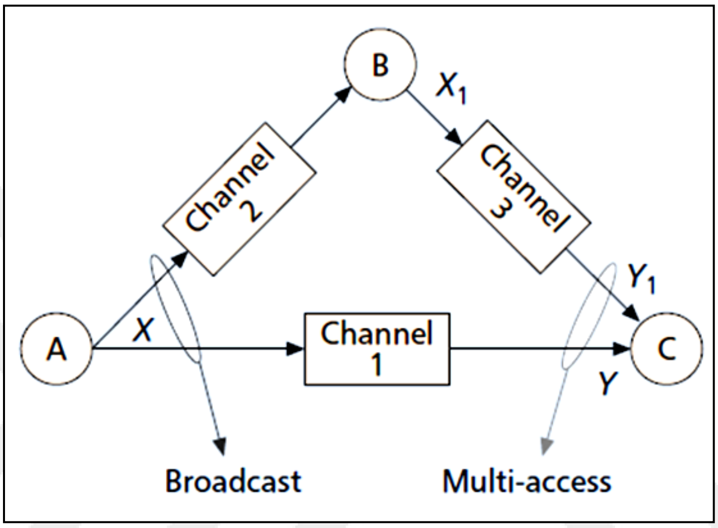

Figure 2.1 Relay channel.

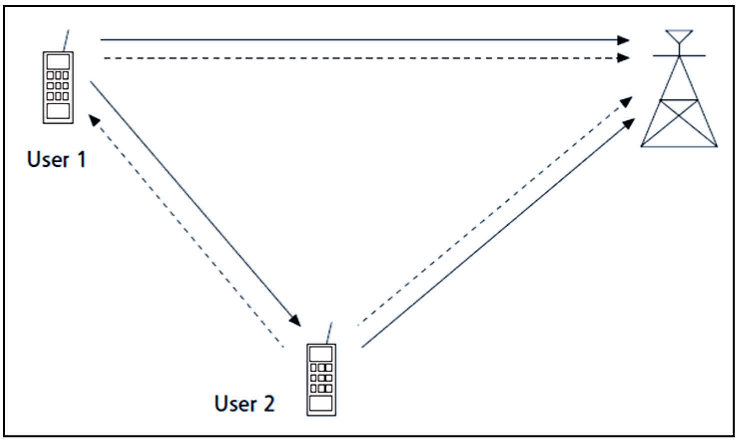

Figure 2.2 Modern Relaying.

2.1.2 Introduction

In simple definition of cooperative communications based system is organizing all or some part of communication points in a network to help one to another to provide communication or improve quality of available communication. This can be pictured as in Fig 2.3.

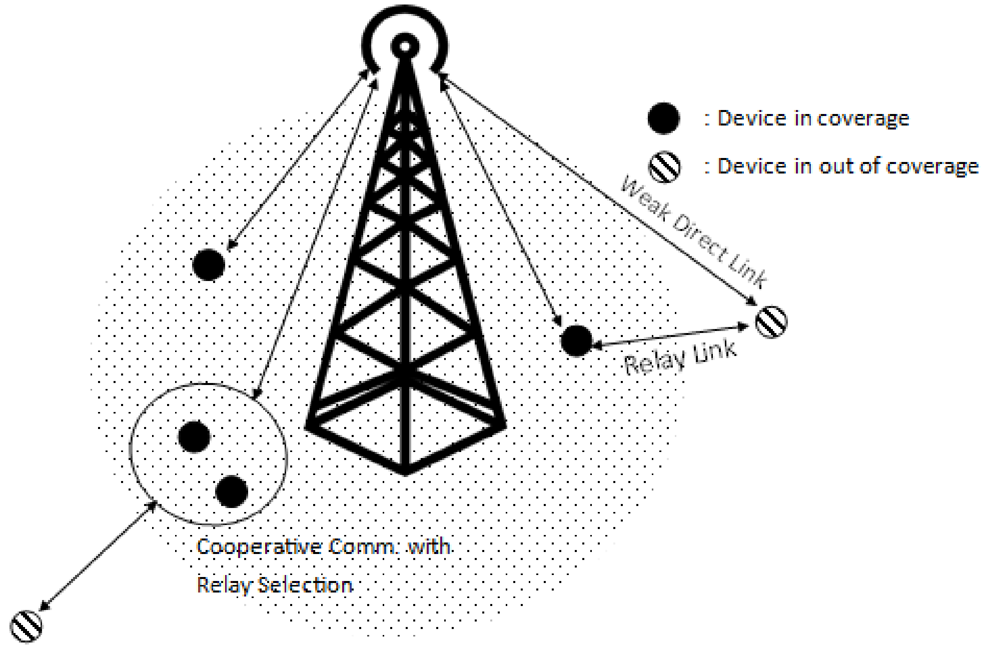

Figure 2.3 Cooperative communications in cellular networks.

Cooperative system (CS), in the case of absence of direct link (DL), provides only available channel. In Figure 2.3, source A is out of coverage area, so it has to cooperate with some mobile users to be able to receive service. It is also seen that among R relays, one relay is chosen to help the source A by the network. When the direct link available it is employed as a second link known relay link (RL) to contribute the quality of service. For example for source B, the relay link is provided along with the direct link. It is also possible to use relay link in the coverage area to support higher throughput.

In the RL, communication is provided through an active point which is named relay(R). If the relay link is used without condition it is known fixed relaying (FR) while it is named adaptive relaying (AR) in the case that RL is being used if the quality of direct link goes below a certain threshold.

In CS there are different protocols. These protocols are due to type of relay employment. If the relay is used to amplify received signal to send to destination it is named amplify and forward (AF) protocol or non-regenerative as seen in Figure 2.4. But in the case we use the relay to decode signal and re-encode to send destination is named decode and forward (DF) or generative protocol which is shown in Figure 2.5.

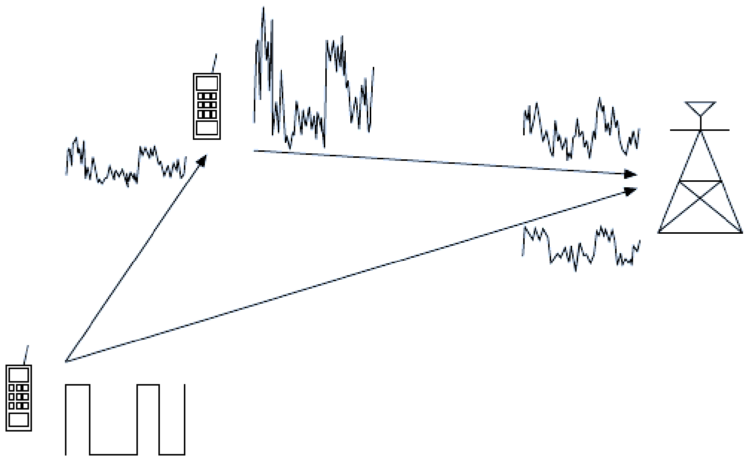

Figure 2.4 AF relaying.

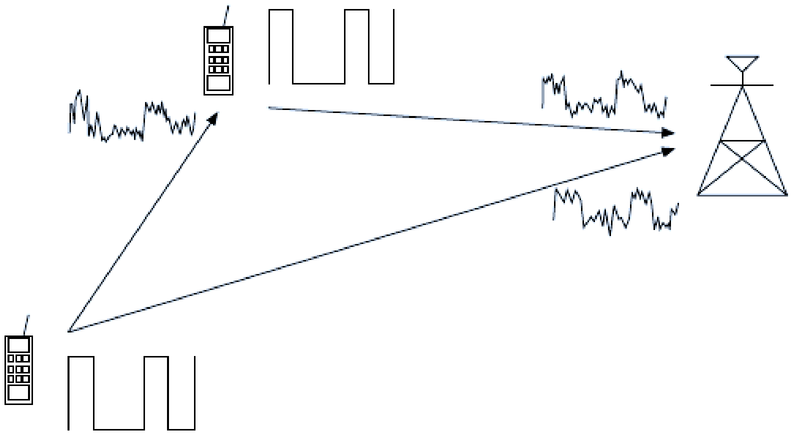

Figure 2.5 DF relaying.

Depending on where or in what condition it will be used, one can be more advantageous than the other one. For example if relay node is a mobile station (MS), AF can be better choice since it requires less computation which may be better handled in small devices such as MS. If there is no much worries of power consuming or the relay node is not depending on battery power DF can be used. Below we explain AF and DF in details for relaying since the scope of this thesis is limited with it.

2.1.3 Protocols in Cooperative Communication

There are two basic protocols in cooperative system and the others can be considered derivation of these two which are explained in the following.

2.1.3.1 Amplify and Forward Protocol

Focusing on two communicating point named source and destination on a given network as seen Figure 2.6, we will provide the way AF system operates.

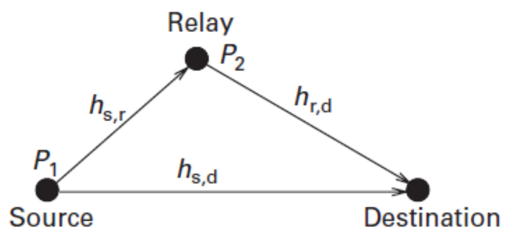

Figure 2.6 Three node cooperation.

In AF system, the relay receives the signal from source and scales it before retransmit to destination. The AF system can be modeled as follows. Assuming source transmits the data x, the received data at relay (R) and destination (D) can be given as in Eq. (2.1) and Eq. (2.2):

$$y_{sr} = \sqrt{P} h_{sr} x + n_{sr} \tag{2.1}$$

$$y_{sd} = \sqrt{P} h_{sd} x + n_{sd} \tag{2.2}$$

where subindices *sd* and *rd* represent the source-relay and relay destination link respectively. In Eq. (2.1) and Eq.(2.2)

y_{sr} : The received signal at *R*

y_{sd} : The received signal at *D*

n_{sr} : Noise for *S*-*R* channel

n_{sd} : Noise for *S*-*D* channel

h_{sr} : The channel fading coefficients for S-*R* channel

h_{sd} : The channel fading coefficients for S-*D* channel

P: Power used for transmission both at *R* and *D*

In this derivation it can be assumed that all the channels are Rayleigh flat fading channels and the terms n_{sr} and n_{sd} are given as the additive white Gaussian noise with zero-mean and variance N_0.

The relay amplify the signal with gain β_r inversely proportional the received power which is given as in Eq. (2.3).

$$\beta_r = \frac{\sqrt{P}}{\sqrt{P\left|h_{sr}\right|^2 + N_0}} \tag{2.3}$$

The amplified and sent signal by R is received at the destination node which can be given as in Eq. (2.4).

$$y_{rd} = \beta_r \sqrt{P} h_{rd} y_{sr} + n_{rd}$$

$$y_{rd} = \frac{\sqrt{P}}{\sqrt{P\left|h_{sr}\right|^2 + N_0}} \sqrt{P} h_{rd} \left(h_{sr} x + n_{sr}\right) + n_{rd}$$

$$y_{rd} = \frac{\sqrt{P}}{\sqrt{P\left|h_{sr}\right|^2 + N_0}} \sqrt{P} h_{rd} h_{sr} x + \tilde{n}_{rd} \tag{2.4}$$

In Eq. (2.4) $\tilde{n}_{rd}$ is an additive white Gaussian noise with zero-mean and variance:

$$\tilde{N}_0 = \left(\frac{P|h_{rd}|^2}{P|h_{sr}|^2 + N_0} + 1 \right) N_0 \tag{2.5}$$

Having data flows from two links named S-R-D and S-D link, the destination do combining to obtain final output. The D generally uses Maximum Ratio Combiner (MRC) which is optimal technique to maximize signal-to-noise ratio. Signal-to-noise ratio of the MRC is equal to sum of those received from S-R-D and S-D links. Assuming MRC has the knowledge of channel coefficients, the output can be given as in Eq. (2.6)

$$y_{MRC} = k_1 y_{sd} + k_2 y_{rd} \tag{2.6}$$

In (2.6) k_1 and k_2 are chosen to maximize the SNR at the output and they can be calculated as in Eq. (2.7)

$$k_1 = \frac{\sqrt{P} h^*_{sd}}{N_0} \tag{2.7}$$

$$k_2 = \frac{\sqrt{\frac{P}{P|h_{sr}|^2 + N_0}} \sqrt{P} h^*_{sr} h^*_{rd}}{\left(\frac{P|h_{rd}|^2}{P|h_{sr}|^2 + N_0} + 1 \right) N_0} \tag{2.8}$$

The instantenous SNR can be calculated as

$$\gamma = \gamma_1 + \gamma_2 \tag{2.9}$$

$$\gamma_1 = \frac{\left| k_1 \sqrt{P} h_{sd} \right|^2}{|k_1|^2 N_0} = \frac{P|h_{sd}|^2}{N_0} \tag{2.10}$$

$$\gamma_2 = \frac{\left| k_2 \frac{\sqrt{P}}{\sqrt{P|h_{sr}|^2 + N_0}} \sqrt{P} h_{rd} h_{sr} \right|^2}{\tilde{N}_0 |k_2|^2}$$

$$= \frac{\frac{P^2}{P|h_{sr}|^2 + N_0} |h_{sr}|^2 |h_{rd}|^2}{\left(\frac{P|h_{rd}|^2}{P|h_{sr}|^2 + N_0} + 1\right) N_0} = \frac{1}{N_0} \frac{P^2 |h_{sr}|^2 |h_{rd}|^2}{P\left(|h_{sr}|^2 + |h_{rd}|^2\right) + N_0} \tag{2.11}$$

which can be used to calculate the bit error rate in advance.

2.1.3.2 Decode and Forward Protocol

In decode-and-forward relaying which is given in Figure 2.5, the received signal is decoded at the relay and re-encoded before it is transmitted to destination. The received signal x is shown $\tilde{x}$ after re-encoding at relay due to possible decoding errors. Forwarding incorrectly decoded signal to destination reduces system performance. In chapter 3, link adaptive system is introduced to overcome this problem. By introducing link adaptive relaying (LAR), it will be shown that the system will also have full diversity.

2.1.3.3 Types of Cooperative Communication

Basically cooperative communication can be examined in two types: one-way and two-way cooperative communication.

2.1.3.4 One-way Cooperative Communication

One-way cooperative system offers a half-duplex communication. There are four phases to exchange information between two wireless nodes. In the first two phases one node sends information. In the second phase the other node transmits. There may be direct link too. In the case of available direct link, the transmitting node remains silence in the second phase to let the relay link to complete transmission. The same frequency is used for transmission and receiving, hence a spectral loss occurs.

2.1.3.5 Two-way Cooperative Communication

Two-way cooperative communication (TW-CC) differs in terms of coding they use for transmission in modern relaying. If the network coding is used the transmission requires three phase to be completed. The more complex system can employ PNC to reduce total phases to two phases. Generally direct link is not considered in in TW-CC. It is because the large distance between two nodes causes high path loses, hence the received power on direct link is too weak. There are special cases TW-CC is used to save the power. Assuming the direct link is good enough we can calculate the power required for transmission from one node to other and compare it the power which is required to transmit to relay and from relay to destination node. The SNR is inversely proportional to pathloss, hence it may be given as $SNR\alpha 1/d^n$. The n power is subject to change from 2 to 6. The 2 is used in the case the direct link is available between two nodes. In the multipath environment 4 can be used. We calculate TW-CC power consumption ratio to non-cooperative transmission as

$$10\log\left(\frac{(P/2)/(d/2)^6+(P/2)/(d/2)^6}{1/d^6}\right)=64dB,$$

where we consider the system operates in much cluttered environment, hence $n=6$ is used and P is the transmitter power taken one and half and one in nominator and denominator respectively since the relay is considered at midpoint. The results shows $64\ dB$ power saving. As this power saving tends to decline in the availability of direct link, considering most of the wireless transmission cannot enjoy direct transmission, the contribution of TW-CC is highly appreciated.

2.1.4 Network Coding and PNC

The network coding (NC) and physical network coding (PNC) are two important developments in cooperative relaying. We will first introduce traditional or non-coded cooperative relaying since we believe it makes readers to appreciate novelty of network coding better. Later we will introduce network coded transmission and lastly the physical network will be explained.

2.1.4.1 Non-coded transmission

In traditional cooperative relaying, exchange of information between two nodes occurs in four time slots. We may explain this with help of Fig. 2.7

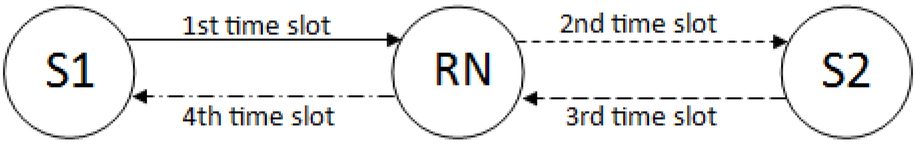

Figure 2.7 Four time slot communication.

S1 and S2 are two wireless nodes located far apart from each other. No direct communication can be provided between them due to weak signal power caused by path loss. The exchange of information without interference first S1 transmits to relay node (RN). The RN retransmit it to S2 and the same process is repeated in reverse direction to help to S2 transmit to S1 through RN. As indicated on the figure it takes four time slot to exchange information.

2.1.4.2 Network coded transmission

The exchange of information is reduced to three time slots by using network coding. It can be figured as follows.

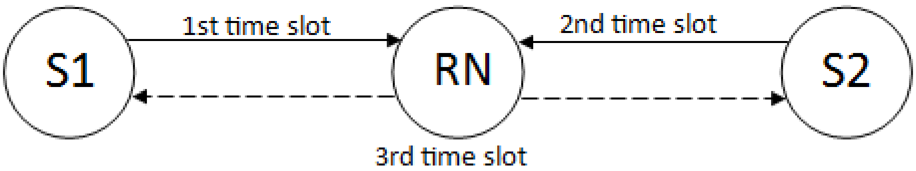

Figure 2.8 Three time slot communication.

In the first time and second time slot S1 and S2 transmits to relay node consequently. The RN does XOR operation on received information which creates $S1 \oplus S2$.This is transmitted to S1 and S2 in the third time slot. Both S1 and S2 do XOR operation on received information, $S1 \oplus S2$ which is given as $(S1 \oplus S2) \oplus S1$, $(S1 \oplus S2) \oplus S2$ for S1 and S2 nodes respectively. The result is exchange of information between S1 and S2. For an example, let S1, S2 have 111, 101 respectively. After 1st and 2nd time slot RN will have 111 and 101. XOR of these two produces $(111 \oplus 101) = 010$ which is transmitted to S1, S2 in the 3rd time slot. After reception, both S1 and S2 XOR 010 with their own bits which produces S1's bits at S2 node and S2's bits S1 node.

2.1.4.3 Physical-Layer Network coding

Physical-layer network coding (PNC) takes development provided by network coding one step forward. In PNC, the total time slot required for exchange of information is just two time slot. In PNC, wireless interference becomes blessing rather than a trouble. In the next lines we explain how it happens.

We consider Figiru 2.9 where two wireless nodes S1 and S2 want to exchange information. We assume QPSK modulation is used for transmssion. Given that a_1 and b_1 are two bits to be transmitted from S1 and a_2 and b_2 are two bits are to be from S2, the received signal at the relay node can be wtitten as follows

$$\underbrace{\underbrace{a_1 \cos(wt)}_{In-phase\,Comp.} + \underbrace{b_1 \sin(wt)}_{Quadrature\,Comp.}}_{from\,S1} + \underbrace{\underbrace{a_2 \cos(wt)}_{In-phase\,Comp} + \underbrace{b_2 \sin(wt)}_{Quadrature\,Comp.}}_{from\,S2}$$

It can wtitten in passband as

$$(a_1 + a_2)\cos wt + (b_1 + b_2)\sin wt$$

It can be written in baseband as

$$I = (a_1 + a_2),\; Q = (b_1 + b_2)$$

for in-phase and quadrature component. Definetly the relay node can not decode the information from received message. Actually it does not need to decode. What it needs to do is to transmit a signal to the S1 and S2 nodes from which they can extract the sent message. Let us examine it on an example. As given in table.1, we assume S1, S2 will transmit 0,1 respectivily(second row) on in-phase component.The bits first mapped as -

1, 1 respectivily. The sum is 0. The *zero* sum is mapped to 1 and the *two* sum is mapped to 0. The bits are mapped to 1 and -1 as usally. Later, the mapped information is transmitted to S1 and S2 into second time slot. What S1 and S2 do is to XOR what they receive from relay. Thus, transmission occurs total in two time slot. The relay does not decode which can be even considered as to respect to privacy of communication between S1 and S2.

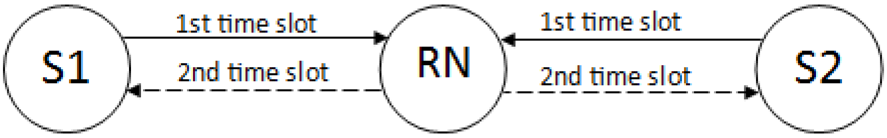

Figure 2.9 Two time slot communication.

Table 2.1 PNC communication.

S1 Bits	S2 Bits	Mapping at S1	Mapping at S2	Received at RN	PNC at RN	Mapping at RN	Received at S1&S2
1	1	1	1	2	0	-1	-1
0	1	-1	1	0	1	1	1
1	0	1	-1	0	1	1	1
0	0	-1	-1	-2	0	-1	-1

De-mapping at S1&S2	(S1 bits) XOR (Received Bits) to get S2 at S1
0	$1 \oplus 0 = 1$
1	$0 \oplus 1 = 1$
1	$1 \oplus 1 = 0$
0	$0 \oplus 0 = 0$

2.1.5 Diversity and Cooperative Communications

Generally bit error rate performance of a communication system is inversely proportional to signal to noise ratio of the system. When communication depends on strength of single path, it is more likely that the channel will experience a deep fade and the errors will cause degradation in the performance of the system. A common remedy to it is to introduce other paths the signal can go through which assume each path has different fading nature, hence communication becomes more reliable as long as one of the path stays out of deep fading (Tse and Viswanath 2005). It can be concluded that the more path is used the less likely deep fade occurs; therefore the system performance is increased. This way of handling fading is known diversity and it can be used to reduce effect of fading on the system performance. Three main diversity techniques are known as frequency diversity; when the channel is frequency selective, time diversity; with the help of coding etc. and space diversity where at the transceiver more than one antenna spaced sufficiently.

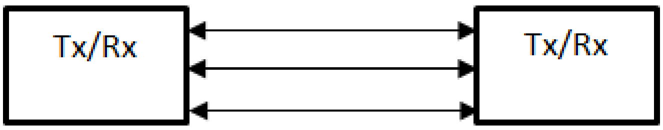

Figure 2.10 Diversity.

In cooperative communication, space diversity is existed naturally. In the case each transceiver (a device which can both receive and transmit) has one antenna one can perceive CC as a system either with receiver diversity or transmitter diversity. These two can achieve what is intended to achieve with diversity on itself. In this thesis receiver diversity system is explained to help to understand diversity created with the help of relay link in CC.

Receiver diversity can be imagined as in Figure 2.11 for a wireless system where receiver has N antennas.

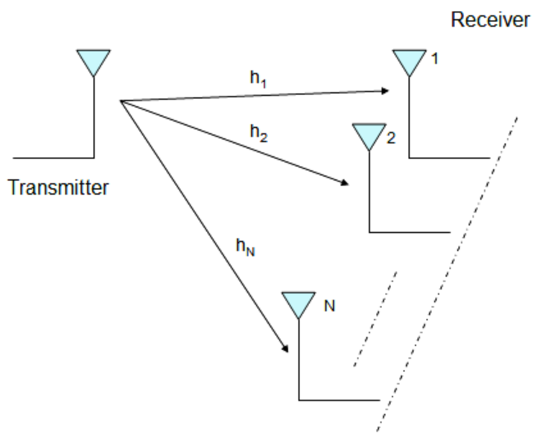

Figure 2.11 Receiver diversity (www.dsplog.com).

The receiver will get the copy of sent signal, $s(t)$, on each antenna which may be assumed as $s_1(t), s_2(t), \dots s_L(t)$. In ordinary wireless system the received signal is given $y = hx + n$ where x is sent signal whereas it is as follows for diversity involved system with L antenna.

$$\begin{aligned} y_1 &= h_1 x + n_1 \\ y_2 &= h_2 x + n_2 \\ \dots &\quad \dots \quad \dots \\ y_L &= h_L x + n_L \end{aligned} \tag{2.12}$$

Eq.(2.12) can be written as

$$\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ y_L \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \\ . \\ . \\ h_L \end{bmatrix} x + \begin{bmatrix} n_1 \\ n_2 \\ . \\ . \\ n_L \end{bmatrix} \equiv \vec{y} = \vec{h}x + \vec{n} \tag{2.13}$$

In Eq.(2.13) $[y_1\ y_2\ \dots\ y_L]^T$ is the vector for received information from each independent path through respective channel shown with the vector $[h_1 h_2 \dots\dots h_L]^T$, and $[n_1 n_2 \dots\dots n_L]^T$ is noise for each path.

The destination station combines information with maximum ratio combiner (MRC). MRC is showed to be most optimal combining technique when the related channels knowledge is available and it is vital to examine.

MRC combines received signals in the vector $\vec{y}$ as follows

$$\left[w_1^* y_1 + w_2^* y_2 + w_3^* y_3 + ... + w_L^* y_L\right] \tag{2.14}$$

In Eq. (2.14) w is weighting coefficient for related channel and $[\ ]^*$ is used to indicate conjugate operation.

Eq. (2.14) can be written as $\vec{w}^H \vec{y}$, which is known beam former and $\vec{w}^H$ is given as

$$\left[w_1^* + w_2^* + w_3^* + ... + w_L^*\right] \tag{2.15}$$

Fixing Eq. (2.13) in to Eq. (2.14), the beam former output is calculated as

$$= \vec{w}^H (\vec{h}x + \vec{n}) = \underbrace{\vec{w}^H \vec{h}x}_{\substack{\text{signal} \\ \text{component}}} + \underbrace{\vec{w}^H \vec{n}}_{\substack{\text{noise} \\ \text{component}}} \tag{2.16}$$

Bit error rate performance of beam former can be determined based on the output signal to noise ratio which is calculated as $\gamma_{out} = \frac{P_s}{P_n}$, where P_s and P_n are signal power and noise power respectively.

The noise power is;

$$E\left\{\left|\vec{w}^H \vec{n}\right|^2\right\} = E\left\{\left(\vec{w}^H \vec{n}\right)\left(\vec{w}^H \vec{n}\right)^*\right\} =$$

$$E\left\{\left(w_1^* n_1 + w_2^* n_2 + ... + w_L^* n_L\right)\left(w_1 n^*{}_1 + w_2 n^*{}_2 + ... + w_L n^*{}_L\right)\right\} =$$

$$E\left\{\sum_{i=1}^{L} \underbrace{\left|w_i\right|^2 \left|n_i\right|^2}_{\left(w_i^* n_i\right)\times\left(w_i n_i^*\right)} + \underbrace{\sum_i \sum_j w_i w_j^* n_i^* n_j}_{i \neq j}\right\} \tag{2.17}$$

The second part in addition in Eq. (2.17) becomes zero since the noise on different channel is assumed to be independent and in the first part of the equation expectation is taken for n_i since w_i is fixed value, hence it becomes as,

$$= \sum_{i=1}^{L} |w_i|^2 \, E\{n_i\}^2$$

$$= \sum_{i=1}^{L} |w_i|^2 \sigma_n^2 \tag{2.18}$$

In Eq. (2.18) σ_n^2 is expected value of noise and $|w_i|^2$ can be written as $\|\vec{w}\|^2$, hence Eq. (2.18) is written as

$$P_n = \sigma_n^2 \vec{w}^H \vec{w} = \sigma_n^2 \|\vec{w}\|^2 \tag{2.19}$$

Eq. (2.19) is known power of noise at the output of beam former. Hence the SNR at the output is given as

$$\gamma_{out} = \frac{|\vec{w}^H \vec{h}|^2 \, P}{\vec{w}^H \vec{w} \sigma_n^2} \tag{2.20}$$

In Eq. (2.20) P is the transmitting power. By choosing right $\vec{w}$, the output SNR is maximized. In Eq. (2.10), if $\vec{w}^H \vec{w} = 1$ is taken, to maximize $\vec{w}^H \vec{h}$, the optimal $\vec{w} = \frac{\vec{h}}{\|\vec{h}\|}$ is chosen to maximize output SNR which is:

$$\gamma_{out} = \frac{|\vec{w}^H \vec{h}|^2 \, P}{\sigma_n^2} = \left| \frac{\vec{h}^H}{\|h\|} \vec{h} \right|^2 \frac{P}{\sigma_n^2} \tag{2.21}$$

Eq. (2.20) is maximized output of beam former and it is given as

$$\gamma_{out} = \left\|\vec{h}\right\|^2 \frac{P}{\sigma_n^2} \quad (2.22)$$

The system's instantaneous bit error rate performance can be calculated based on Eq. (2.22) as

$$P_{ins,err} = \theta\left(\sqrt{g\gamma_{out}}\right) \quad (2.23)$$

In Eq.(2.23) $g = \left\|h\right\|^2$. The average bit error rate is given as in chapter 3.

2.2 MIMO & VIRTUAL MIMO

MIMO is a system requires multiple antennas at transmitter and receiver. A simple type of MIMO can be shown as in Figure 2.12 where it is clearly seen that each transceiver has more than one antenna. MIMO system, having multiple antennas, can be used to provide diversity. In MIMO systems, the data can be transmitted parallel which means it uses same time and frequency for transmission with the same transmitter power, hence transmitting rate can be increased without needing extra transmission power. The data is multiplexed into available space between transmitter and receiver which is known spatial diversity. Spatially diversity is known multiplexing parallel information stream into space. In MIMO, x transmitter antennas transmits the data

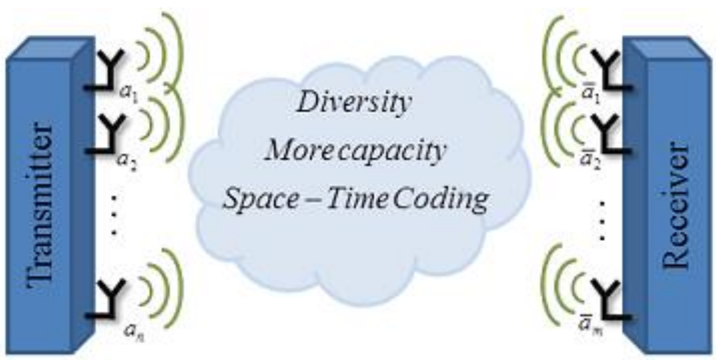

Figure 2.12 MIMO (http://wcsp.eng.usf.edu/research.html).

through MIMO channel and y receive antennas receive the data. This can be represented with x and y for transmit symbol vector and receive symbol vector respectively.

$$\begin{bmatrix} h_{11} & h_{12} & . & . & h_{1t} \\ h_{21} & h_{22} & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ h_{r1} & . & . & . & h_{rt} \end{bmatrix} \tag{2.24}$$

In Eq.(2.24) h_{rt} is the channel between r_{th} receive antenna and t_{th} transmitter antenna. Therefore the received data is calculated with

$$\begin{bmatrix} y_1 \\ . \\ . \\ . \\ y_r \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & . & . & h_{1t} \\ h_{21} & h_{22} & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ h_{r1} & . & . & . & h_{rt} \end{bmatrix} \begin{bmatrix} x_1 \\ . \\ . \\ . \\ x_t \end{bmatrix} \tag{2.25}$$

Eq.(2.25) can be given as $\vec{y} = H\vec{x}$ in short notation where H represents channel matrix. If we express the received data at 1st antenna as

$$y_1 = h_{11}x_1 + h_{11}x_2 + h_{11}x_3 .... h_{1t}x_t \tag{2.26}$$

It is seen that all transmitted data interfered in receive antenna one which is valid for the rest of the receive antennas. The Eq.(2.26) can be written as in Eq.(2.27) when the noise is added.

$$\begin{bmatrix} y_1 \\ . \\ . \\ . \\ y_r \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & . & . & h_{1t} \\ h_{21} & h_{22} & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ h_{r1} & . & . & . & h_{rt} \end{bmatrix} \begin{bmatrix} x_1 \\ . \\ . \\ . \\ x_t \end{bmatrix} + \begin{bmatrix} n_1 \\ . \\ . \\ . \\ n_r \end{bmatrix} \tag{2.27}$$

Eq.(2.27) can be given as $\vec{y} = H\vec{x} + \vec{n}$.

MIMO can be of different form depending on number of antennas used at transmitter and receiver. In the case, one transmitter antenna is used with receive antenna, the received information is formulated as

$$\begin{bmatrix} y_1 \\ . \\ . \\ . \\ y_r \end{bmatrix} = \begin{bmatrix} h_1 \\ . \\ . \\ . \\ h_r \end{bmatrix} x + \begin{bmatrix} n_1 \\ . \\ . \\ . \\ n_r \end{bmatrix} \tag{2.28}$$

Eq. (2.28) can be written $\vec{y} = \vec{h}x + \vec{n}$. This is named SIMO (Single Input Multi Output) and it is actually receive diversity system. The other way around is to have many transmitter antenna while having one receive antenna. This can be shown as

$$y = \begin{bmatrix} h_1 & h_2 & . & . & h_t \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_t \end{bmatrix} + n \tag{2.29}$$

Eq. (2.29) can be given $y = \vec{h}^T \vec{x} + n$. This is named as MISO (Multi Input Single Output) and it represents transmitter diversity.

Both MISO and SIMO can be though a part of cooperative system. When cooperative system is considered from transmitter relay side it can be taken as SIMO while it can be considered MISO from relay receive side in one way communication.
The noise expressed in vector form in MIMO is assumed to be Gaussian independent for each channel; hence the power of noise is given as $E\left[\left|n_i\right|^2\right] = \sigma^2$.The noise component uncorrelated at each receive antenna; hence it is $E\left[n_i n_j^*\right] = 0$, therefore the correlation matrix is given as

$$E\left[\vec{n}\vec{n}^H\right] = E\left(\begin{bmatrix} n_1 \\ n_2 \\ . \\ . \\ n_r \end{bmatrix}\begin{bmatrix} n_1^* & n_2^* & . & . & n_r^* \end{bmatrix}\right) =$$

$$E\begin{pmatrix} |n_1|^2 & n_1 n_2^* & . & . & n_1 n_r^* \\ n_2 n_1^* & |n_2|^2 & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ n_r n_1^* & . & . & . & |n_r|^2 \end{pmatrix}$$

$$= \begin{pmatrix} \sigma_n^2 & 0 & . & . & 0 \\ 0 & \sigma_n^2 & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ 0 & . & . & . & \sigma_n^2 \end{pmatrix} = \sigma_n^2 I \qquad (2.30)$$

Hence the covariance matrix is $R_n = E\left(\vec{n}\vec{n}^H\right) = \sigma_n^2 I$ .The sent data can be extracted from received data as in Eq. (2.31)

$$\vec{y} = H\vec{x} + \vec{n}$$
$$H^{-1}\vec{y} = H^{-1}H\vec{x} + \vec{n} \qquad (2.31)$$

This can be done as long as the inverse of channel matrix exist which requires that the input and output are equal in MIMO system. Provided that the channel matrix is a square matrix, the inverse still might not be existed; hence general solution for this is required. In cooperative system, generally inputs and outputs are not equal. Therefore we will need this general solution for reception at the both end of transmission. Considering the case where number of receive antennas is greater than the transmitter antennas, there will be channel matrix H which is not square, and then the exact solution might not be exist. Therefore the minimum error solution is found as solution of the system which is given as

$$\bar{e} = \left\| \bar{y} - H\bar{x} \right\|^2 \tag{2.32}$$

In Eq. (2.32) $\vec{x}$ is chosen such that the minimum error is minimized which is known least square solution.

$$= \left(\bar{y} - H\bar{x}\right)^T \left(\bar{y} - H\bar{x}\right)$$

$$= \frac{\partial\left(\left(\bar{y} - H\bar{x}\right)^T \left(\bar{y} - H\bar{x}\right)\right)}{\partial\vec{x}}$$

$$= \bar{y}^T \bar{y} - \bar{x}^T H^T \bar{y} - \bar{y}^T H\bar{x} + \bar{x}^T H^T H\bar{x} \tag{2.33}$$

$$= 0 - H^T \bar{y} - H^T \bar{y} + H^T H\bar{x} + H^T H\bar{x}$$

$$= -2H^T \bar{y} + 2H^T H\bar{x}$$

By setting the derivative of Eq. (2.33) to zero, the optimal value is found as

$$\begin{aligned} \left(H^T H\right)\bar{x} &= H^T \bar{y} \\ \tilde{\bar{x}} &= \left(H^T H\right)^{-1} H^T \bar{y} \end{aligned} \tag{2.34}$$

Eq. (2.34) holds for complex equations too as

$$\tilde{\bar{x}} = \left(H^H H\right)^{-1} H^H \bar{y} \tag{2.35}$$

In Eq. (2.35) $\tilde{\bar{x}}$ is approximated optimal solution that minimizes the least square error and it is known as zero forcing receiver in MIMO system. This type receiver does not perform well due to noise amplification when the channel matrix has very low fading parameters, therefore MMSE might be used to provide high SNR. For example if it is a SISO channel, the received signal and estimated $\tilde{x}$ are given as

$$\begin{aligned} y &= hx + n \\ h^{-1}y &= h^{-1}hx + h^{-1}n \\ \frac{y}{h} &= x + \frac{n}{h} \end{aligned} \tag{2.36}$$

Eq. (2.36) means that in the case h is very small in magnitude, the noise is amplified very much, hence the estimation of sent information is not possible which is also the case for matrix type channel.

To eliminate the problem faced with zero forcing receivers, MMSE is used in MIMO system. Before explaining MIMO-MMSE a linear estimator is explained. Linear estimator states that estimated x is given as $\tilde{x} = \bar{C}^T \bar{y}$ where $\bar{y}$ is vector of measurements and $\bar{C}^T$ is used for the measurements are considered to be linear combination of x. The aim is to choose proper $\bar{C}^T$ to minimize the mean of $\left\{ \left\| \tilde{x} - x \right\|^2 \right\}$.

The minimized mean is given as $\arg \min_{\tilde{x}} E \left\{ \left\| \tilde{x} - x \right\|^2 \right\}$ and calculated as

$$= \left(\bar{C}^T \bar{y} - x \right) \left(\bar{C}^T \bar{y} - x \right)^T$$

$$= \bar{C}^T \overline{yy}^T \bar{C} - x\bar{y}^T \bar{C} - \bar{C}^T \bar{y} x^T + xx^T \tag{2.37}$$

where $E(\overline{yy}^T) = R_{yy}$, $E(x\bar{y}^T) = R_{xy}$ or $E(\bar{y}x^T) = R_{xy}^T = R_{yx}$ are covariance matrix of y and cross covariance matrix x and y respectivily. Taking the expectation of Eq.2.37 and substituting R_{yy} , R_{xy} , R_{yx} , R_{xx}

$$= \bar{C}^T R_{yy} \bar{C} - R_{xy} \bar{C} - \bar{C}^T R_{yx} + R_{xx}$$

$$= \bar{C}^T R_{yy} \bar{C} - 2\bar{C}^T R_{yx} + R_{xx}$$

Solving the derivative of above equation help us to find the minimum value of the $\bar{C}$ as

$$= 2R_{yy} \bar{C} - 2R_{yx} = 0, \; \bar{C} = R_{yy}^{-1} R_{yx}$$

This gives us the linear minimum mean squared estimation of x .The estimation is given as $\tilde{x} = \bar{C}^T \bar{y}$ which holds for linear complex combining and given as $\tilde{x} = \bar{C}^H \bar{y} = R_{xy} R_{yy}^{-1} \bar{y}$. In the case x is a vector, C becomes a matrix. For MIMO-MMSE, the covariance matrix of transmitted, recived symbols and cross corelation matrix are given as

$$R_{xx} = E\left\{\bar{x}\bar{x}^H\right\} = E\left\{\begin{bmatrix} |x_1|^2 & x_1x_2^* & \ldots & x_1x_t^* \\ x_2x_1^* & |x_2|^2 & \ldots & x_2x_t^* \\ \ldots & & & \ldots. \\ x_tx_1^* & x_tx_2^* & \ldots & |x_t|^2 \end{bmatrix}\right\} = P_d I$$

$$R_{yy} = E\left\{\bar{y}\bar{y}^H\right\} = E\left\{\left(H\bar{x}+\bar{n}\right)\left(H\bar{x}+\bar{n}\right)^H\right\} =$$

$$E\left\{H\bar{x}\bar{x}^H H^H + \underbrace{\bar{n}\bar{x}^H}_{0} H^H + H\underbrace{\bar{x}\bar{n}^H}_{0} + \underbrace{\bar{n}\bar{n}^H}_{\sigma_n^2}\right\} = HR_{xx}H^H + \sigma_n^2 I$$

$$R_{yy} = HR_{xx}H^H + \sigma_n^2 I = P_d HH^H + \sigma_n^2 I$$

$$R_{yx} = E\left\{\bar{y}\bar{x}^H\right\} = E\left\{\left(H\bar{x}+\bar{n}\right)\bar{x}^H\right\} = E\left\{Hx\bar{x}^H + \underbrace{\bar{n}\bar{x}^H}_{Expected\ 0}\right\} = P_d H$$

$$\bar{C} = R_{yy}^{-1}R_{yx} = P_d\,(P_d HH^H + \sigma_n^2 I)^{-1} H \qquad (2.38)$$

Eq.2.38 is known the MMSE estimator for MIMO system. Hence the estimated symbols vector is given as $\tilde{x} = \bar{C}^H\bar{y} = P_d H^H (P_d HH^H + \sigma_n^2 I)^{-1}\,\bar{y}$ or it can be written as

$$\tilde{x} = P_d\,(P_d HH^H + \sigma_n^2 I)^{-1} H^H\,\bar{y} \qquad (2.39)$$

This can be also used to get the estimated symbol for a SIMO transmission as

$$\tilde{x} = \frac{P_d h^*}{P_d\,\|h\|^2 + \sigma_n^2}\,\bar{y} \qquad (2.40)$$

Eq. 2.40 is reduced to zero-forcing receiver when the SNR is high as $P_d\,(P_d HH^H)^{-1} H^H\,\bar{y} = (HH^H)^{-1} H^H\,\bar{y}$ (The noise power is ignored due to high SNR). $P_d\,(\sigma_n^2 I)^{-1} H^H\bar{y} = (P_d / \sigma_n^2) H^H\bar{y}$ is given for low SNR, hence the problem of noise amplification is overcome.

2.2.1 Channel Decomposition

The channel decomposition may be required when a MIMO CO-OFDM system is employed with decode-forward protocol. The most important shortfall of decode-forward system is known error propagation from relay to destination when the source-relay link is in low SNR regime. This must be detected and the power of forwarded message must be scaled in order to avoid signal distortion at destination. MIMO based system has channel matrix which can be decomposed by using single value decomposition technique in order to get the fading coefficient of each individual MIMO channel separately. By acquiring this, power allocation, link adaptive decode-forwarding can be done. The SVD goes as follows;

Let $\bar{y} = H\bar{x} + \bar{n}$, where $\bar{x}$ is transmitted information vector of t transmitters, $\bar{y}$ is received information vector of r receivers with the noise vector of $\bar{n}$ and H is $r \times t$ channel matrix. SVD decomposition substitutes the channel matrix H with $U \sum V^H$, hence $\bar{y} = U \sum V^H \bar{x} + \bar{n}$ is obtained. $U, \sum, V^H$ matrixes are given as follows;

$U = [u_1\, u_2\, u_3 \ldots u_t]_{r\times t}$, where u_i is i^{th} column and the columns are orthonormal to one another given as $\|u_i\|^2 = 1$ and $u_i^H.u_j = 0$ if $i \neq j$.

$V = [v_1^H\, v_2^H\, v_3^H \ldots v_t^H]^T$, where $\|v_i\|^2 = 1$, $v_i^H.v_j = 0$ if $i \neq j$ and $V^H V = VV^H = I$

$\sum = \begin{pmatrix} \sigma_1 & & 0 \\ & \ddots & \\ 0 & & \sigma_t \end{pmatrix}_{t\times t}$ where σ_t is known singular value and must be order as $\sigma_1 \geq \sigma_2 .... \geq \sigma_t \geq 0$.

Substituting $U, \sum, V$, the received can be written as

$$\bar{y} = \underbrace{[u_1\, u_2\, u_3 \ldots u_t]}_{U}{}_{r\times t} \underbrace{\begin{pmatrix} \sigma_1 & & 0 \\ & \ddots & \\ 0 & & \sigma_t \end{pmatrix}}_{\Sigma}{}_{t\times t} \underbrace{\begin{bmatrix} v_1^H \\ v_1^H \\ . \\ v_t^H \end{bmatrix}}_{V^H} \bar{x} + \bar{n}$$

where $\bar{x}$ is given as $\bar{x} = V\tilde{x}$, which is known pre-coding at transmitter. Multiplying $\bar{y}$ with U^H the signal, $\bar{y} = \sum \tilde{x} + \tilde{n}$ is obtained which may be given as

$$\begin{bmatrix} \tilde{y}_1 \\ \tilde{y}_2 \\ . \\ \tilde{y}_t \end{bmatrix} = \begin{pmatrix} \sigma_1 & & 0 \\ & \ddots & \\ 0 & & \sigma_t \end{pmatrix}_{t\times t} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ . \\ \tilde{x}_t \end{bmatrix} + \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \\ . \\ \tilde{n}_t \end{bmatrix}$$

where σ_i is known fading parameter for i^{th} channel. The SNR for i^{th} channel is also given as $\sigma_i{}^2 P / \sigma_n{}^2$, where P *and* σ_n^2 are transmitter and noise power respectively. Because $\tilde{n} = U^H n$ and $E\{U^H n\} = \{U^H nn^H U\} = \sigma_n^2 I$.

In SVD based MIMO system, the feedback is required to transmitter which uses for pre-coding.

2.2.2 Water Filling

The water filling algorithm can be used in CO-OFDM or MIMO based CO-OFDM. Since we know individual fading coefficient for sub-carriers or MIMO channel, the power can be allocated proportional to channel power in order to maximize the channel capacity by which we mean maximum rate of information. For a given SNR, the channel capacity is given with $\log_2(1+SNR)$.It can be rewritten for each decomposed MIMO channel as $\log_2(1+P_i\sigma_i^2/\sigma_n^2)$.Hence the total capacity is $\sum_{i=1}^{t}\log_2(1+P_i\sigma_i^2/\sigma_n^2)$ where P_i is the power allocated to i^{th} channel. The water filling basically allocates more power to better channel and it may be explained as;

The total power allocated to t channels is given as

$$P_1 + P_2 + ... + P_t \le P$$

We want maximize the total capacity which is subject to total power can be formulated as

$$\max_{P_1+P_2+...+P_t \le P} \sum_{i=1}^{t} \log_2 (1 + P_i \sigma_i^2 / \sigma_n^2)$$

The constrained problem is solved with Lagrange multiplier method which can be written as

$$x = \sum_{i=1}^{t} \log_2 (1 + P_i \sigma_i^2 / \sigma_n^2) + \lambda (P - (P_1 + P_2 + ... + P_t))$$

where λ is Lagrange multiplier. $dx / P_i = 0$ is solved for each channel. For example, for 1st channel, it is given as

$$\frac{dx}{dP_1} = \frac{\sigma_1^2 / \sigma_n^2}{1 + P_1 \sigma_1^2 / \sigma_n^2} + (-\lambda) = 0$$

$$P_1 = \frac{1}{\lambda} - \left(\sigma_1^2 / \sigma_n^2 \right)$$

In general the allocated power for i^{th} channel is given as $P_i = \frac{1}{\lambda} - \left(\sigma_i^2 / \sigma_n^2 \right)$ on condition that the power for every channel is positive quantity. Hence if it is calculated less than zero it is set to zero. Therefore the total power is $\sum_{i=1}^{t} P_i = \sum_{i=1}^{t} \frac{1}{\lambda} - \left(\sigma_i^2 / \sigma_n^2 \right) = P$.

The water filling algorithm is pictorially shown as in Figure 2.12. In the figure each bar's height shows the noise ratio the channel power. The higher the bar is the less the power allocated for the channel. Beside this any channel higher than $1/\lambda$ is allocated zero power and the channel less than $1/\lambda$ is filled the reach $1/\lambda$ as the total power constrained allows. The initial assumption is taken as if $1/\lambda$ greater than all noise/channel power and all powers calculated and the power for last channel is checked. If it is negative, the total number the power allocated is reduced one. This algorithm is repeated to allocate optimum power all channels.

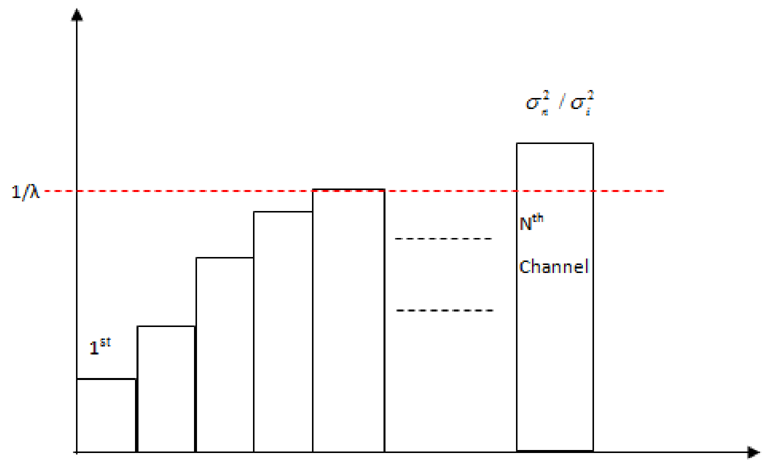

Figure 2.13 Water filling.

2.3 OFDM

OFDM stands for orthogonal frequency division multiplexing. It is now underlying multiplexing of very important communication system; hence it has been accepted as a standard. Some of the places it is being used are digital television, digital audio broadcasting, DSL internet access, 4G&5G cellular networks. High spectral efficiency, ability to convert frequency selective channel due to multipath to flat fading channel, robust to inter symbol interference, easy implementation by FFT are given some advantages of OFDM. In the following we will provide a brief introduction to multicarrier transmission and OFDM.

2.3.1 Historical Background

The early systems use the frequency division multiplexing (FDM) to carry different signals in the same medium. In FDM, spectral overlap is avoided to eliminate inter-carrier interference. The non-overlapping carrier is also pretext of spectral inefficiency. Hence, a system with overlapping carriers is studied. It is seen that inter-carrier interference can be avoided between overlapping carriers as long as the carriers are mathematically orthogonal to one another. This became to be known OFDM. The study of Chang (Chang 1966) is known the first appeared about orthogonal carriers. Chang also holds the patent named OFDM. The efficiency of parallel data transmission system is analyzed by Saltzberg (Saltzberg 1967). In OFDM, orthogonally of sub-carriers is a must. Unless it is provided OFDM cannot be benefitted. The requirement of using many oscillators for both modulation and demodulation can distort the orthogonally of sub-carriers. Indeed it was the first problem encountered in OFDM system. Weinstein and Ebert (Weinstein and Ebert 1971) showed that DFT can be used to modulate/demodulate the message signal to/from sub-carriers, hence, the orthogonally of the sub-carriers can be provided easily. In the next section we explain it with mathematical background.

2.3.2 Introduction

To introduce OFDM we will briefly mention about frequency division multiplexing (FDM).

It is assumed that bandwidth (BW) B is provided for communication. When the all B is used for transmission of one symbol at a time it is known single carrier communication and the symbol time is given as $T_s = 1/B$ second where B is given in hertz. The symbol rate calculated as $R_s = 1/T_s = B$

In FDM, B is divided into many sub channels as shown on figure 2.14

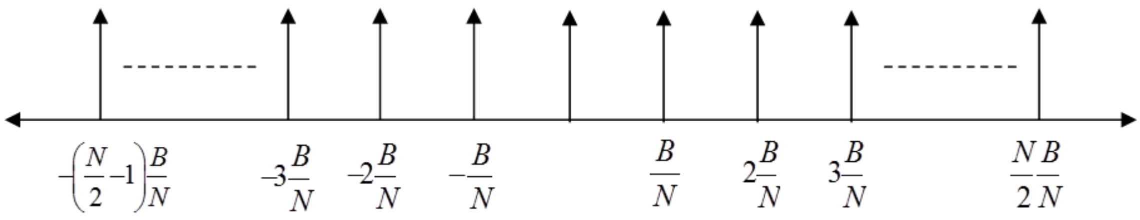

Figure 2.14 Frequency Division Multiplexing.

In Figure 2.14 each sub channel has B/N bandwidth and center frequency of i^{th} channel is $i\frac{B}{N}$ which is shown f_i. If x_i is the information to be transmitted, it can be modulated to i^{th} sub-carrier as follows

$$s_i(t) = x_i \exp(j2\pi f_i t)$$

This equation becomes as follows when f_i is fixed

$$s_i(t) = x_i \exp(j2\pi i \frac{B}{N} t)$$

$s_i(t)$ can be written as follows for all sub-carriers

$$s(t) = \sum_i s_i(t) = \sum_i x_i \exp(j2\pi i \frac{B}{N} t)$$

We can express it as in following equation in the absence of noise, which is actually received signal:

$$y(t) = s(t) = \sum_i x_i \exp(j2\pi f_i t)$$

This can be demodulated coherently as

$$= \frac{B}{N} \int_0^{N/B} y(t) \exp(j2\pi f_\ell t)^* dt$$

$$= \frac{B}{N} \int_0^{N/B} \sum_i \left[x_i \exp(j2\pi i \frac{B}{N} t) \right] \exp(j2\pi \ell \frac{B}{N} t)^* dt$$

In this equation, $(.)^*$ stands for complex conjugate and integration is performed for the size of a sub-carrier N/B. This equation is solved for i^{th} carrier as

$$= \frac{B}{N} \sum_i \int_0^{N/B} x_i \exp\left(j2\pi (i - \ell) \frac{B}{N} t \right) dt$$

in which, integration part results 0 for $i \neq \ell$ and for $i \neq \ell$, it is as

$$= \int_0^{N/B} x_i \exp\left(j2\pi (i-\ell) \frac{B}{N} t \right) = \int_0^{N/B} x_i \exp\left(j2\pi (0) \frac{B}{N} t \right) = \int_0^{N/B} 1dt = \frac{N}{B}$$

therefore, demodulation for i^{th} carrier produces

$$\frac{B}{N} x_\ell \frac{N}{B} = x_\ell$$

Notice that integration above produces zero for all orthogonal sub-carriers. To obtain information from all sub carriers, above demodulation must repeated for all sub carriers. In terms of data rate, multi carrier modulation does not offer any advantage since it can be given as $\frac{N}{N/B} = B$, the same amount as in the single carrier, and it is hard to implement. But the system will be robust against inter symbol interference (ISI) since, each sub carrier will be very narrow and its' BW will not be greater than coherence BW (B_c).

2.3.3 Implementation of OFDM with FFT

In a very important paper titled as "Data transmission by frequency-division multiplexing using the discrete Fourier transform" (Weinstein & Ebert, 1971), an easy way is shown to modulate or demodulate all sub carriers at once. If the sent signal is sampled every $T_s = 1/B$ and considering k^{th} sample, it is given as

$$s(t) = s(kT_s) = x(k) = \sum_i x_i \exp\left(j2\pi i \frac{B}{N} t \right), t = kT_s = k \frac{1}{B}$$

$$x(k) = \sum_i x_i \exp\left(j2\pi i \frac{B}{N} \frac{k}{B} \right)$$

$$x(k) = \sum_i x_i \exp\left(j2\pi i \frac{k}{N} \right)$$

The last equation is recognized as inverse discrete Fourier transform (IDFT) and often it is calculated with fast Fourier transform (FFT) algorithm. Thus complexity of system is reduced and all carriers are used orthogonally which is named OFDM.

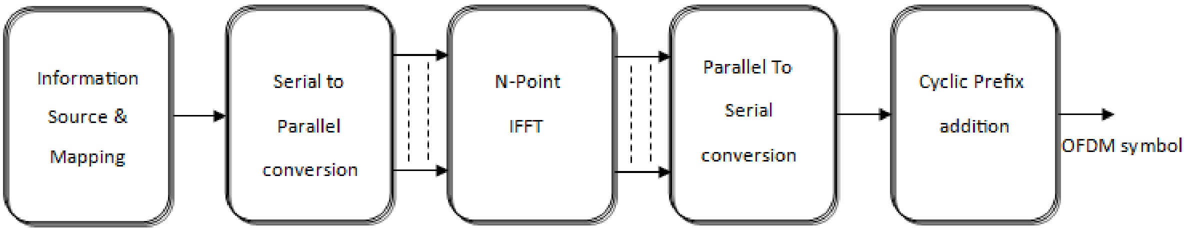

Figure 2.15 OFDM transmitter.

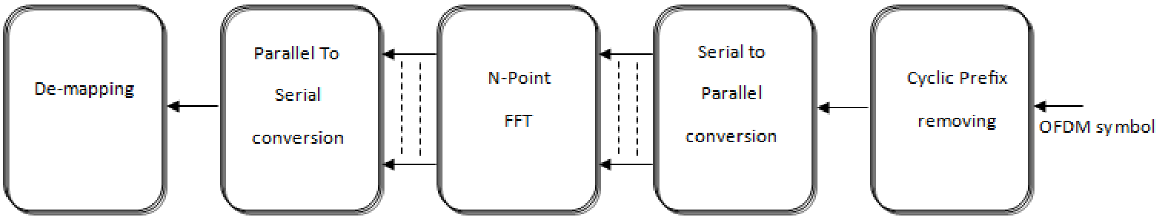

Figure 2.16 OFDM receiver .

In OFDM system, cyclic prefix is used to make sure successive OFDM symbols don't interfere one another in frequency selective channel. Given two OFDM symbols as S_1 and S_2 as

$$S_1 = \left[x_1(0), x_1(1), \ldots\ldots x_1(N-2), x_1(N-1)\right]$$

$$S_2 = \left[x_2(0), x_2(1), \ldots x_2(N-2), x_2(N-1)\right]$$

and rewriting them successively

$$x_1(0), x_1(1), \ldots\ldots x_1(N-2), x_1(N-1) x_2(0), x_2(1), \ldots x_2(N-2), x_2(N-1)$$

and passing them through L multi-tap channel given as

$$h(0)\quad h(1)\quad h(2)....................h(L-1),$$

the received OFDM symbols are given as

$$y(0) = h(0)x_2(0) + \underbrace{h(1)x_1(N-1) + h(2)x_1(N-2) + ... + h(L-1)x_1(N-L+1)}_{\text{int}\,erference}$$
$$y(1) = h(0)x_2(1) + h(1)x_2(0) + \underbrace{h(2)x_1(0) + ... + h(L-1)x_1(N-L+2)}_{\text{int}\,erference}$$

where inter symbol interference occurs as shown.(This is actually discrete convolution of two signals given by $y[n] = \sum_{i=-\infty}^{\infty} h(i)x(n-i)$). To overcome this problem at least $L-1$ symbols of an OFDM symbol is appended to beginning of the OFDM symbol which is known cyclic prefix procedure. After appending cyclic prefix, the received symbol is

$$y(0) = h(0)x_2(0) + h(1)x_2(N-1) + h(2)x_2(N-2) + ... + h(L-1)x_2(N-L+1)$$

where all samples are from same symbol. Convolution channel with all symbols given as

$$y(0) = h(0)x_2(0) + h(1)x_2(N-1) + h(2)x_2(N-2) + ... + h(L-1)x_2(N-L+1)$$

$$y(1) = h(0)x_2(1) + h(1)x_2(0) + h(2)x_2(1) + ... + h(L-1)x_2(N-L+2)$$
$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots$$
$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots$$
$$y(N-1) = h(0)x_2(N-1) + h(1)x_2(N-2) + h(2)x_2(1) + ... + h(L-1)x_2(N-L)$$

which is named as circular convolution and symbolized with $\otimes$. Therefore received symbols can be given as

$$y = h \otimes x$$

and by taking Fourier transform, it can be written for k^{th} sub-carrier as

$$Y(k) = H(k).X(k)$$

By using zero forcing receiver or MMSE we can extract the information. The zero forcing receiver is given as for k^{th} sub-carrier

$$\tilde{X}(k) = Y(k) / H(k) = X(k) + N(k) / H(k)$$

This is known soft decoding and it may be also given as

$$H(k)^* Y(K) = |H(k)|^2 X(k) + N(k) / H(k)$$

The MMSE for the for k^{th} sub-carrier is given as

$$\tilde{X}(k) = H^*(k)Y(k) / |H(k)|^2 + \sigma_n^2$$

We further like to note that the length of cyclic prefix must be at least $L-1$ for L tab channel to avoid inter symbol interference. The system loses spectral efficiency due to addition of cyclic prefix given as $Cyclic\,prefix\,length / Total\,OFDM\,symbol\,length$ or $(L-1)/(N+L-1)$. The loss of efficiency can be reduced by increasing the number of sub-carriers used given as $\lim_{N\to\infty}(L-1)/(N+L-1) = 0$. The cost of increasing number of sub-carriers is the decoding delay of receiver which can be reduced with fast computing system.

CHAPTER 3

LINK ADAPTIVE SYSTEMS

3.1 OFDM BASED LINK ADAPTIVE ONE-WAY DF RELAYING CS

3.1.1 Abstract

OFDM based one-way DF relaying cooperative communication system has recently received significant attention to improve the reliability and performance of wireless communication systems. In this paper, link adaptive relaying (LAR) approach which combats performance degradation due to error propagation in digital relaying based wireless networks has been applied to the OFDM based one-way DF relaying cooperative system. It is shown that power of each sub-carrier in OFDM system can be separately adapted as in the single carrier one way link adaptive system which reduces power consumption at relay and improves BER performance of considered system. The error performance analysis of proposed system where link adaptation is used for per sub carrier by deriving BER expression over frequency selective Nakagami-m fading channel is investigated. The results show that our proposed system outperforms and saves power at the relay and by using link adaptive relaying the proposed system achieves full diversity. BER derivation is done for Rayleigh fading channel (m=1) under high SNR condition in which the relay decodes the data of source perfectly. Monte-Carlo simulation results are provided in order to confirm the numerical results by considering various position of relay.

3.1.2 Introduction

Fluctuation on a signal due to fading is a challenging problem for wireless communication. It distorts the signal and therefore, causes loss of information (Johnson Jr, Sethares and Klein 2011) . Spatially diversity is an excellent solution to reduce the effect of fading (Goldsmith 2005). Multi-Input Multi-Output (MIMO) is a system which provides diversity with no more extra power and bandwidth .MIMO uses multi antenna both on the receiver and the transmitter.

It is a physical fact that antennas located on a device must have a certain distance so that signal propagated from each antenna can go through different fading environment. Recent technologies enable us to use very high frequency on devices for electronic communication. This provides very small wavelength with which minimum distance between antennas is calculated, yet it is still too big for small size mobile wireless communication tools to accommodate two or more antennas. Therefore, MIMO is a well-adapted to systems with relatively bigger size such as base stations and may be applied to mobile phones with two antennas but not more considering today's mobile phone size and their operating frequencies. We may have small devices which cannot accommodate more than one antenna. In such situation, the recent studies offer a solution known cooperative system (CS) (Sendonaris, Erkip and Aazhang, User cooperation diversity. Part I. System description 2003). This system uses other user's resources to create a virtual MIMO system (Nosratinia, Hunter and Hedayat 2004). When two nods want to communicate, nods located between the two nods let their antennas and systems to be used by communicating nods which can be thought that the two nods in communication have antennas as many as the nods between them. When it happens in one way at a time, it is named one way cooperative system. In the CS, the nods which open their resources for the sake of other users' communication called relays. The relay is responsible for retransmitting the received signal to the destination. The type of operation in relay names the system as generative or non-generative system which also known decode and forward (DF) or amplify and forward (AF) system in general (Uysal and Global 2010). In AF relaying, relay terminal transmits a scaled version of received signal without decoding message. In DF relaying, relay node decodes its received signal and then re-encodes it for transmission to destination (Nosratinia, Hunter and Hedayat 2004). The fundamental destructive effect encountered in AF based wireless networks is the retransmission of the amplified version of the noise terms while the most important problem in DF based cooperative systems is the error propagation due to the decoding errors at the relay nods which cause reduction in the effective signal-to-noise ratio (SNR) at the destination.

The relay furthermore can adapt the power of retransmitting signal according to two channel condition between source-relay and relay-destination links in DF cooperative systems (Sirigina, Tio and Madhukumar 2010), (Wang, Giannakis and Wang 2008). This reduces power consumption and increase BER performance in order to achieve full diversity. The error performance of such systems furthermore can be increased by using OFDM based multiplexing. In OFDM system, available channels are divided into many sub-channels therefore power factor can be adjusted to per sub-channel which introduces sensitivity, instead of adjusting power factor depending on one single channel condition. OFDM can also promise good performance in terms of higher speed, lesser interference (Horlin and Bourdoux 2008). Another advantage of OFDM based system comes from orthogonally located sub-carriers which use bandwidth efficiently, therefore capacity of the system is increased. It is worth to remind that when a given channel divided into many sub channels, it becomes flat fading for each sub-carrier due to allocation of very narrow bandwidth to each one; therefore the system becomes more robust to multi-path fading effect. The other advantage of OFDM is cyclic prefix which is used to reduce inter-symbol interference between consequent OFDM symbols. All of these mentioned advantages of OFDM made it underground multiplexing technique for modern communication systems. The discovery of using fast Fourier transform (FFT) to eliminate usage of oscillator for each sub-carrier and coherent demodulators made it as simple but useful tool (Weinstein and Ebert 1971). From designing perspective, OFDM promises less complexity by reducing complexity of equalizer at receiver side.

As an important modulation technique for wireless communication OFDM has been studied in cooperative system recently. The study in (Li and Wang 2011) considers effect of sub-carrier mapping both DF and AF systems which get more complex as the number of sub-carrier increases. In (Vu and Kong 2012), joint sub-carrier matching and a power allocation algorithm under total power constraint in DF two way relay systems is studied and an optimal sub-carrier mapping is offered. In (Ding and Uysal 2009), the author investigated selective relaying schemes in AF based cooperative OFDM system where per-sub-carrier based selection named selective OFDMA compared to selection scheme based on entire OFDM block named selective OFDM and it is shown that the earlier one outperforms the later. In (Lin and Stefanov 2007), coded cooperative system is examined and guidelines for the choice of partners in coded cooperative OFDM systems is provided. The author of (Shin, et al. 2007) design an OFDM based cooperative system in which underlying structure of the cooperation protocol is used for frequency synchronization. In (Jiang, Liao and Chen 2013), resource allocation is studied with OFDM based DF cooperative system.

The most important problem encountered in digital relaying based cooperative communication systems is the decrase in effective SNR at the destination nods, which occurs as a result of detection errors at the relays. This stuation, which is termed error propagation, causes significant decrase in the diversity degree of system. The CRC (Cyclic redundancy check) based approaches where only the data blocks that are detected correctly are forwarded constitute one of the ways to overcome performance decrases stemming from error propagation. However, CRC not only decreases the bandwidth efficiency of the system, but it also increases the costs and complexity as it requires additional decoding and encoding processes in the relay nods. LAR (link adaptive relaying) is one of the important approach in combating performance decrases caused by error propagation without employing CRC approach. LAR approach is based on the idea that the power of the relay is scaled with a coefficient that is dependent on the channels gain of the source-relay and relay-destination links. The studies in (Wang, Giannakis and Wang 2008) and (Sirigina, Tio and Madhukumar 2010) consider link-adaptive cooperative system which is named link adaptive regenerative relaying.

To the best of our knowledge LAR model is not applied the OFDM based cooperative system at sub-carrier level. In this paper, we investigate the error performance analysis of OFDM based link-adaptive one-way DF relaying cooperative communication systems where link adaption is done for per sub carrier by driving BER expression over frequency selective Nakagami-*m* fading channel. By adapting power of each sub-carrier in OFDM based DF system, power consumption at the relay node is reduced and higher BER performance is obtained. The system is also simulated with different path loss parameter such that link adaptive system performance is considered for relay being either close to destination or source.

3.1.3. System and Channel Model

As shown on Fig. 1, source (S) node communicates destination (D) node via both direct and relaying link. The relay node acquires the channel knowledge of R-D link with feedback from D. Assuming the channel is static for a short time, link adaptive factor is calculated based on this channel knowledge. The details are explained below.

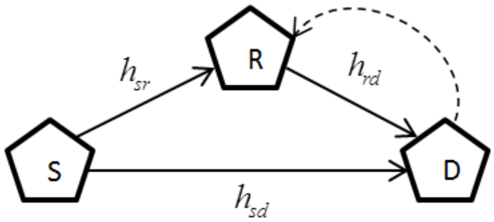

Figure 3.1 The link adaptive cooperative system model.

We assume the system use BPSK mapping and all nodes can do OFDM multiplexing or de-multiplexing. OFDM works as explained in (Yildirim and Ilhan 2014). For the system, we assume that fading coefficient randomly change for every OFDM symbol. The distribution for this randomness is given with Nakagami-*m* which is assumed to be statistically independent, but not necessarily identically distributed. Therefore, the probability density functions(pdf) of channel coefficient can be given as.

$$f_{|h|}(|h|) = \frac{2m^m}{\Omega^m \Gamma(m)} |h|^{2m-1} \exp\left(-\frac{m}{\Omega}|h|^2\right) \tag{3.1}$$

where the subscripts are dropped for convenience. Here, m is a parameter describing the fading severity given by $m = \Omega^2 / \mathrm{E}[(|h|^2 - \Omega)^2] \geq 1/2$ with $\Omega = \mathrm{E}[|h|^2]$ and $\mathrm{E}[.]$ denoting the expectation operator. Taking Ω equal to one, one can normalize the power of fading process to unity. Further note that the pdf in (1) reduces to Rayleigh distribution when $m = 1$.

The one tap channels h_{sr}, h_{rd}, h_{sd} are given for source-relay, relay-destination and source-destination links fading coefficients respectively. For simplicity it is assumed that number of BPSK symbols to be transmitted is equal to number of sub-carrier, which is given as n, therefore we have one OFDM symbol. These n symbols multiplexed to n sub-carrier with inverse fast Fourier transform (IFFT) and multiplied with the related channel which can be written as in Eq. (3.2)

$$T_{sr} = h_{sr}\ S + n_{sr} \tag{3.2}$$

for source-relay and it is given as in Eq. (3.3)

$$T_{sd} = h_{sd}\ S + n_{sd} \tag{3.3}$$

for source-destination where S is one OFDM symbol, n_{sd} and n_{sr} complex Gaussian noise terms with zero mean and variance of N_0 .The R node uses h_{sr} and h_{rd} to calculate the link adaptive power factor α which can be given as

$$\alpha = \{\alpha_1, \alpha_2, ..., \alpha_n\}$$

where α_i can be calculated as

$$\alpha_i = min(\gamma_{sr(i)}, \gamma_{rd(i)}) / \gamma_{rd(i)}$$

if $\gamma_{sr(i)} < \gamma_{rd(i)}$

$$\alpha_i = \gamma_{sr(i)} / \gamma_{rd(i)} \tag{3.4}$$

and if $\gamma_{sr(i)} \geq \gamma_{rd(i)}$, the system use $\alpha_i = 1$.

In Eq. (3.4), $\gamma_{sr(i)}$ and $\gamma_{rd(i)}$ are used to indicate the instantaneous SNR for source-relay and relay-destination link respectively and they are calculated for each sub-carrier as

$$\gamma_{sr} = |h_{sr}|^2\, \overline{\gamma},$$

$$\gamma_{rd} = |h_{rd}|^2 \, \bar{\gamma},$$

where $\bar{\gamma}$ is average SNR and can be given as

$$\bar{\gamma} = \Omega \, P_t \, / \, N_0.$$

Here $\Omega = \mathrm{E}[|\,h\,|^2]$ and P_t is the average transmitting power at the transmitter (source node). The calculated α is used for retransmitting received signal as

$$T_{rd} = \sqrt{\alpha} \, h_{rd} \, S_r + n_{rd}$$

where S_r stands for re-multiplexed signal vector of encoded symbols. The function of the R node is to take FFT of received signal to de-multiplex to obtain sub-carriers separately and use the feedback from the D node to calculate α for every sub-carrier, then multiply it with decoded signal, and then apply IFFT and parallel to serial conversion to create time domain signal to be sent to destination node. When the channel is given as multi-tap, the way α is calculated for each sub-carrier can be shown as Fig. 3.2 on which S/P and P/S means serial to parallel and parallel to serial respectively. The MRC receiving technique is used at the destination node. Thus the function of the D node is to maximally combine the signals received both from the R node and the D node and continuously provide feedback of channel state information to the R node. In all above equations, the magnitudes of channels are Nakagami-*m* random variables (Simon and Alouini 2005).

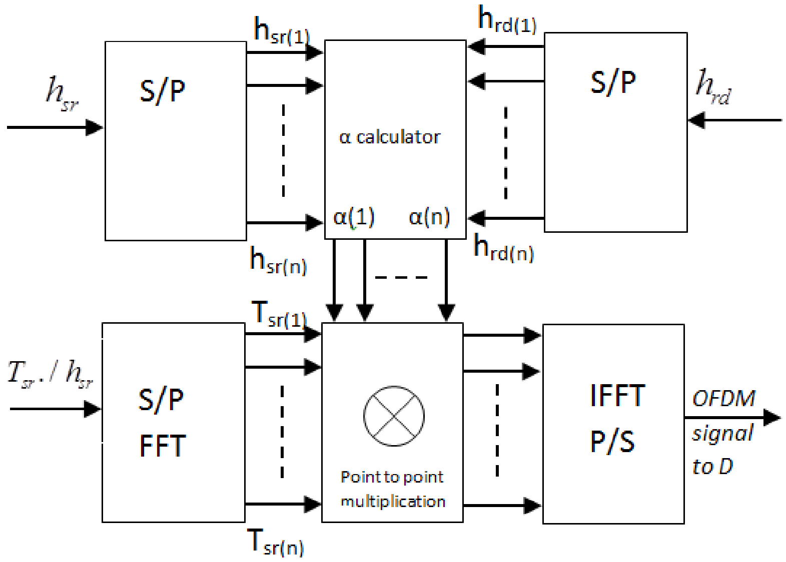

Figure 3.2 OFDM based link adaptive relaying.

3.1.4 BER Derivation of Proposed System

In this section we will investigate the BER analysis of the proposed system under high SNR condition for Rayleigh channel, which is actually a special case of Nakagami-*m* distribution when m is taken as one, and we will take the following steps in order;

1. We will derive BER of the links (S-D and S-R-D).
2. Derivation of BER for MRC will be done.

An OFDM symbol can be defined as

$$S_{sd}(n) = (1/N)\sum_{k=0}^{N-1} S(k)e^{j2\pi\Delta f kt}$$

where n is the index number for related OFDM symbol which is $n = (1,\ 2, 3, ..., \infty)$ but here we assume we have just one OFDM symbol and k is the index number for BPSK modulated symbol. Given that the fading coefficient is $h_{sd}(n)$ for nth symbol, the received OFDM symbol at the D node can be written as

$$y_{sd}(n) = h_{sd}(n)\, S_{sd}(n) + n_{sd}(n)$$

in baseband, where $n_{sd}(n)$ is additive white Gaussian noise component. The related signal to noise ratio can be given as

$$\gamma_{sd}(n) = |h_{sd}(n)|^2\, P_t \,/\, \sigma_{sd}{}^2,$$

where P_t is the power at the transmitter and $\sigma_{sd}{}^2$ is the noise power or variance which is equal to N_0.

The BER for the given SNR can be written with $Q\sqrt{\gamma_{sd}(n)}$, where $Q(.)$ is standard Q function, which is for binary orthogonal signal and it is given with $Q\sqrt{2\gamma_{sd}(n)}$ for antipodal BPSK (G.Proakis and Salehi 2008). Since $|h_{sd}(n)|$ is a random variable, it is averaged over Rayleigh distribution when fading parameter $m=1$ to calculate average BER $(P_{e,sd})$ as

$$P_{e,sd}(n) = \int_0^\infty Q\left(\sqrt{\gamma_{sd}(n)}\right) f_A(a)da \tag{3.5}$$

where $f_A(a)$ is probability distribution function of channel fading coefficient given as (Simon and Alouini 2005).

$$f_A(a) = 2ae^{-a^2}, \quad a \geq 0$$

Calculating Eq. (3.4) by direct integration the average BER can be found as

$$P_{e,sd}(n) = \frac{1}{2}\left[1 - \sqrt{\bar{\gamma}_{sd}(n) / (2 + \bar{\gamma}_{sd}(n))}\right] \tag{3.6}$$

for nth symbol. In Eq. (3.6), $\bar{\gamma}_{sd}(n) = E\left[|h_{sd}(n)|^2\right] P_t / \sigma_{sd}^{\ 2}$. If we rewrite Eq. (3.6) as

$$P_{e,sd}(n) = \frac{1}{2}\left[1 - \sqrt{1/(1+(2/\bar{\gamma}_{sd}(n)))}\right]$$

and consider high SNR condition, $2/\bar{\gamma}_{sd}$ becomes very small, therefore Eq. (3.6) is approximated as

$$P_{e,sd}(n) = \frac{1}{2}\left[1-(1-\frac{1}{2}\frac{2}{\bar{\gamma}_{sd}(n)})\right] = \frac{1}{2\bar{\gamma}_{sd}(n)}$$

The same average bit error rate will be valid for S-R-D link since, under high SNR, it can be assumed that no error occurs at the relay node, and therefore the link adaptive power scaling factor is taken as $\alpha = 1$, which means the symbol is transmitted with full power from the relay node. Therefore, the BER for S-R-D link is considered same with S-D link as calculated earlier and it is given as

$$P_{e,rd}(n) = \frac{1}{2}\left[1-(1-\frac{1}{2}\frac{2}{\bar{\gamma}_{rd}(n)})\right] = \frac{1}{2\bar{\gamma}_{rd}(n)}.$$

The second step is to calculate maximally combined output at the destination node which is achieved with maximal ratio combiner (MRC). Considering that $h_{sd}(n)$ and $h_{rd}(n)$ are given for corresponding OFDM symbol for S-D and R-D link respectively, we define a vector of h as $h^T = \left[h_{sd}(n), h_{rd}(n)\right]$. To maximize the correspondent symbols of direct and relaying links we define weighting vector as W and calculate SNR for MRC as (Adve 2015).

$$\gamma(n) = \frac{|W^H h|^2 P_t}{W^H W \sigma_n^{\ 2}} \tag{3.7}$$

where, $W = \frac{h}{\|h\|}$ is given to maximize the received SNR and Eq. (3.7) becomes as

$$\gamma(n) = \|h\|^2 \frac{P_t}{\sigma_n{}^2}$$

Defining $g = \|h\|^2$, it can be written as $g = |h_{sd}(n)| + |h_{rd}(n)|$ which is actually a chi-squared random variable with two L degrees of freedom and it's probability density function can be given as (G.Proakis and Salehi 2008)

$$f_G(g) = \frac{1}{(L-1)!} g^{L-1} e^{-g}$$

Therefore the instantaneous BER of *nth* symbol is given as

$$P_{e,MRC}(n) = Q\left(\sqrt{g\bar{\gamma}(n)}\right). \tag{3.8}$$

Here $\bar{\gamma}(n) = P_t / \sigma_n^2$ and average of Eq. (3.8) is calculated by

$$P_{e,MRC}(n) = \int_0^\infty Q(\sqrt{g\bar{\gamma}(n)})\, f_G(g)\, dg\,.$$

Solving above equation, the average BER is given as

$$P_{e,MRC}(n) = \left(\frac{1-\lambda}{2}\right)^L \sum_{\ell=0}^{L-1} C_\ell^{L-\ell-1} \left(\frac{1+\lambda}{2}\right)^L$$

where

$$C_\ell^{L-\ell-1} = \frac{(L-\ell-1)!}{\ell!((L-\ell-1)-\ell)!}$$

$$\lambda = \sqrt{\frac{\overline{\gamma}(n)}{2+\overline{\gamma}(n)}}$$

where $\overline{\gamma}(n) = P_t / \sigma_n^2$. For high SNR, this can be further simplified as

$$P_{e,MRC}(n) = C_L^{2L-1} \frac{1}{2^L} \left(\frac{1}{\overline{\gamma}(n)} \right)^L$$

where $\frac{1-\lambda}{2}$ and $\frac{1+\lambda}{2}$ are given as follows respectively

$$= \frac{1}{2}\left(1-\sqrt{\frac{\overline{\gamma}(n)}{2+\overline{\gamma}(n)}}\right) = \frac{1}{2}\left(1-\frac{1}{(1+2/\overline{\gamma}(n))^{1/2}}\right)$$

$$= \frac{1}{2}\left(1-\left(1-\frac{1}{2}\frac{2}{\overline{\gamma}(n)}\right)\right) = \frac{1}{2\overline{\gamma}(n)}$$

$$= \frac{1}{2}\left(1+\sqrt{\frac{\overline{\gamma}(n)}{2+\overline{\gamma}(n)}}\right) = \frac{1}{2}\left(1+\frac{1}{(1+2/\overline{\gamma}(n))^{1/2}}\right)$$

$$\cong \frac{1}{2}\left(1+1-\frac{1}{\overline{\gamma}(n)}\right) \cong \frac{1}{2}.2 = 1$$

For the system, $L = 2$ is taken, Eq. (28) becomes

$$P_{e,MRC}(n) = C_2^3 \frac{1}{2^2} \left(\frac{1}{\overline{\gamma}(n)} \right)^2 = \frac{3}{4}\left(\frac{1}{\overline{\gamma}(n)} \right)^2$$

It is noted that SNR in the given equations above should be multiplied with two for antipodal BPSK case, therefore the last equation can be written as

$$P_{e,MRC}(n) = C_2^3 \frac{1}{2^2}\left(\frac{1}{\overline{\gamma}(n)}\right)^2 = \frac{3}{4}\left(\frac{1}{2\overline{\gamma}(n)}\right)^2$$

for antipodal BPSK modulation.

3.1.5 Simulation and Numerical Results

In this section, we present Monte-Carlo simulations for OFDM based link-adaptive one-way DF relaying cooperative communication systems in Nakagami-*m* fading channels. The simulation results are obtained for BPSK modulation and OFDM is used as underlying multiplexing technique with *64* sub-carriers. The system is simulated for various values of link adaptive power scaling factor α and fading parameter *m*.

Fig.3.3 shows the BER performance of proposed system under different fading environment which is defined with value of *m*. As seen in the figure, link-adaptive system performance is improved through fading channel. The BER performance of proposed system is enhancing with the increases of the value of fading parameter *m* as expected for higher *m*, the channel becomes more similar to Gaussian channel.

In Fig. 3.4, BER performance of the system is considered for several power scaling factor of α. It is clear that one can increase transmitter power at the relay by purely increasing power scaling factor of α. But the study suggests that increasing it will not produce better throughput as one may expect and it will also cause loss of energy. Furthermore it can reduce the performance. For example when the power is doubled at relay by simply setting $\alpha = 2$ the system will need $6dB$ more power compared the link adaptive system for $m = 1$. This is can be also observed in the higher value of m. For example, to achieve 10^{-4} bit error rate with $m = 2$ the system with $\alpha = 2$ will still need $4dB$ more power compared to link adaptive one. It is worth to note that the case $\alpha = 1$ represents the non-link-adaptive transmission whose throughput is worse than link adaptive situation too and $m = 1$, represents the BER performance of Rayleigh fading environment in which no line of sight exist and it is very common case to many wireless phenomena where link adaptive system produces a good respective result without wasting no more energy.

In the next figure, Fig. 3.5, we have considered the system performance including path-loss parameter provided that $m = 1$. The variance of fading coefficient between both source to relay and relay to source is obtained by using a path-loss model in the form of $\sigma^2_{sr,rd} = d^{-v}_{sr,rd}$ and the path loss coefficient is fixed as $v = 2$. In the two extreme situations ($\mathrm{d}_{sr} = 0.9$: the relay is so close to destination and $\mathrm{d}_{sr} = 0.1$: the relay is so close to source) in which relay is very close to either source or destination, the link adaptive system will perform at least as good as non-link adaptive case or better and lesser power will be consumed. This is expected result due to way the power scaling factor calculated. Considering Eq. (3.4) with which the power scaling factor α is calculated, it is easily seen that when the relay is so close to source, less error occurs at the relay or SNR for S-D link will be higher, therefore α will become one, so the link adaptive system will produce same performance of non-link-adaptive system. When relay close to destination, more errors occur at the relay or SNR for S-D link is lower, therefore α calculated close to zero, hence the effect of relaying link on MRC is reduced and better throughput obtained. The more common case in which the relay close to midway, link adaptive system achieved 10^{-4} bit error rate with $7dB$ less power.

In the last figure, Fig. 6, numerical and simulation results are provided together for S-D, S-R, R-D links in high SNR condition. As expected, through high SNR, the plots overlap, and the small difference are considered due to approximation done in calculation which shows the accurate numerical analysis derived earlier.

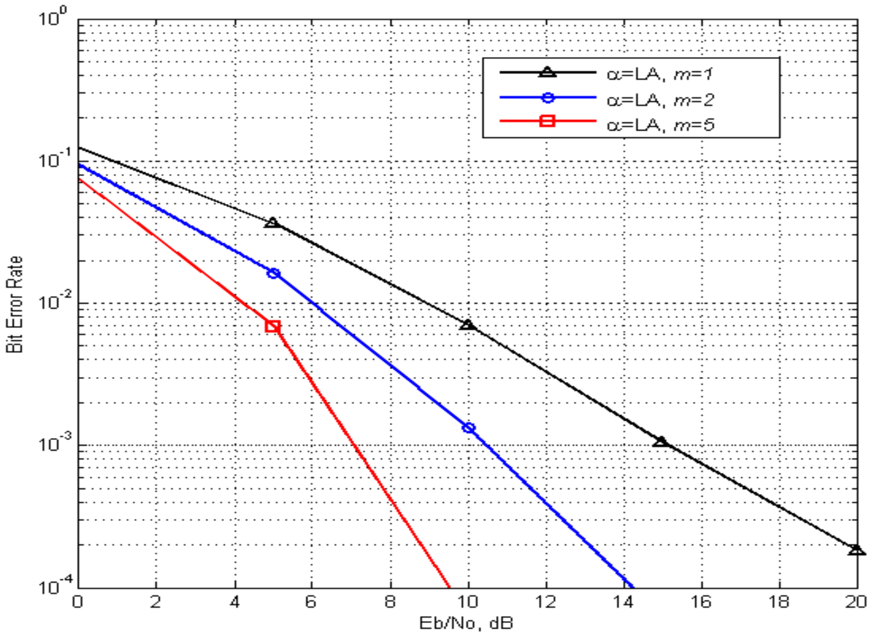

Figure 3.3 Link adaptive system BER performance.

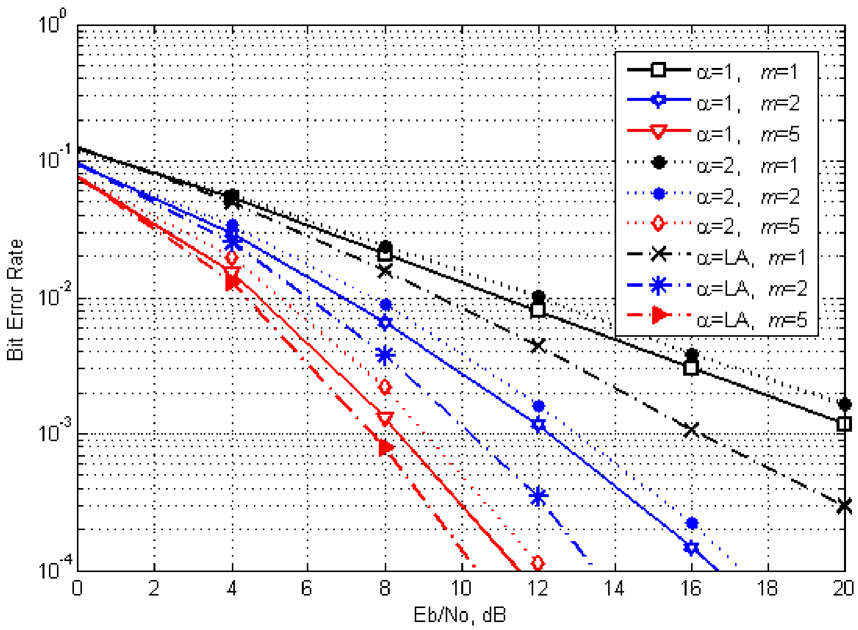

Figure 3.4 BER performance of proposed system for various power factor α .

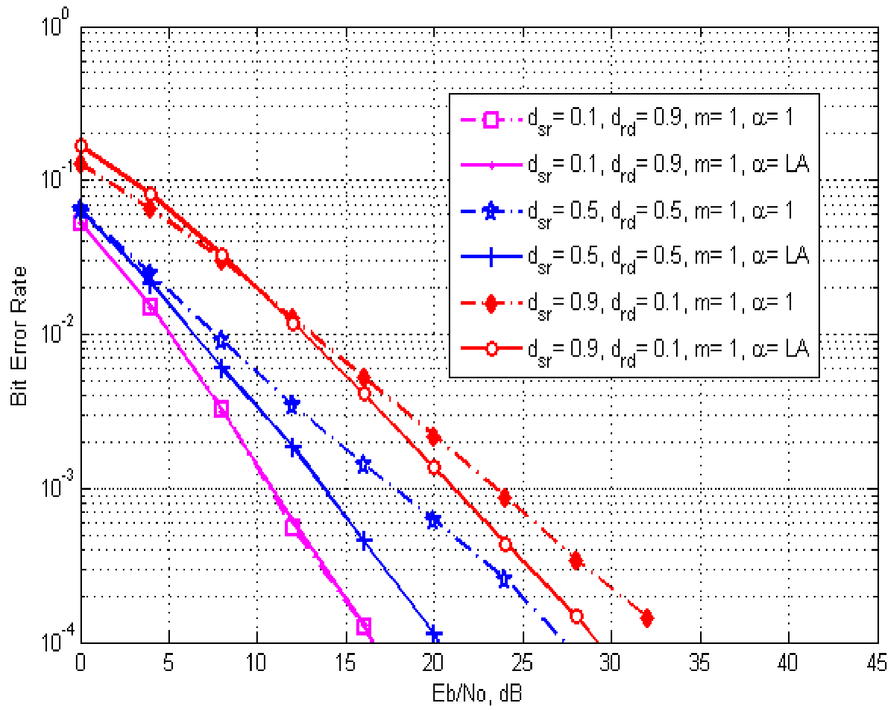

Figure 3.5: The system performance with path loss.

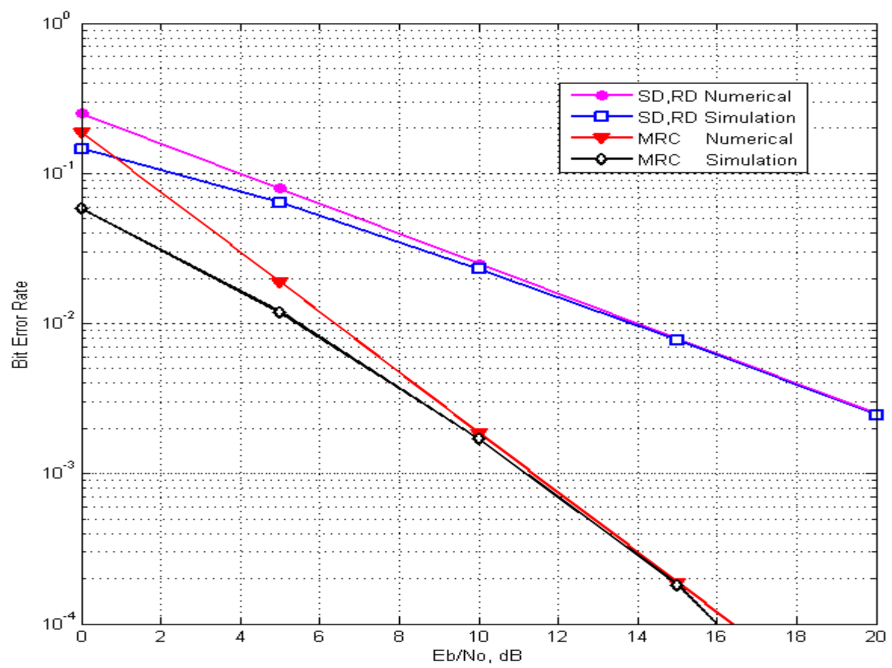

Figure 3.6: Simulation and Numerical results of the system.

3.1.6 Conclusions

In this paper, we have implemented OFDM based one-way link-adaptive DF relaying cooperative system. The relay node in the considered system use a different adaptive power factor for each sub-carrier obtained from S-R and R-D fading channels coefficient. The suggested system will be reducing power of only the sub-carriers whose corresponding sub-carriers in the S-R link has lesser power, thus reducing probability of propagating error to D. This lets the considered system outperform any system which is either a single carrier link adaptive or multi-carrier but not sub-carrier link adaptive. It is noted that the more sub-channels are used the better performance is achieved since more sub-channels are set link adaptively and frequency selective channels are transformed to flat channels. We have considered the system for various position of relay as well as various α and m. The results obtained suggest that the proposed system produces better throughput in all the cases considered.

Further, we have derived BER in high SNR condition for both individual links and maximum ratio combiner output. Assuming high SNR condition reduced complexity in calculation, yet provided clear enough idea about behavior of the system. Simulation and numerical analysis are provided with figures showing and proving the performance of the system.

CHAPTER 4

RESOURCE ALLOCATION

4.1 RELAY SELECTION IN OFDM BASED TWO-WAY CS

4.1.1 Abstract

In this paper, error performance analysis of relay selection in orthogonal frequency-division multiplexing (OFDM) based amplify-and-forward (AF) relaying two-way cooperative communication systems is examined over frequency selective Nakagami-*m* fading channels. In the selection process, we investigate a simple suboptimal min-max criterion for relay selection, where a single relay that minimizes the maximum bit error rate (BER) of two source nodes will be selected. Also, the effect of relay positioning is examined. Results show that BER performance of proposed system increases with the number of relays and also, is enhancing with the increase of the value of fading parameter m.

4.1.2 Introduction

The demand on wireless commutations have always been increasing due to fast developing technology introducing fancy wireless-equipped devices into our daily life. This drives the researches to put more effort to develop systems with higher capacity, reliability, spectral efficiency, and speed with less power consumption (Goldsmith 2005). As well explained in (Johnson Jr, Sethares and Klein 2011) , one of the most challenging problem in wireless communication is known as fading and an excellent way to overcome fading effects in wireless systems is to create space diversity by using multiple antennas. Therefore the researchers developed Multi Input Multi Output (MIMO) systems to minimize fading effects which offered greater increase in wireless capacity with neither increasing transmission power nor bandwidth requirement (Teletar

1995)In a short time, MIMO is well accepted in all communication area yet it has implementation challenges on mobile devices with small physical size due to requirement of multi antenna placement on the device and minimum distance between these antennas. Hence, a new system with the advantages of MIMO known as cooperative communication (CC) was developed. CC is actually a virtual model of MIMO (Nosratinia, Hunter and Hedayat 2004) where wireless mobile devices in a network with one antenna act as virtual antenna for one user. This, cooperation of users in a network, increases the wireless system capacity without having real MIMO systems (Sendonaris, Erkip and Aazhang, User cooperation diversity. Part I. System description 2003). As soon as introduced, CC drew great interest of researchers. Initial applications considered one way communication with cooperation where a signal from a source is transmitted to destination via relays which is named one way cooperative communication (OW-CC). Soon after this, the researchers develop the idea of two way cooperative communication (TW-CC) which introduces higher spectral efficiency and capacity (Rankov and Wittneben 2007).

In primitive TW-CC, two users exchange information through another user called Relay (R) whose resources are employed to process and forward the received signal to the destination (D) or users. The type of process at R names the type of CC as Amplify and Forward (AF) or Decode and Forward (DF) in general are studied in literature intensively. AF, since has less complexity and close throughput to the DF which is in favor of relay in terms of less computation, is chosen to establish cooperative link generally in practice as well as in this paper (Boyer, Falconer and Yanikomeroglu 2004). In AF relaying, the relay terminals retransmit a scaled version of received signals without decoding the message.

Recently, it has been shown that the performance of two-way wireless relay networks can further be improved by selection of the relays for transmission (Lozano and Jindal 2010), (Chen, Wang and Zhang 2009), (Li, Louie and Vucetic 2010). Specifically, the authors in transmission (Lozano and Jindal 2010) and (Chen, Wang and Zhang 2009), show that diversity related to number of relays that the more relays are employed the better throughput is achieved however it means waste of resources too if there is possibility to achieve better performance without increasing number of relays. In the study of (Li, Louie and Vucetic 2010), it is shown that best relay selection throughput is as good as a system with multi relayed communication. In (Zhang and

Gong 2009), the max-min sum rate selection algorithm was proposed for AF two-way communication networks based on outage probability. In (Nguyen, Nguyen and Le-Ngoc 2011), the authors analyzed the diversity orders of relay selection scheme and in (Jing 2009) a max-min relay selection algorithm for two-way communication systems was presented. In (Ilhan 2014),relay selection schemes for two way AF relay networks were proposed.

It is shown in (Schenk and Linnartz 2008), that OFDM is a promising technique in combating multipath effects and inter-symbol interference. The cyclic prefix is used to minimize the interference between successive symbols while deep fading effect is reduced with the use of narrowband sub-carriers. The system is simply built by modulating each OFDM symbol with orthogonal sub-carriers. Inverse Fast Fourier Transform (IFFT) seems to be most practical way for building OFDM transmitter. A given binary stream is arranged in matrix format, whose number of column is equal to number of sub-carrier, then IFFT is taken and cyclic prefix (CP) is appended. The implementation of OFDM is given in (Negi and Cioffi 1998).

The studies related to cooperative systems with OFDM, in particular to two-way cooperative communication can be categorized in two groups. In the first category, OFDM is considered an assistive tool as a transmission technique to avoid frequency selective fading, to provide fast data transmission, to have bandwidth-efficiency, to combat inter-channel interference and inter-symbol interference. OFDM is used as an underlying modulation technique and the studies consider how to improve OFDM based CC systems. In (Rabiei, Namgoong and Al-Dhahir 2011), the performance of AF system is examined under phase noise. The authors of (Li, Xiong and Feldman, OFDM Transmission scheme for asynchronous two-way multi-relay cooperative networks with analog network coding 2013) addressed to synchronization issue and develop a new OFDM transmission scheme which can handle timing and carrier frequency synchronization better. The second category studies use OFDM as a main player in their system and involve it directly in relaying, optimal resource allocation, creating diversity, channel estimation, sub-carrier allocation or matching. In (Gui, Dai and Cimini 2008), OFDMA is used based on sub-carriers relaying and in (Ng and Yu 2007) subscribers of a cooperative cellular network are used as relays for one another.

In this paper, we investigate the error performance analysis of relay selection OFDM based AF relaying two-way cooperative communication systems by driving BER expression over frequency selective Nakagami-*m* fading channels. By using OFDM based system, the complexity of equalizer at the receiver side is reduced and bandwidth efficiency of considered system is improved due to the orthogonally of sub-channels. Also, the effect of relay positioning is examined.

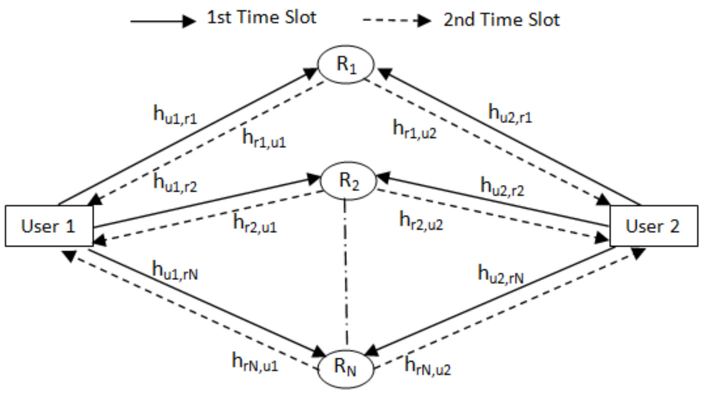

Figure 4.1 The system model.

4.1.3 System and Channel Model

We consider two users as *user1* and *user2*, as shown on Figure 4.1, want to communicate each other over N relays network. In the *1st time slot* both users send their messages to the relays in the network. The best relay chosen and assuming the channel condition is stable for a short time, the combined message at the relay sent back to users on same link in the *2nd time slot*. The details are explained below.

An *n*-bit binary data stream $d[a]=\{a[1],...,a[N]\}_{1\times N}$ modulated with one of *M-PSK* (phase shift keying) modulation is given as $s[i]=\{s[1],s[2],s[3],\ldots,s[N]\}$ where i is index of symbol. $s[i]$ is converted into matrix format of $F_{m\times n}$ where n, number of columns, is chosen according to size of IFFT operation which is the same number of sub-carrier in the OFDM system. Each column of $F_{m\times n}$ is called an OFDM symbol and it can be shown for first column as $F_{(1\times 1:N)} = \{[s[1], s[2], s[3], ..., s[N]\}^T$ then IFFT of $F_{m\times n}$ is taken. To implement cyclic prefix, last k rows of the matrix is copied and congregated to the matrix before the first row. The first column of obtained matrix is given as $F_{IFFT,m+k\times 1}$, where k is the size of cyclic prefix. The matrix is converted to vector which we show as $F_{1\times((m+k)\times n)}$. This is the serial data which we get from OFDM transmitter to send to relays. All these processes could be pictured as in [15] and can be formalized as $F(t) = \sum_{k=0}^{N-1} s_k e^{j2\pi kt/T}$, s_k is symbol at k^{th} index, N is the number of symbol including cyclic prefix, and $e^{(j2\pi kt/T)}$ is complex component of FFT. $F(t)$ is now time-domain based signal. Here we assume $user1$ and $user2$ have their OFDM modulated signal as F_1 and F_2, respectively. Assuming the best relay with channels, h_{u1ri} and h_{u2ri} where $i = (1, 2, ..., N)$, is chosen among N relays as given at subsection C, F_1 and F_2 are transmitted to the relays as shown Fig. 1, with addition of independent and identically distributed complex Gaussian noise with zero mean and variance N_0. The received signal at i_{th} relay can be written as

$$Y_{ri} = h_{u1ri}.F_1 + h_{u2ri}.F_2 + n_{ri} \tag{4.1}$$

The rest is to amplify the received signals at the relay and forward it to users as given in subsection B. In (1), the magnitudes of h_{u1ri} and h_{u2ri} are assumed to be statistically independent, but not necessarily identically distributed Nakagami-m random variables (Simon and Alouini 2005).Therefore, their probability density functions can be given as

$$f_{|h|}(|h|) = \frac{2m^m}{\Omega^m \Gamma(m)} |h|^{2m-1} \exp\left(-\frac{m}{\Omega}|h|^2\right).$$

In the equation given above, the subscripts $u1ri$ and $u2ri$ are dropped for convenience. Here, m is a parameter describing the fading severity given by $m = \Omega^2 / \mathrm{E}[(|h|^2 - \Omega)^2] \geq 1/2$ with $\Omega = \mathrm{E}[|h|^2]$ and E[.] denoting the expectation operator. Taking Ω equal to one, one can normalize the power of fading process to unity. Further note that the pdf in (2) reduces to Rayleigh distribution when $m = 1$.

The message in Eq. (4.1) at the relay is amplified by using the amplification factor G which is given as in Eq. (4.2).

$$G = \sqrt{\frac{P_{ri}}{P_{u1}\left|h_{u1ri}\right|^2 + P_{u2}\left|h_{u2ri}\right|^2 + N_0}} \tag{4.2}$$

where P_r, P_{u1} and P_{u2} are considered transmitting power at the relay, $user1$ and $user2$, respectively and N_0 is the noise power. The amplified and forwarded signals received by users are given as follows after subtracting self-interference part from other user.

$$Y_{u1} = G\sqrt{P_r}\sqrt{P_{u2}}h_{u2ri}h_{u1ri}F_2 + n$$

$$Y_{u2} = G\sqrt{P_r}\sqrt{P_{u1}}h_{u2ri}h_{u1ri}F_1 + n$$

The corresponding signal-to-noise power ratio (SNR) at $user1$ and $user2$ are given as follows.

$$\gamma_{r,u1} = \frac{\gamma_{ri,u1}\gamma_{u2}\left|h_{u2ri}\right|^2\left|h_{u1ri}\right|^2}{\left(\gamma_{ri,u1} + \gamma_{u1}\right)\left|h_{u1ri}\right|^2 + \gamma_{u2}\left|h_{u2ri}\right|^2 + 1}$$

$$\gamma_{r,u2} = \frac{\gamma_{ri,u2}\gamma_{u1}\left|h_{u2ri}\right|^2\left|h_{u1ri}\right|^2}{\left(\gamma_{ri,u2} + \gamma_{u2}\right)\left|h_{u2ri}\right|^2 + \gamma_{u1}\left|h_{u1ri}\right|^2 + 1}$$

where, $\gamma_{ri,u1} = \gamma_{ri,u2} = P_r / N_0$, $\gamma_{u1} = P_{u1} / N_0$, $\gamma_{u2} = P_{u2} / N_0$. If we assume all transmitting power equal that is $P_r = P_{u1} = P_{u2} = P$ and P >> N_0 we can rewrite these equations as,

$$\gamma_{r,u1} = \frac{\left|h_{u2ri}\right|^2\left|h_{u1ri}\right|^2}{\left|h_{u1ri}\right|^2 + 2\left|h_{u2ri}\right|^2}$$

$$\gamma_{r,u2} = \frac{\left|h_{u2ri}\right|^2\left|h_{u1ri}\right|^2}{\left|h_{u2ri}\right|^2 + 2\left|h_{u1ri}\right|^2}$$

For a given network, to choose the best relay we assume that the worst channel condition dominates overall performance of any relay between users. For example if h_{u1ri}, h_{u2ri} are the channel coefficients between $user1$ and $user2$ to represent the network respectively, and the power of h_{u1ri} is less than that of h_{u2ri} the performance of considered system depends on the coefficient of h_{u1ri} where $i = 1..N$ is the index of the relay. This can be shown as follows

$$h_i = \arg\max_i \min\{|h_{1,i}|^2, |h_{2,i}|^2\}$$

The max h_i helps us to choose the best R_i which is the selected relay for transmission.

4.1.4 BER Performance

The OFDM based system can be considered same in terms of BER with the type of modulation used for mapping bits to symbol when we ignore the effect of cyclic prefix and assume we use all the sub-carriers for the sake of simplicity.

Assuming M-PSK symbol is used for mapping and R_i relay is selected, the symbol error probability (SER) can be given for Rayleigh fading channels as $P_s = uQ(\sqrt{v\gamma_i})$ (Guo, Ge and Ding 2011), where $u = 2, v = 2\sin^2(\pi / M)$, γ_i is the received SNR and $Q(.)$ is the standard Q function. The BER expression can be approximated as $P_b = P_s / l\mathrm{og}_2 M$.

In Nakagami-m fading channel, observing same assumption done for Rayleigh fading, by using the moment generating function (MGF) based approach we can calculate the average SER expression for many type of modulation. Thus, the MGF expression for two-way communication can be written as (Yang, et al. 2011).

$$\Phi_{\gamma_r}(s) = -\frac{2m_i^{m_i}(m_j-1)!}{\bar{\gamma}_i^{m_i}\Gamma(m_i)\Gamma(m_j)} \sum_{p_i=0}^{m_i-1} \sum_{p_j=0}^{m_j-1} \sum_{k=0}^{pj} \frac{1}{p_j!} \binom{p_j}{k}$$
$$\times \binom{m_i-1}{p_i} \left(\frac{m_i}{\bar{\gamma}_i}\right)^{-\frac{\sigma_i+1}{2}} \left(\frac{2m_j}{\bar{\gamma}_j}\right)^{\frac{2\mu_j+\sigma_i+1}{2}} \times \left[b_i s_1 + \left(\delta_i - (\sigma_i+1)\right)s_2 + as_3\right].$$

where

$$s_1 = -\frac{\sqrt{\pi}(2a)^{\sigma_i+1}\Gamma\left(\delta_i+\sigma_i+2\right)\Gamma\left(\delta_i-\sigma_i\right)}{\left(b_i+s+a\right)^{\delta_i+\sigma_i+2}\Gamma(\delta_i+\frac{3}{2})}\times$$

$${}_2F_1\left(\delta_i+\sigma_i+2,\sigma_i+\frac{3}{2};\delta_i+\frac{3}{2};\frac{b_i+s-a}{b_i+s+a}\right)$$

$$s_2 = -\frac{\sqrt{\pi}(2a)^{\sigma_i+1}\Gamma\left(\delta_i+\sigma_i+1\right)\Gamma\left(\delta_i-(\sigma_i+1)\right)}{\left(b_i+s+a\right)^{\delta_i+\sigma_i+1}\Gamma(\delta_i+\frac{1}{2})}\times$$

$${}_2F_1\left(\delta_i+\sigma_i+1,\sigma_i+\frac{3}{2};\delta_i+\frac{1}{2};\frac{b_i+s-a}{b_i+s+a}\right)$$

$$s_3 = -\frac{\sqrt{\pi}(2a)^{\sigma_i}\Gamma\left(\delta_i+\sigma_i+1\right)\Gamma\left(\delta_i-\sigma_i+1\right)}{\left(b_i+s+a\right)^{\delta_i+\sigma_i+1}\Gamma(\delta_i+\frac{3}{2})}\times$$

$${}_2F_1\left(\delta_i+\sigma_i+1,\sigma_i+\frac{1}{2};\delta_i+\frac{3}{2};\frac{b_i+s-a}{b_i+s+a}\right)$$

wherein ${}_pF_q\left(a_1,...,a_p;b_1,...,b_q;x\right)$ is the generalized hyper geometric function. By using MGF $\Phi_{\gamma_r}(s)$, the average SER expression can be calculated for M-PSK modulation as

$$P_s = \frac{1}{\pi}\int_0^{\pi-\pi/M}\Phi_{\gamma_r}\left(\frac{\sin^2(\pi/M)}{\sin^2(\theta)}\right)d\theta.$$

Using the given equations, average BER can be calculated and when $m=1$ assigned, BER of Rayleigh channel can be obtained. Simulation result of the system is given for Nakagami-m and Rayleigh channel on the following figures.

4.1.5 Simulation Results

In this section, we present Monte-Carlo simulations for two-way OFDM based AF relaying cooperative system with relay selection over Nakagami-m fading channels. The simulation results are obtained for 4-PSK modulation and OFDM is used as underlying multiplexing technique with 64 sub-carriers. It is assumed that the distance from *user*2 to *user*2 is normalized to one and the variance of channels between users and relays are inversely proportional to distance. The path loss coefficient is taken $v = 4$ Three figures are provided each of which is obtained by changing one of the three parameters which are number of the relays, the fading parameter m, and the position of relays. Also, we assume that the links from sources to relays and relays to sources are symmetrical.

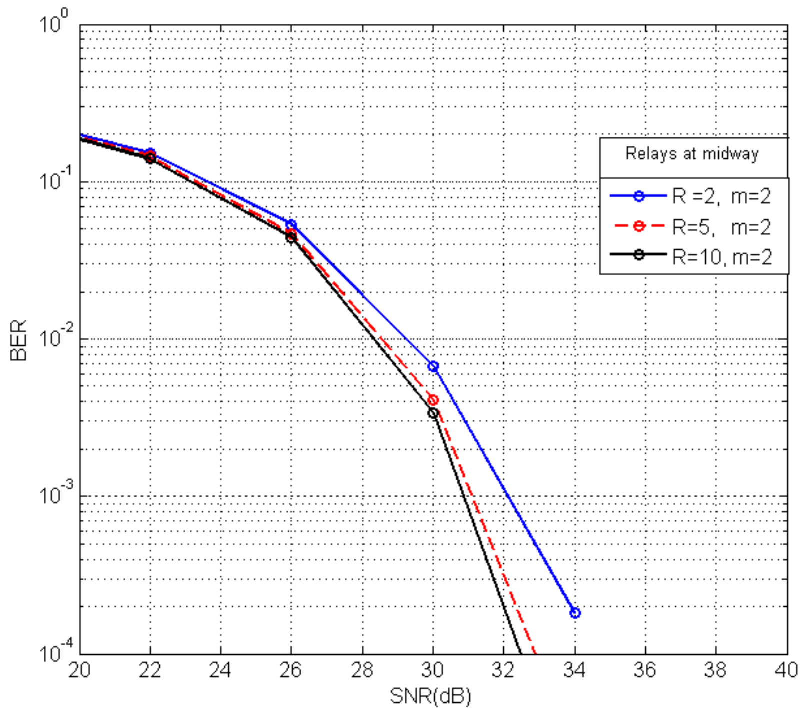

Figure 4.2 The system performance of different network with $m = 2$.

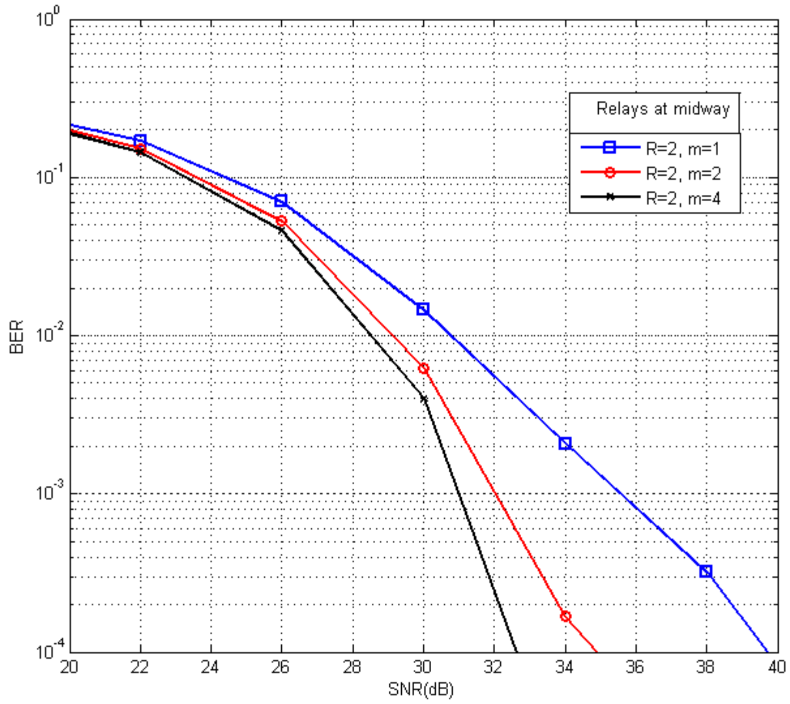

Figure 4.3 The system performance with different fading parameters when R =2.

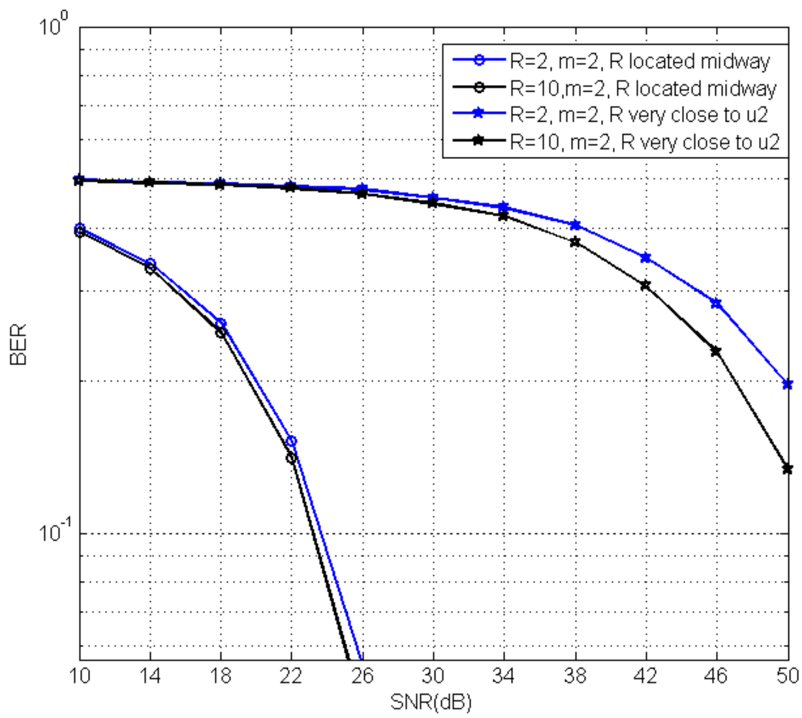

Figure 4.4 Comparison of the system performances for various positions of the relays.

In Figure 4.2, we present the BER performance of considered system with relay selection for fading parameter *m=2* when the relays are located at midway. The obtained results clearly show that the BER performance yields smaller performance improvement as the number of relays decreases.

In Figure 4.3, the system performance over Nakagami-*m* fading is given where relays are assumed to be at the equal distance to users. As we increase the fading parameter *m*, the channel becomes more similar to AWGN channel. Hence, the system achieves great improvement in the throughput compared to Figure 4.2. When $m = 1$, Nakagami-*m* fading is distributed as Rayleigh fading and the system performance is decreased as shown on the figure.

In Figure 4.3, we have considered two situation over Nakagami-*m* fading when fading parameter *m=2*. The first one considers that relays are located in the midway and in the second case we consider that relays are so close to second user while being far away from first user. The Figure 4.3 shows that the system having relays located to midway has better performance which is decreased as the relays are located other than midway.

4.1.6 Conclusions

In this paper, we examined the performance of an OFDM based AF relaying two-way cooperative communication with relay selection over Nakagami-m fading channels for 4-PSK modulation. In the simulation results, the position of relays is considered too. The results show that the BER performance of proposed system increases with the number of relays and the BER performance is enhancing with the increase of the value of fading parameter.

4.2 POWER ALLOCATION IN OFDM BASED TWO-WAY WITH RS

4.2.1 Abstract

In this paper, error performance analysis of relay selection in orthogonal frequency-division multiplexing (OFDM) based amplify-and-forward (AF) relaying two-way cooperative communication system is examined over frequency selective Nakagami-m fading channels with power allocation at source, relay and destination

nodes. Furthermore, we allocated the power to the sub-channels at three terminals. Power allocation is done under the total power constraints based on scaling factor obtained by available channel knowledge of links between the nodes. It is shown that as relay selection can achieve full diversity and improves bit error rate (BER) performance, the power allocation can further improve the performance. Results show that BER performance of proposed system increases with the power allocation and it improves through higher value of fading parameter m.

4.2.2 Introduction

One of the great achievements in wireless communication system is the use of multi antennas on transceivers which is known as Multi-Input Multi-Output (MIMO). The greatness of MIMO comes from the fact that it provides higher BER performance without extra power cost [1], however, MIMO cannot be applied to small devices. This inspired the development of a new system known as cooperative system (CS).

In cooperative system (CS), small devices act in cooperation to benefit one another [2]. In CS, communication between two terminals, source (S) and destination (D), is supported by another terminal-relay (R). The relay link is used to provide diversity in different time slots, hence the quality of service is improved. This type of CS is known as one-way (OW) relaying since any given time one terminal stays in silent. In Fig 4.5, a model for two-way (TW) cooperative system is provided with more than one relay. In TW, there are two phases as multiple access (MAC, 1st time slot) and broadcast phase (BC, 2nd time slot). In MAC, both U1 and U2 send their signals to relays. The selected relay, assuming relay selection is used, processes the signal and sends it back to the users. In TW, physical-layer network coding (PNC) is used to overcome spectral loss due to half duplexing. Thanks to PNC, TW can provide full-duplex communication and each user can extract the transmitted message.

The types of signal processing in relay terminal are various and each one creates different protocol. The most common protocols are amplify-forward (AF) and decode-forward (DF). In DF based CS, the signal is decoded, re-encoded and sent to the destination. In AF, the relay amplifies the signal and retransmits. AF uses channels knowledge to calculate the best amplification factor. Depending on the condition, either AF or DF can be advantageous. This allows the designer to design a system which intelligently changes to the advantageous one which is named as adaptive relaying.

In TW or OW, there can be more than one relay. The studies show that as more relays are used, better performance is obtained. But using the more relay can also be considered as a waste of resources when it is possible to achieve it by less relay. The introduction of relay selection (RS) realizes it. In RS, the best relay is selected instantly and used for relaying. The studies show that diversity order can be achieved by relay selection.

A great multiplexing technique in communication is orthogonal frequency division multiplexing (OFDM) . In OFDM, provided channel is divided into many to create sub-channels. Due to narrowness of the sub-channels, the fading becomes flat. Furthermore, carriers are orthogonally located to the sub-channels; hence, the bandwidth is used more efficiently. The up-conversion or down-conversion to the sub-carriers can be achieved by the help of FFT (Fast Fourier Transform), thus, great complexity is reduced.

The allocation of resources has become very important field of study in the wireless communication. One of the resources is power. The power should be used effectively and it should be used at the right amount at the right place, known as power allocation (PA). The expected result of PA is to improve overall performance of the system. The studies show that, under the limited power constraint, the performance of the system can be optimally improved by distributing the total power which tries to maximize the achievable sum-rate.

In this study, the power allocation is done for two-way communication based on OFDM. The total power is first allocated to three terminals (U1, U2, R) and then each terminal allocates the power to sub-channels optimally. Furthermore, we used Nakagami-m channel so that the system performance can be simulated under various fading environments.

The rest of the paper is organized as follows; section II gives the details of the system, section III has the simulation results and section IV is conclusion.

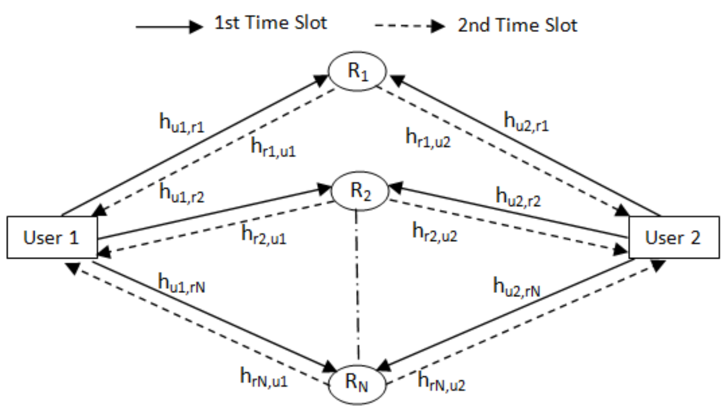

Fig.4.5 The system model.

4.2.3 System Model

Figure 4.5 depicts the two way relaying where two users intended to communicate. The communication is achieved through relay nodes since no direct link is available. It is assumed that all users or nodes have OFDM transceivers. The working principle of OFDM system is given in (Yildirim & Ilhan, 2014). The system uses M-QAM (M-Ary Quadrature Amplitude Modulation) mapping. The relay selection is done based on simple max-min comparison given as below and the best channels pair is chosen.

$$h_i = \arg\max_i \min\{|h_{u1,ri}|^2, |h_{u2,ri}|^2\}$$

In the above equation, $h_{u1,ri}$, $h_{u1,ri}$ and $h_{u2,ri}$ represents the channel between $U1-R_i$ and $U2-R_i$ respectively and the magnitudes of $h_{u1,ri}$ and $h_{u2,ri}$ are assumed to be statistically independent, but not necessarily identically distributed Nakagami-*m* random variables [7]. Therefore, their probability density function can be given as

$$f_{|h|}(|h|) = \frac{2m^m}{\Omega^m \Gamma(m)} |h|^{2m-1} \exp\left(-\frac{m}{\Omega}|h|^2\right)$$

In the above equation the subscripts $u1ri$ and $u2ri$ are dropped for convenience. Here, m is a parameter describing the fading severity given by

$m = \Omega^2 / \mathrm{E}[(|h|^2 - \Omega)^2] \geq 1/2$ with $\Omega = \mathrm{E}[|h|^2]$ and $\mathrm{E}[.]$ denoting the expectation operator. Taking Ω equal to one, one can normalize the power of fading process to unity. Further note that the probability density function above reduces to Rayleigh distribution when $m = 1$.

The received signal at selected relay and amplified signal are given in the following equations respectively.

$$Y_{ri} = h_{u1ri} U_1 + h_{u2ri} U_2 + n_{ri}$$

$$Y_{u1} = G\sqrt{P_r}\sqrt{P_{u2}}\, h_{u2ri} h_{u1ri} U_2 + n_1$$

In the above equation, the amplification factor G is given as,

$$G = \sqrt{\frac{P_{ri}}{P_{u1}\left|h_{u1ri}\right|^2 + P_{u2}\left|h_{u2ri}\right|^2 + N_0}}$$

In the above equation, P_r, P_{u1}, P_{u2}, N_o the transmitter power at relay, user1, user2 and power of noise, respectively.

The power can be optimally distributed by employing (Shin, Lee, Lim, & Shin, 2009) as given in the following equations for i^{th} sub-carrier at users and relay under total power constraint, $\max\limits_{P_{u1,i}, P_{u2,i}, P_{r,i}} R_{sum,i}$ subject to $P_{u1,i} + P_{u2,i} + P_{R,i} \leq P_{tot,i}$, to maximize sum of rate.

$$P_{u1,i} = P_{tot,i} \frac{\left|h_{2,i}\right|^4}{\left|h_{1,i}\right|^4 + \left|h_{2,i}\right|^4 + \left|h_{1,i}\right|^2 \left|h_{2,i}\right|^2}$$

$$P_{u2,i} = P_{tot,i} \frac{\left|h_{1,i}\right|^4}{\left|h_{1,i}\right|^4 + \left|h_{2,i}\right|^4 + \left|h_{1,i}\right|^2 \left|h_{2,i}\right|^2}$$

$$P_{R,i} = P_{tot,i} \frac{\left|h_{1,i}\right|^2 \left|h_{2,i}\right|^2}{\left|h_{1,i}\right|^4 + \left|h_{2,i}\right|^4 + \left|h_{1,i}\right|^2 \left|h_{2,i}\right|^2}$$

4.2.4 Simulation Results

In this section, we present Monte-Carlo simulations for power allocation in two-way OFDM based AF relaying cooperative system with relay selection over Nakagami-m fading channels. The simulation results are obtained for 4-QAM modulation and OFDM is used as underlying multiplexing technique with 64 sub-carriers. It is assumed that the links from sources to relays and relays to sources are symmetrical.

In Fig.4.6, we present the BER performance of considered system in comparison to conventional one where power allocation is not considered for fading parameter   The system is simulated in three networks with 2, 5 and 10 relays. The results show that as the number of relays is increased in the network, the performance of both systems improves and the proposed system with OPA (optical power allocation) significantly improves the performance in Rayleigh channel.

In Fig.4.7, both system performances are given for   in two networks having two and ten relays. The results confirm that as the channel becomes more similar to Gaussian by increasing of , both systems' performances improves. It is also seen that OPA lets the proposed system outperform the non-OPA system.

4.2.5 Conclusions

In this paper, we studied the performance of a power allocation in OFDM based AF relaying in two-way cooperative communication with relay selection over Nakagami-m fading channels. It is shown that by using the channel knowledge, the total power of the system can be allocated among sub-carriers at selected relay, user1 and user2. This enables the system to achieve higher performance of BER. The system is simulated for the networks with various number of relays and showed an improved performance. Power allocation system also outperforms the non-power allocation system in all fading environments such as Rayleigh and AWGN (Additive White Gaussian Noise) channel. In summary, the power is used more effectively with enhanced performance.

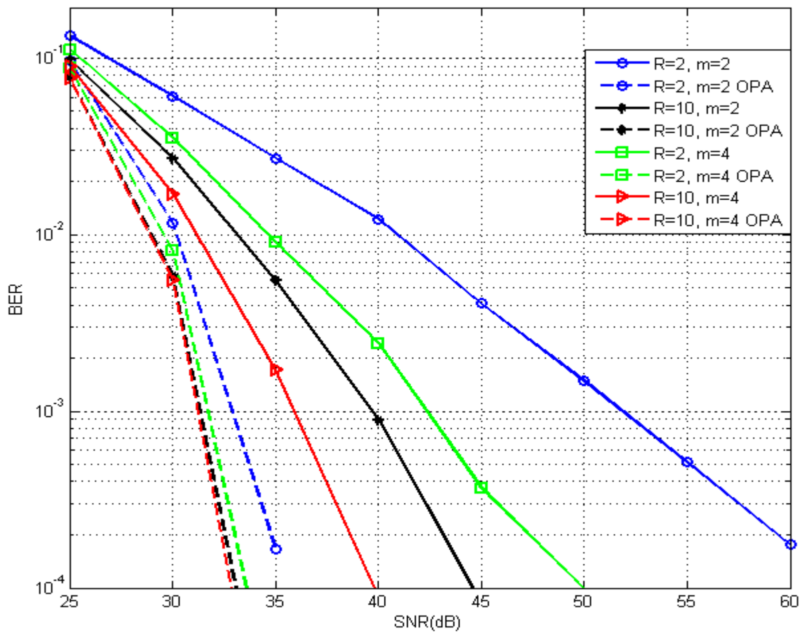

Figure 4.6 The system performance in Rayleigh channel.

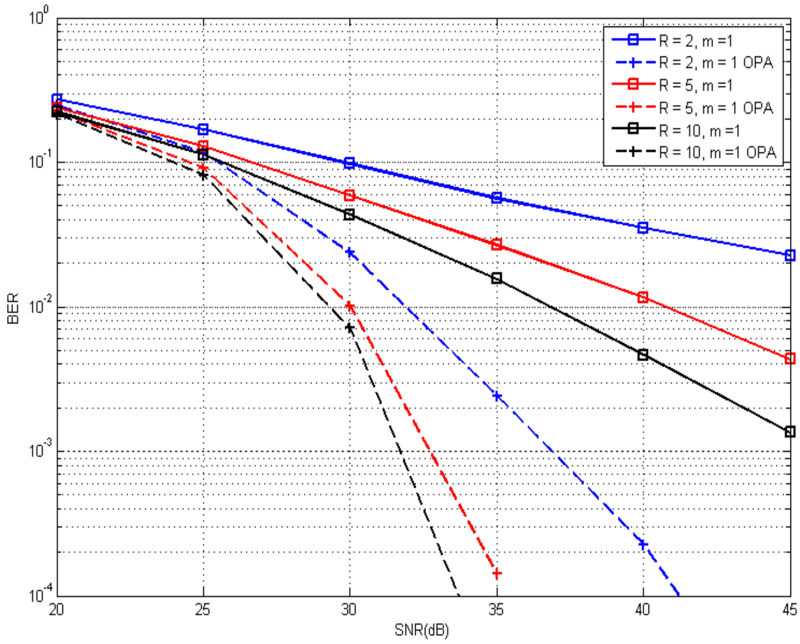

Figure 4.7 The system performance on different network for various *m*.

4.3 MIMO RECEIVERS IN TWO-WAY DF RELAYING

4.3.1 Abstract

In this paper, error performance analysis of two-way cooperative communication system with decode-and-forward (DF) relaying examined over frequency selective Rayleigh fading channels. It is considered that all the nodes in the system are equipped with two antennas. Zero forcing, maximum likelihood, minimum mean square estimator receiver are employed at the nodes. BPSK is used as mapping method. The end user (node) bit error performance is studied. The system is simulated. The simulation plots are provided. The results show that for BPSK mapping maximum likelihood receiver produce better bit error rate performance.

4.3.2 Introduction

The electronic devices communicate through wireless channels increases every day because the wireless communication can be installed easily and it is very cost effective. The recent development enabled wireless network to provide data transmission speed over a Gigabit per seconds. A simple example is that many of us use wireless hardware on the computers to connect to the internet. The speed satisfies us and we do not need worry about boring cables mess around our table. But the wireless communication has some disadvantages too. For example, if a device is located far away from an ad-hoc hub or there are some obstacles between the two communicating device, the communication can be very difficult. Actually one may not connect the network due to very weak signal reception power. What is the solution? Maybe a computer or a device between the hub and the device can help. This is exactly what happens in two-way communication (TWC) (Li, Louie and Vucetic 2010). When there is no direct connection or the connection is very weak, another devices located at midway receives signals, processes it and forwards to destination device. The helping device is known relay. When there is no fix relay device and each device is a relay to others it becomes a cooperative network. TWC is one type of cooperative relaying. In modern TWC, physical layer network coding (PNC) is used (Zhang, Liew and Lam 2006). PNC significantly increases capacity of the transmission by reducing number of time slot required to exchange information into two time slots.

In cooperative two-way relaying the data processing at relay device names the type of protocol. There are two general cooperative protocols; amplify and forward

(AF) and decode and forward (DF) .AF uses the available channel knowledge to amplify the received signal. The amplified signal is sent to the destination later. In DF, the received signal is first decoded into bits. The bits are mapped into symbols again and retransmitted to the destination (Nosratinia, Hunter and Hedayat 2004).

The cooperative system is also known as virtual MIMO. It is well known fact that when the received signal to noise power is low or the signal is distorted badly due to frequency selective fading, the bit error rate (BER) performance becomes very low. MIMO, multi-input multi-output, provides spatial diversity by employing more than one antenna at transceivers (Laneman, Tse and Wornell 2004). Spatial diversity significantly increase the system BER performance without having extra power or bandwidth cost. MIMO cannot be used in small size devices due to lack of spaces required to locate antennas. The antennas must be spaced such that one can make sure there is no correlation on the received signals at different antennas. Since this space cannot be provided, MIMO is not applicable to the small electronic devices. When there is chance of using MIMO, cooperative system can be employed. In CS, the wireless devices let their resources cooperate in order to create a virtual MIMO. The modern system joins the power of MIMO with virtual MIMO (Yu, et al. 2015). That is to say that a device can be a part of MIMO as well as a cooperative system.

The different version of MIMO are single-input (SIMO), multi-input (MISO). SIMO is the same with receiver diversity and MISO is used instead of transmit diversity. The transmit diversity is realized with help of Alamouti code (Alamouti 1998). Multi-path once was very big problem for wireless communication. Thanks to signal combining technics employed at receiver side, the diversity is rather useful now. Selection combiner, maximum ratio combiner and equal gain combiner are three well known combining techniques (Goldsmith 2005).

The recent studies combine MIMO and CS. This type system may employ different type of receivers. In (Gao, et al. 2012), zero forcing receivers in MIMO two-way system is examined. In (Li, Wang and Zhang 2012), MMSE receiver is examined only in MIMO two-way system with three phase communication. There is a need to compare the BER performance of different type of receivers and to the best of our knowledge, there is no single study compares zero-forcing, MMSE and ML in MIMO two-way decode and forward with PNC. Hence, in this study we examined the MIMO based two-way DF with PNC systems' bit error rate performance for three well known receiver types.

The rest of paper is organized as follows. In the next section we introduce a system model in which the receiver models of MIMO as well as CS protocols are given. The section III discusses simulation results and the last section is the conclusion remark.

4.3.3 System Model

We consider three computers as computer one (C1): Transmitting computer, computer two (CR): Relaying computer and computer three (C3): receiving computer. This can be in reverse order too. Actually all the computers do receive and transmit but to make it simple to explain we choose it as given. C1 has to communicate C3 through CR. CR receives the signal from C1 and forwards it to C3 by using DF protocol. This is given as in Fig.4.8. CR is the relaying computer and use DF protocol. The system model is given as in Fig.4.9. As seen in the figure, DF will digitize or restore the signal back to original state and if the distortion on the signal is not much, the signal will be completely restored.

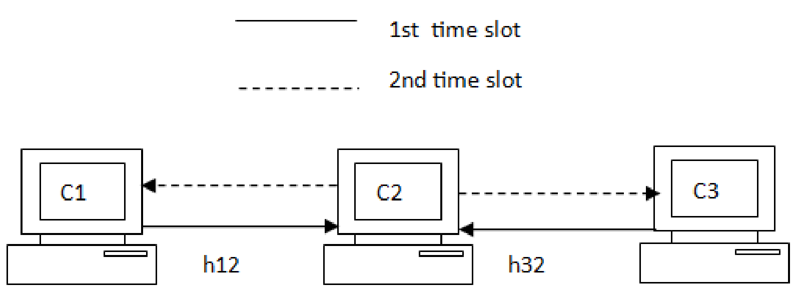

Figure 4.8 The System Model.

In the first time slot, C1 and C3 broadcast to CR and in the second time slot CR broadcast back to C1 and C3. C2 separates two signals with PNC. In this example we consider each computer has wireless transceiver with two antennas.

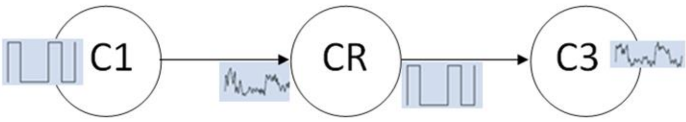

Figure.4.9 DF Protocol.

Assuming a photo is to be transmitted, it will be converted to bits and mapped with binary phase shift keying (BPSK). The BPSK symbol vector is given as $X_n = \{x_1, x_2, ..., x_n\}$.

The symbols of message signal X_n is sent the transmitter antennas at C1 two by two. That means at the first time interval x_1, x_2 and at the second time interval, x_3, x_4, and so on. Since each computer has two antennas, between any two computers, there are available four channels. This can be shown as in Fig.4.10 where, for example, h_{11} means the channel between first antenna of CR and first antenna of C1. In the following, all the channels h_{ij} coefficients (the one causes distortion effect on the signal) have Rayleigh distribution with probability density function of

$$p(z) = \frac{z}{\sigma^2} e^{-\frac{z^2}{2\sigma^2}}, z \geq 0$$

and $n_{Ci_i j}$ is the independent and identically distributed additive white Gaussian noise with normal distribution.

The received signal at first antenna of CR from C1 can be written as

$$\gamma_1 = h_{11}.x_1 + h_{12}.x_2 + n_{C1_1 1}$$

The received signal at second antenna of CR from C1 can be written as

$$\gamma_2 = h_{21}.x_1 + h_{22}.x_2 + n_{C1_2 1}.$$

The last two equations can be put in matrix notation as

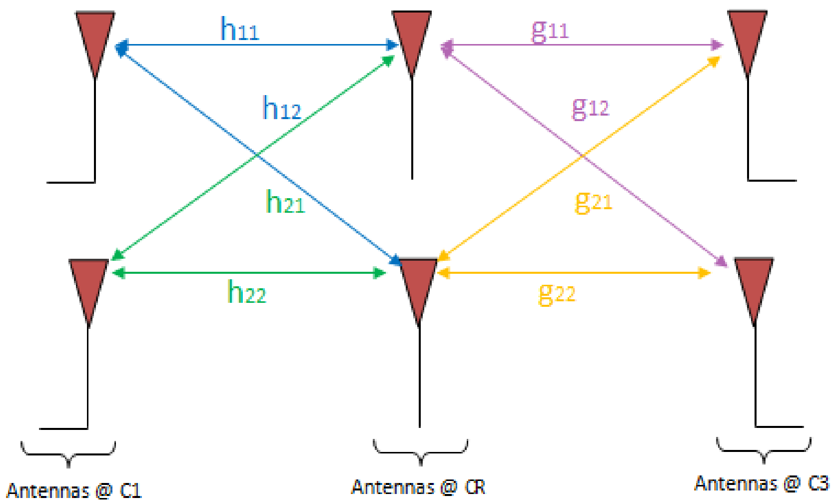

Figure 4.10 Two-way with MIMO with each node having two antennas.

$$\begin{bmatrix} \gamma_1 \\ \gamma_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{C1\_1} \\ n_{C1\_2} \end{bmatrix}.$$

The received signal at first antenna of CR from C3 can be written as

$$\lambda_1 = g_{11} y_1 + g_{12} y_2 + n_{C3_1 1}.$$

The received signal at second antenna of CR from C3 can be written as

$$\lambda_2 = g_{21} y_1 + g_{22} y_2 + n_{C3_2 1}.$$

The last two equations can be put in matrix notation as

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} n_{C3\_1} \\ n_{C3\_2} \end{bmatrix}.$$

The signal sum up at antennas of C3 given as

$$\begin{bmatrix} h_{11}\, h_{12} \\ h_{21}\, h_{22} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\begin{bmatrix} g_{11}\, g_{12} \\ g_{21}\, g_{22} \end{bmatrix}\begin{bmatrix} y_1 \\ y_2 \end{bmatrix}+\begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

The C3 can separate the signals with PNC . Hence the obtained signals re-encoded and send to destination. The destination is used to indicate C3 if the sender is C1 or vice versa. The arrived signal from C1 at C3 can be given as

$$\begin{bmatrix} \hat{\lambda}_1 \\ \hat{\lambda}_2 \end{bmatrix}=\begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix}\begin{bmatrix} \hat{y}_1 \\ \hat{y}_2 \end{bmatrix}+\begin{bmatrix} n_{C31} \\ n_{C32} \end{bmatrix}.$$

where, we assume the channel g_{ij} is stable for two time slot and $\hat{y}_i$ represent the re-encoded symbols sent from C1.

Below three most used receivers models are explained used to decode received signal at the destination.

Zero forcing receiver:

The receiver at the relaying computer has the data sent from C1 and separated from the one C3 can be given, in short form, as $\gamma = Hx + n$. The pseudo inverse of H is given $W = (H^H H)^{-1} H^H$ where

$$H^H H = \begin{bmatrix} |h_{11}|^2+|h_{22}|^2 & h^*_{11}h_{12} + h^*_{21}h_{22} \\ h^*_{12}h_{11} + h^*_{22}h_{21} & |h_{12}|^2+|h_{22}|^2 \end{bmatrix}$$

where the off diagonals are not zero, hence zero-forcing can experience noise amplification $(.)^H$ is hermitian operator).

$$\gamma = (H^H H)^{-1} H^H Hx + (H^H H)^{-1} H^H n = Ix + \tilde{n} = \tilde{x}$$

where, $\tilde{x}$ is estimated symbol at the relaying computer. $\tilde{x}$ is sent to the destination terminal. The received symbols at the destination are given as $\tilde{\gamma} = G\tilde{x} + n$. The zero forcing receivers is used once again at the destination and the estimated symbols can be given as

$$\tilde{\gamma} = (G^H G)^{-1} G^H G x + (G^H G)^{-1} G^H n = I\tilde{x} + \tilde{n} = \tilde{\tilde{x}}\$.$$

MMSE receiver:

The zero-forcing receiver may have poor performance due to noise amplification. This problem is handled in MMSE. Given that $\gamma = Hx + n$ is the received at relay, MMSE minimize $E\left\{[W\gamma - x][W\gamma - x]^H\right\}$ where $W = [H^H H + N_0 I]^{-1} H^H$ which acts as zero-forcing receiver when the noise is zero.

This gives the estimated symbol $\tilde{x}$ which is sent to the destination terminal and received again with MMSE receiver given as $\tilde{\gamma} = G\tilde{x} + n\$.$. The MMSE receiver seeks the minimize $E\left\{[W\tilde{\gamma} - \tilde{x}][W\tilde{\gamma} - \tilde{x}]^H\right\}$ where $W = [G^H + N_0 I]^{-1} G^H$ and the estimated symbols $\tilde{\tilde{x}}$ is found.

ML receiver:

The maximum likelihood receiver looks for $\bar{x}$ to minimize $\epsilon = |\gamma - H\bar{x}|$. Since the BPSK is used, there are four possible options for $\bar{x}$ which are [(1,1),(-1,-1),(1,-1),(-1,1)] The ϵ for all values of $\bar{x}$ is given as

$$\epsilon_{x_i,x_j} = \left\| \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} - \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_i \\ x_j \end{bmatrix} \right\|^2$$

The estimated transmit symbols are chosen based on $min(\epsilon_{i,j})$ which is, for example, if the minimum is $\epsilon_{1,1}$, then the symbols [1, 1] are transmitted.

The estimated symbols retransmitted again to destination and received with ML as explained above.

4.3.4 Simulation Results

In Fig.4.11, bit error rate performance of the proposed system for three receiver is given at relay station. There is also provided analytic results SIMO and SISO systems for comparison. It is seen that zero forcing perform like SISO which can be considered low performance taking into account that two antennas are located at the receiver. When we apply MMSE receiver instead of zero forcing, the performance increases. The best results are offered by ML receiver. For example the ML receiver shows 20 times better performance at 10*dB*.

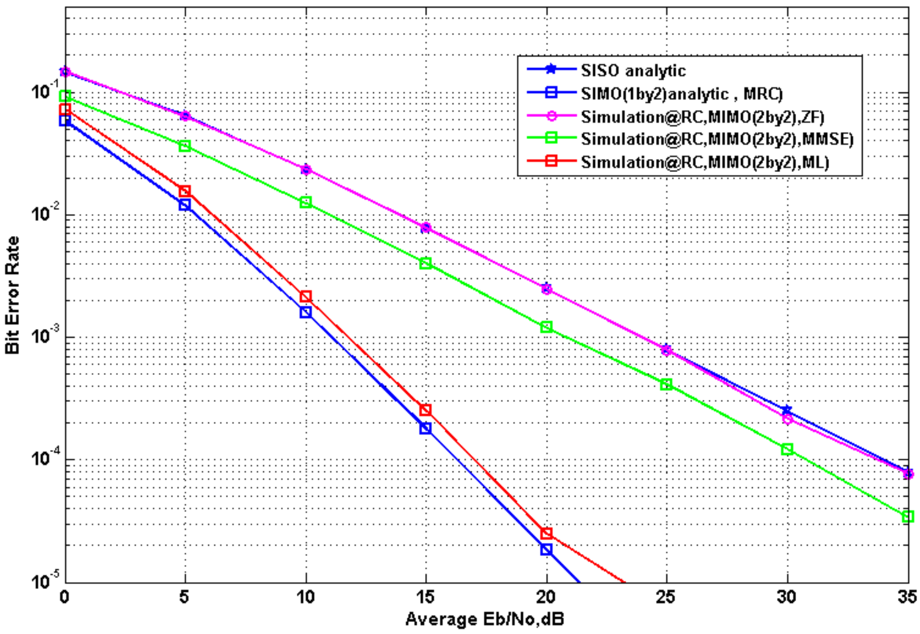

Figure 4.11 Three receiver's performance at the Relay.

In Fig.4.12 bit error rate performance of the proposed system is given at destination station. The performance degrades for all receivers at D. The ML performance at 20dB is 10^{-4} meaning that one bit error in ten thousand bit which is in acceptable level.

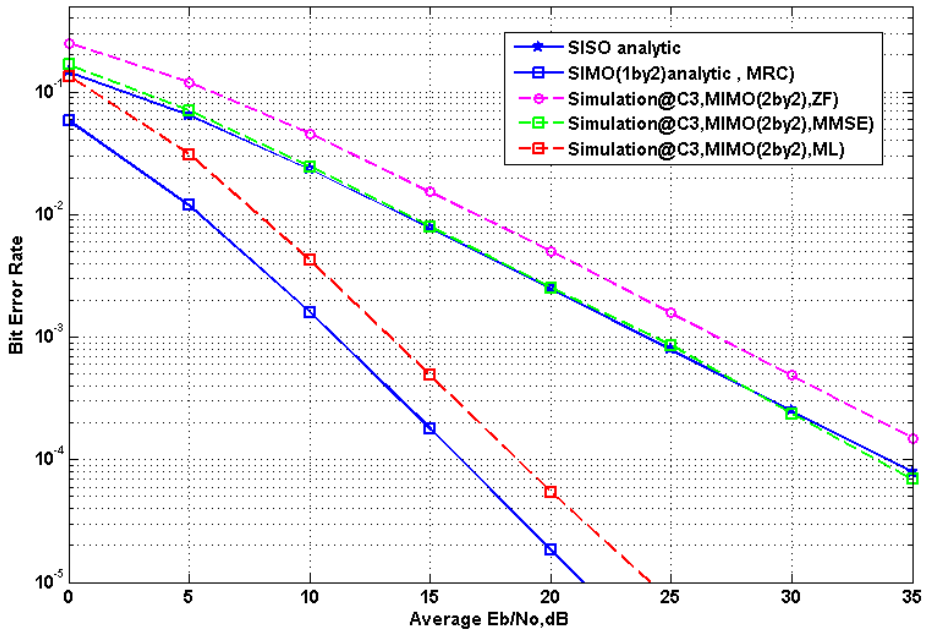

Figure 4.12 Three receiver's performance at the destination.

The last figure shows the performance of relay and destination node together for giving perspective in performance degrading from relay station to destination station. In the figure, it is clearly seen that ML in MIMO with 2 by 2 antennas can achieve the SISO direct transmission.

4.3.5 Conclusions

Two-way communication system with MIMO is implemented over Rayleigh fading channels where we have assumed each node has two antennas. By employing MIMO, first of all the data transmission speed is doubled since two antennas send two different symbols for a given time. Considering the ML performance at the destination, it is seen that the last station will have the bit error rate as low as relay station of SIMO system with the diversity order of two. This shows that by employing MIMO, two-way communication can offer a healthy communication for a node which cannot receive service directly.

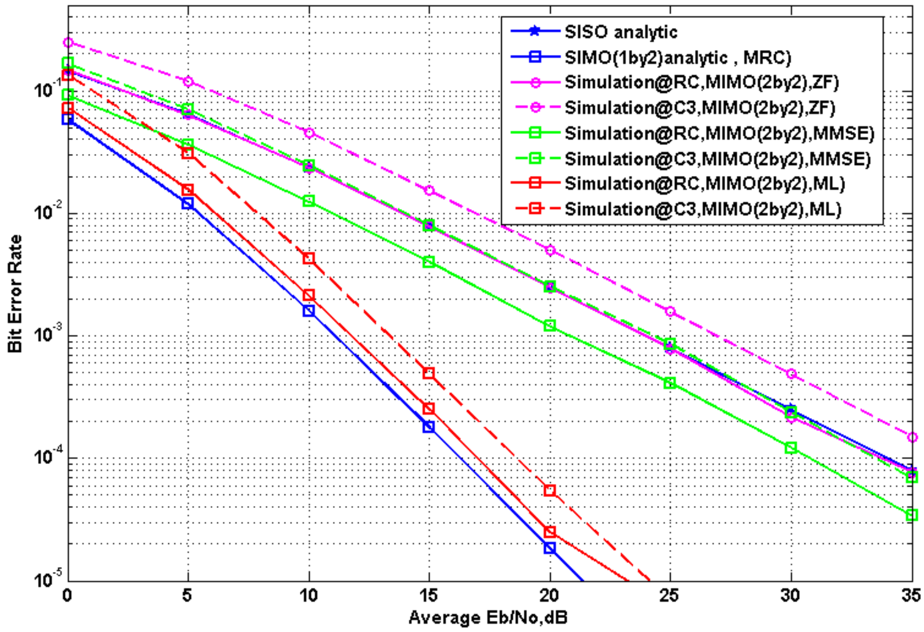

Figure 4.13 Three receivers’ performance at the Relay and Destination.

CHAPTER 5

CONCLUSION

In this chapter, we give a summary of work done in this thesis chapter by chapter and emphasize some important contributions done through research.

The first chapter of this thesis gives a brief development of wireless communication from the beginning to today. In the chapter it is stated that there has been great developments in the wireless communication in the last decays hence it became more reliable, cheap, fast, secure, mobile, and affordable. In small places it has been replaced with wired communication. As a cellular network, it has overtaken the reputation of public switched network. But the demand also increased dramatically with the development of electronic consumer market. Hence, the research for better wireless communication let the new research areas appear. One of these researches is cooperative communication based system. The last decay also witnessed the great contribution of OFDM based technology to wireless communication. It is also showed in the chapter that OFDM based cooperative system is important research topic by citing the most important related research papers in chronological order.

The second chapter explains the cooperative communication starting by giving its historical development. It clearly points out the differences of modern relaying with initial relaying techniques. The types of cooperative communications are explained in the chapter. The very important topics, network coding and physical network coding, are given in detail. The basic protocols explained with supportive figures and formulas. Again in the chapter we explained the OFDM with its historical development. The implementation of OFDM with FFT is given which is considered a corner stone of OFDM technology. The cyclic prefix and its relation to the inter symbol interference is explained. In this chapter we also try to establish the relationship between MIMO and cooperative system, hence we firstly explained diversity in wireless communication, and the receivers such as zero forcing, MMSE, used at the receivers with their related mathematical backgrounds.

The third chapter is completely dedicated to a link adaptive system. In the chapter, it is shown that the most important problem of decode and forward cooperative system, error propagation to the destination due to low SNR at the relay, can be eliminated to boost the performance of the system at the expense of SNR feedback from the destination to relay. Furthermore, it is shown that the system performance can be enhanced by using OFDM. The proposed systems bit error derivation is provided for Rayleigh fading channel and the simulation is given for various Nakagami-m channels.

The fourth chapter is dedicated to resource allocation in cooperative system. The resource allocation is a large and important topic for cooperative communication. It can include relay selection, power allocation for source, relay, and destination node under total power consumption, deciding the type of receivers to be used in the system, the power allocation to the links or the sub-channels. In the chapter we have provided thee studies. The first study considers relay selection. The best relay is selected in different networks and their performance is compared. It is seen that the diversity order can be provided with relay selection as well. In the same study we also consider various positions of relay channel and its effect the system performance. The second study considers the power allocation to the sub-carriers of OFDM based cooperative system. The simulation results shows that by allocation power in given manner the system performance can be enhanced. The last study in this chapter presents a MIMO employed cooperative system to examine various receivers' performance. The simulation results show ML receivers performance is the best yet it may be cumbersome for higher order modulation scheme.

The future studies of this thesis can be extended to resource allocation in MIMO and OFDM based cooperative system with multiuser.

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APPENDIX A

DECLARATION STATEMENT FOR THE ORIGINALITY OF THE THESIS, FURTHER STUDIES AND PUBLICATIONS FROM THESIS WORK

A.1 DECLARATION STATEMENT FOR THE ORIGINALITY OF THE THESIS

I hereby declare that this thesis comprises my original work. No material in this thesis has been previously published and written by another person, except where due reference is made in the text of the thesis. I further declare that this thesis contains no material which has been submitted for a degree or diploma or other qualifications at any other university.

Signature:
Date: March 10, 2016

A.2 FURTHER STUDIES

Further studies related to this thesis work can be done in the following areas:

(a) Two-way OFDM based communication with USRP
(b) OFDM based cooperative system with multiuser.

A.3 PUBLICATIONS FROM THESIS WORK

<u>Academic Journals</u>

- Yıldırım, M., İlhan, H., (2016, February), “OFDM Based Link Adaptive One-Way DF Relaying”, *International Journal of Electronics and Communications*

- Yıldırım, M., Ilhan, H., (2015, May), “Link adaptive one-way DF relaying with OFDM”, *Material Todays Proceedings.*

- Yıldırım, M, Ilhan, H. (2015, May), “Power Allocation in OFDM based two-way cooperative system with relay selection”, *Material Todays Proceedings.*

<u>Conference Proceedings</u>

- Yıldırım, M. & Ilhan, H. (2014, September), “Relay selection in OFDM based two-way cooperative systems”, *IEEE 11th International Conference on Electronics and Computation, (IEEE ICECCO), Abuja, Nigeria.*

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EDUCATION

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Scientific preparation program for engineering in electrical and electronic, Fatih University, Istanbul, Turkey, June, 2009

B.S., Faculty of Technology, Computer and Electronics, Marmara University, Istanbul, Turkey, June 2001

PROFESSIONAL EXPERIENCE

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- Received full university scholarship for graduate studies in Electrical and Electronics Engineering at Fatih University, (2009 - 2011)

PUBLICATIONS

Academic Journals

- Mete Yıldırım, Haci Ilhan, "*OFDM based link adaptive one-way DF relaying, AEU - International Journal of Electronics and Communications*", Volume 70, Issue 5, May 2016, Pages 657-661, ISSN 1434-8411, http://dx.doi.org/10.1016/j.aeue.2016.02.001. (http://www.sciencedirect.com/science/article/pii/S1434841116300425)

- Mete Yildirim, Hacı İlhan, "*Link Adaptive One-Way Decode and Forward (DF) Relaying With Orthogonal Frequency Division Multiplexing (OFDM)*", Materials Today: Proceedings, Volume 3, Issue 5, 2016, Pages 1291-1296, ISSN 2214-7853, http://dx.doi.org/10.1016/j.matpr.2016.03.073. http://www.sciencedirect.com/science/article/pii/S2214785316002856)

- Mete Yildirim, Hacı İlhan, "*Power Allocation in Orthogonal Frequency-division Multiplexing (OFDM) Based Two-way Relaying with Relay Selection*", Materials Today: Proceedings, Volume 3, Issue 5, 2016, Pages 1242-1247, ISSN 2214-7853, http://dx.doi.org/10.1016/j.matpr.2016.03.066 (http://www.sciencedirect.com/science/article/pii/S2214785316002789)

Conference Proceedings

- Yıldırım, M. & Ilhan, H. (2014, October), *"Relay selection in OFDM based two-way cooperative systems",* IEEE 11th International Conference on Electronics and Computation (IEEE ICECCO), Abuja, Nigeria.

- Yıldırım, M. (2015, September), *"OFDM based communication system using USRP"*, IEEE ICECCO, Almaty, Kazakhstan.

AFFILIATIONS

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TECHNICAL SKILLS

- Programming languages: Basic, C, Pascal
- Analytical and statistics programs: Mathematica, MatLab, Multisim, Pspice
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- Operating systems: Microsoft Windows 7, Linux
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