Destination Cooperation in Interference Channels

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ABSTRACT

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Multiple Input Multiple Output (MIMO) techniques are used to exploit spatial diversity and to achieve high bit rates required for emerging multimedia applications. To achieve this spatial diversity, more than one antenna have to be collocated at the transmitter and/or receiver nodes and the separation between those antenna has to be more than half a wavelength to ensure that the signals will experience different channel fading coefficients. One major drawback of this technique which makes it almost impossible to implement on handheld devices is the dimension of these devices.

Cooperative communication can be used to achieve the diversity gains typical of MIMO without the need for multiple antennas on the mobile units. Diversity is attained through collaboration between nodes in the wireless network. In wireless communications, cooperative diversity improves throughput and reliability. To effectively combat multipath fading in wireless networks, we develop energy efficient protocols that employ some cooperation among receiving nodes.

Motivated by the very promising results of cooperative diversity for both uncoded and coded systems as well as the substantial demand for higher data rates; in this thesis, we investigate the 2-user and 3-user destination cooperation in interference channels. We develop a collaboration protocol for the 2-user and 3-user models which is based on the fact that the information presents at one destination node can help in increasing the chance of correctly decoding the previously not decodable information at another destination node. Furthermore, we introduce network coding in the 3-user model and we show that network coding achieves further substantial gain. We demonstrate that the 2-user case outperforms the baseline scheme using orthogonal channels by far. This is due to the cooperative communication. In the cooperative scheme, the receiver nodes in the first time slot, decode the received information from both sources while in the second time slot they cooperate. The scheme provides both diversity and coding gain. Furthermore, we show that an enhanced scheme which exploits the unused information available at each destination node improves the outage probability.

We present the simulation results of various scenarios that illustrate the efficiency of employing such techniques with and without channel coding. We show how the SNR required for obtaining a certain frame error rate varies with the distance between destination nodes. We also show a comparable analysis between the 2-user and 3-user destination cooperation in interference channels on one hand and the baseline orthogonal scheme on the other hand.

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LIST OF ACRONYMS

AWGN	Additive White Gaussian Noise
AF	Amplify and Forward
BER	Bit Error Rate
bps	bits per second
BPSK	Binary Phase Shift Keying
BS	Base Station
CDMA	Code Division Multiple-Access
CF	Compress and Forward
CLT	Central Limit Theorem
dB	decibel
DBL	Data Block Length
DC-IC	Destination Cooperation in Interference Channels
DF	Decode and Forward
DVB	Digital Video Broadcasting
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FDMA	Frequency division multiple access
EF	Estimate and Forward
FER	Frame Error Rate
HK	Han and Kobayashi
IC	Interference Channels
ICCE	International Conference on Consumer Electronics
IEEE	Institute of Electrical and Electronics Engineers

iid	independent and identically distributed
ISI	Inter Symbol Interference
LLR	Log Likelihood Ratio
LTE	Long Term Evolution
MAC	Multiple Access Channel
MAP	Maximum A posteriori Probability
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MS	Mobile Station
NC	Network Coding
OFDM	Orthogonal frequency division multiplex
PDA	Personal Digital Assistant
PDF	Probability Density Function
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RSC	Recursive Systematic Convolutional
SIC	Successive Interference Cancellation
SNR	Signal to Noise Ratio
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TS	Time Slot
WLAN	Wireless Local Area Network
XOR	exclusive OR

LIST OF SYMBOLS

${\alpha_k}^{LM}$	Forward recursion
α_{PL}	Path loss coefficient
$\alpha_n(t)$	Attenuation of the n^{th} path
${\beta_k}^{LM}$	Backward recursion
${\gamma_k}^{LM}$	Branches transition probability
$\bar{\gamma}$	Average received SNR
γ_{min}	Minimum SNR
γ	Instantaneous received SNR
λ	Wavelength of the signal
$\tau_n(t)$	Delay
$\theta_n(t)$	Phase of the n^{th} path
$\sigma^2 = \frac{N_0}{2}$	AWGN variance
C_{AWGN}	Capacity of an AWGN channel
C_{fading}	Instantaneous channel capacity in fading environment
$CN(0, N_0)$	Complex Gaussian Random variable with zero-mean and variance N_0
d	Distance between source and destination
d_0	Reference distance
G_N	N^{th} Generator matrix
d_{ij}	Distance between node i and node j
d_{min}	Minimum Hamming distance
$E[x]$	Expected value of x
E_b	Bit energy

$erfc(x)$	Complimentary error function
E_s	Symbol energy
f_0	Coherent bandwidth
f	Transmitted signal bandwidth
f_c	Carrier frequency
f_d	Doppler spread
G_t	Transmitter antenna gain
G_r	Receiver antenna gain
h	Rayleigh random variable
h_{ij}	Complex channel coefficients from node i node j
$h(t)$	Impulse response
$\|h\|^2$	Chi-square random variable
L	Number of independent transmission paths (Diversity order or branches)
n	Path loss exponent
N	Noise variance
N_t	Number of transmit antenna
N_r	Number of received antenna
P_b	Probability of bit error
P_M	Puncturing matrix
$p(e\|s)$	Conditional Gaussian PDF
$pg_{(ij)}$	Path gain from node i to node j
$P_r(d)$	Received power at distance d
$P_r(d_0)$	Received power at reference distance d_0
P_t	Transmit power

P_e	Error probability
$p(e\|s)$	Conditional Gaussian PDF
P_{outage}	Outage probability
r	Code rate
$r(t)$	Received signal
$r_b(t)$	Received baseband signal
R	Transmission rate
(R_1, R_2)	Rate pairs for the standard Interference channels
t	Time
T_c	Channel coherence time
T_m	Excess delay between the first and last received component
T_s	Symbol duration
V	Relative velocity
$x(t)$	Transmit band pass signal
$x_b(t)$	Baseband signal
U_j	Public part of the message in HK achievable rate region at rate S_j
V_j	Private part of the message in HK achievable rate region at rate T_j
$\hat{X}_i$	Decoded message at node i
$X(t)$	Transmitted signal at time t
$Y(t)$	Received signal at time t
$Z(t)$	Zero-mean AWGN process with variance N

1 INTRODUCTION

In wireless communication systems, the broadcast nature of electromagnetic waves leads to multipath propagation of wireless signals which consequently causes variations in received signal strength as a function of transceiver location and frequency. Combined with transceiver motion, these effects produce wireless channel variations in space, frequency and time. Those variations are called fading. Diversity techniques for mitigating and exploiting multipath fading are essential to improving the performance of wireless communication systems and networks

The relaying process in cooperative wireless communication is crucial for overcoming the path loss experienced due to the large distance between the source and destination. The broadcast nature of a wireless communication channel is exploited by receiving the same copy of the message over the destination nodes. The closest user node (other than the destination) that is able to decode the message correctly can help the destination.

To achieve similar spatial diversity gain to MIMO systems without having multiple collocated antennas at each node, one can achieve cooperative diversity through additional nodes relaying information between source and destination nodes.

There are two basic modes of operation for the cooperating node [17]: amplify and forward (AF) where the cooperating node just amplifies the signal and forwards it to the destination, and decode and forward (DF) where the cooperating node decodes the message then re-encodes, modulates and forwards it to the destination. Recently, other protocols like estimate and forward (EF) [18] and compress and forward (CF) [19] have been shown to improve system performance.

The earliest work on interference channel (IC) was initiated by Shannon [38], and then continued further by Ahlswede [9]. However, the problem of determining the capacity of an IC has been an open problem for the past thirty years.

In [7], the authors are assuming that the channel is full duplex and transmission is occurring in the same band at the same time. Based on the eminent paper by Han and Kobayashi [13], the authors in [7] extended their information theoretic work on the sum rates of the channels and the gain achieved from cooperation.

1.1 MOTIVATION

Interference is a major aspect in wireless communication when multiple sources are communicating with their respective destinations over a shared channel. There has been interest and intensive research recently in exploring strategies for interference mitigation via cooperation between the nodes in a wireless network [51], [52], [53], [54].

Recent developments in handheld devices, that combine data, audio and video applications, have substantially increased the demand for higher data rates, lower power reliable communications over wireless channels. Yet many technological challenges such as fading remain in designing robust wireless networks that deliver the necessary performance to support emerging applications.

Spatial diversity technique is the most efficient way to increase data rates and reliability in wireless communications. This technique that employs several collocated antennas at both ends of the wireless link to form a multiple input multiple output (MIMO) system provides full diversity gain if these antennas are properly separated [6], [50] (more than half a wavelength in a uniform scattering environment [49]). The drawback of this technique resides in the size of the handheld devices which makes it almost impossible to realize such technique at an affordable price. This problem has motivated researchers to look for another technique, which is called cooperative diversity that achieves similar diversity gain to MIMO system [30]. Cooperative diversity benefits from the fact that handheld users are randomly moving in the city areas, if these mobile devices communicate with each other, they can form a virtual MIMO system [25], [26], [27].

1.2 MAIN CONTRIBUTION

Our main contribution in this thesis is as follows:

We have developed a destination cooperative framework for 2-user and 3-user destination cooperation in interference channels.

In the 2-user model, the transmission cycle of one frame consists of two phases: the broadcast phase and the cooperation phase. In the broadcast phase, the two source nodes transmit their information to both destination nodes. Then, if the destination node is unable to decode the message from its respective source node, or it is just able to decode the other node's message it remains silent during the cooperation phase, waiting for potential cooperation from the other destination node. If the destination node is able to decode the message from both source nodes, in this case, the other node's information is transmitted to the other destination node during the cooperation phase (basic or "egoistic" cooperation mode). One way to enhance the cooperation is by exploiting the fact that the destination node is able to decode its information but not the other's node. In this case, the destination node is able to cooperate by transmitting its information to the other destination node in the cooperation phase (enhanced cooperation mode). The information exchanged between destination nodes during the cooperation phase is most probably received error free because the links between cooperating nodes are interference free and in general closer to each other's. Therefore, in the enhanced cooperation mode this received information can help the destination node to reliably perform again successive interference cancellation on the received signal that was transmitted during the broadcast phase and decode its own information. This improves the overall performance of the system.

In 3-user model, the transmission cycle consists of three phases: the broadcast phase and two cooperation phases. In the broadcast phase which is similar to the one in 2-user model, the three source nodes transmit their information to the three destination nodes. Then, one of the $(2^3)^3 = 512$ cases is presented at the destination nodes. This is due to the fact that there are three messages and three destination locations, making an overall 3x3=9 message-location pairs. Presence or absence of a message at a given location results in $2^9 = 512$ cases.In the cooperation phases, we also consider the basic and the enhanced cooperation schemes. In the basic scheme, the information is exchanged between destination nodes during both cooperation phases based on their availability at the destination nodes and based on the constraint that only two transmissions are allowed during the cooperation phase. This leads to a high outage probability. In the enhanced cooperation scheme, the main focus is on how to reduce the number of cases that are considered as outage to very few which leads to significant performance improvement in the overall system. Furthermore, we introduce network coding in both basic and enhanced schemes.

We simulate the performance of the above models with various flavors. We considered channel and network coding in which we implement turbo codes and the simple XOR operation respectively. We illustrate the impact of the number of decoding iterations, the puncturing scheme; the data block length and the interleaver type on the frame error rate. We show how the total SNR varies with the distance between destination nodes. Moreover, we demonstrate the impact of network coding on the overall performance of the system. Additionally, we show a comparison between the 2-user, 3-user and the baseline models. We also compare various scenarios in which nodes are located at different distances from each other. The simulation results show that the diversity gain is fully maintained in the 2-user model while is degrading with the SNR in the 3-user model. We show as well the gain of the network coding scheme. We also show the advantage of having more users cooperating together in a cooperative network.

1.3 THESIS ORGANIZATION

The remainder of this thesis is organized as follows:

In Chapter 2, we present a review on wireless communication in fading environments, capacity of interference channels, diversity techniques, turbo coding and network coding.

In Chapter 3, we present the analysis and the simulation results on the 2-user destination cooperation in an interference channel. We introduce a new cooperation scheme and we compare the results with the basic cooperation and the baseline schemes. We illustrate the effect of the number of decoding iterations, puncturing scheme, data block length and the interleaver type on the performance of the system.

In Chapter 4, we extend the work to 3-user destination cooperation in interference channels. We develop an enhanced cooperation scheme that reduces the overall outage probability and uses the available cooperation time slots efficiently. We consider various scenarios where the distances between different nodes reflect practical cases. We demonstrate the advantage of using network coding. We show a performance comparison between the orthogonal scheme, 2-user and 3-user destination cooperation in interference channels.

In chapter five, we summarize the contribution to the thesis and we suggest further future research directions.

1.4 PUBLICATIONS

Boulos Wadih Khoueiry, M. Reza Soleymani, "Destination cooperation in interference channels" IEEE International Conference on Consumer Electronics, accepted, Jan 2012.

2 Literature Review and Background

In this chapter, we present the fundamental work and literature review of wireless communication in fading channels. We start by an introduction on the wireless channels modeling, the performance analysis of a simple communication model in both AWGN and Rayleigh block fading channels. Then we present a brief overview on the capacity of the Gaussian interference channel. We continue on the diversity techniques to combat fading then; we briefly introduce turbo coding, network coding and nested codes.

2.1 Wireless Channels modeling

In mobile communication systems, a wireless channel generally suffers from large scale and small scale fading (variations of the characteristics of the channel over time and frequency). Additionally, interference from other nodes broadcasting in the same spectrum band and noise generated at the destination node cause significant distortions. Large scale fading is attributed to path loss which is due to the large distance between source and receiver nodes, and shadowing which is observed when moving at a speed greatly higher than the wavelengths. Small scale fading is a random effect observed in the temporal and spatial dimensions which is categorized as slow fading versus fast fading and flat fading versus frequency selective fading. In this section, we describe the major channel distortions affecting wireless transmissions.

Thermal noise is generated at the destination by the thermal agitation of electrons in the circuit [46]. Noise is generally modeled as additive (adds up to the signal) white (flat power spectral density over the bandwidth) Gaussian distributed (due to the central limit theorem and the fact that noise is the cumulative result of contributions from a large number of independent sources). The AWGN channel model in baseband form is given as

$$\boldsymbol{Y}(t) = \boldsymbol{X}(t) + \boldsymbol{Z}(t) \tag{2.1}$$

Where $X(t)$ is the transmitted signal, $Y(t)$ is the received signal at the destination and $Z(t)$ is a zero-mean AWGN process with variance N.

2.1.1 FADING CHANNELS

The radio signal propagates from the transmitter to the receiver via multiple different paths due to the obstacles and reflectors existing in the wireless channel. Figure 2.1 illustrates this multipath propagation model which arises because the propagation signal reflects off, refracts through and diffuses around objects in the channel environment.

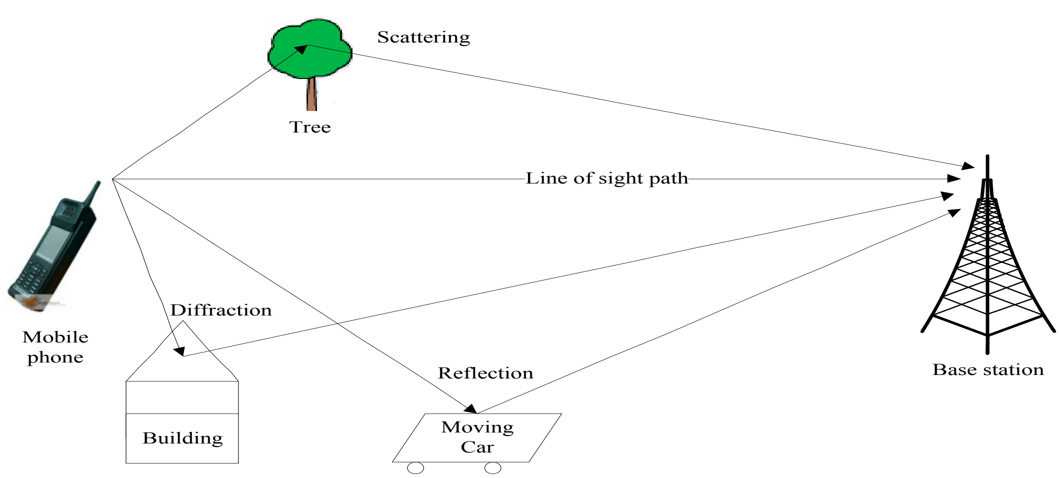


Figure 2.1 Typical mobile channel illustrating Multi-path propagation

The multiple copies of the transmitted signal might add constructively at the receiver which results in increasing the SNR or destructively in decreasing the SNR. This phenomenon is called fading in wireless channels which can be categorized as Large and small scale fading [47, 48].

Figure 2.2 illustrates a typical received signal behavior in mobile communication channel; when the signal falls below its mean level, the resulting signal fades and when the received signal deeply drops below the average level, the system performance greatly degrades and therefore the channel is in deep fade.

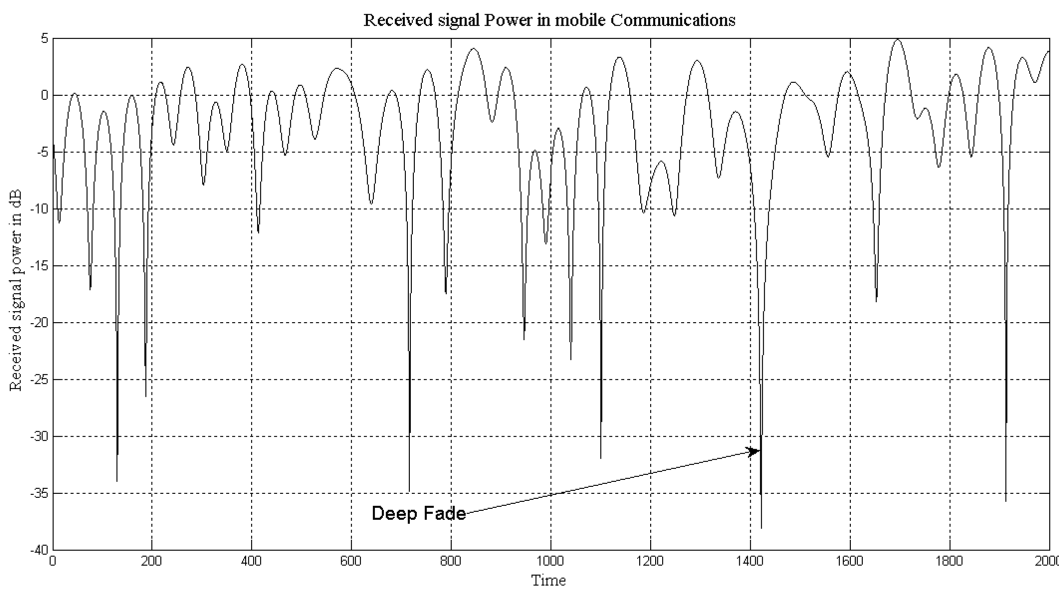


Figure 2.2 Typical behavior of the received signal in mobile communications

- **Large scale fading channels**

The large scale fading represents the average signal power attenuation over distance between the source and destination, called propagation path loss, or scattering from prominent terrain contours between the transmitter and the receiver, called shadowing [4]. Shadowing is observed when moving over large geographic areas and the receiver is often represented as being shadowed by such prominences. Large scale fading is considered constant in time, for a specific non changing environment, distance and frequency.

In practical indoor and outdoor radio channels, the average signal power decays with distance d and path loss exponent n greater than two. The free space transmission formula of Friis permits to compute the received power, $P_r(d)$, at the destination when the source transmits with power P_t as [4]

$$P_r(d) = P_t.\left(\frac{\lambda}{4\pi d}\right)^n.G_t.G_r = \alpha_{PL}P_t \tag{2.2}$$

where G_t and G_r are the gains of the transmitter and receiver antennas, λ is the wavelength of the signal, and d is the distance between source and destination. The path loss exponent depends on frequency, antenna height, and propagation environment and ranges from 2 (free space propagation) to 6. The term $\alpha_{PL} = G_t.G_r.\left(\frac{\lambda}{4\pi d}\right)^n$ is called the path loss coefficient. At distance d, the received power is related to the power received at a reference distance, d_0, and received power at reference distance, $P_r(d_0)$, by

$$P_r(d) = P_r(d_0).\left(\frac{d_0}{d}\right)^n. \tag{2.3}$$

Table 2.1 illustrates the typical path loss exponents for various environments [4].

Environment	Path loss exponent
Free Space	2
Urban area cellular radio	2.7 to 3.5
In building line of sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Table 2.1 path loss exponent for various environments

Figure 2.3 illustrates the normalized power, in dB, for various values of the path loss coefficient n.

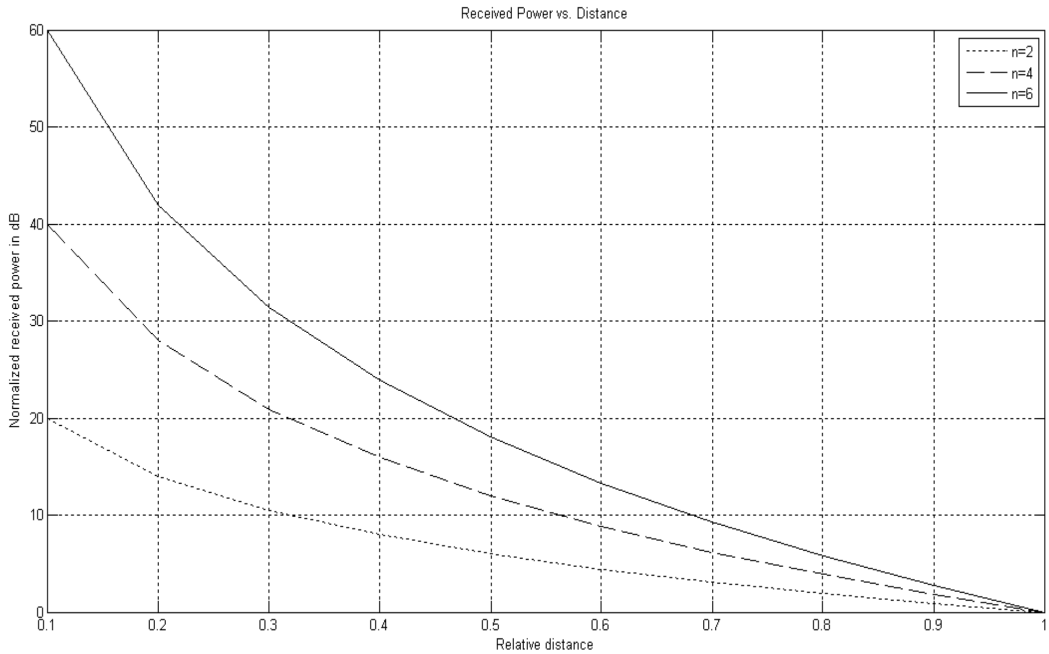


Figure 2.3 Normalized received power in dB, $\mathbf{10\ log_{10}}\left(\frac{P_r(d)}{P_r(d_0)}\right)$

The effect of large scale fading on the transmitted signal is modeled as multiplicative coefficient and the channel model in equation (2.1) is modified as

$$\boldsymbol{Y}(t) = \sqrt{\frac{P_r(d)}{P_t}}\ \boldsymbol{X}(t) + \boldsymbol{Z}(t)\ =\ \sqrt{\alpha_{PL}}\ \boldsymbol{X}(t) + \boldsymbol{Z}(t) \tag{2.4}$$

One can define the instantaneous SNR of the received signal $\boldsymbol{X}(t)$as the ratio of the received signal power and the noise power, as given by

$$\gamma = \frac{P_r(d)}{N} = \alpha_{PL}.\frac{P_t}{N} \tag{2.5}$$

where N is the noise variance. The term $\frac{P_t}{N}$ is sometimes called transmit SNR.

- **Small scale fading channels**

Small scale fading describes the rapid variations of the amplitude and phase of a radio signal over a short period of time and distance. Fading is caused by interference between two or more versions of the transmitted signal which arrives at the receiver.

Multipath in the radio channel which results in small scale fading can be visualized in rapid changes in signal strength over small time interval and random frequency modulation due to varying Doppler shifts on different multipath signals and time dispersion caused by multipath propagation delay.

In addition to the multipath propagation, other factors that influence small scale fading are speed of the mobile, speed of surrounding objects and transmission bandwidth of the signal [4].

- **Flat fading versus frequency selective fading**

Assume that a narrow pulse is transmitted from the source. Because of the multipath nature of the wireless channel, the destination receives a sequence of delayed pulses of various magnitude and delay as shown in Figure 2.4 (Spreading of the impulse in time). For a single transmitted impulse, the excess delay T_m between the first and last received component represents the maximum delay during which the multipath signal power falls to some threshold below of the strongest component.

Viewed in frequency domain, for an impulse signal of infinite bandwidth, the bandwidth of the received series of impulses is finite. This means that the channel has filtered out some frequency content of the signal. The coherence bandwidth f_0 is a statistical measure of the range of frequencies over which the channel passes all spectral components with approximately equal gain and linear phase. Excess delay and coherence bandwidth are approximately related by $f_0 \approx \frac{1}{T_m}$ $\qquad (2.6a)$

In a multipath environment, the time spreading causes a signal to undergo either flat fading or frequency selective fading. In flat fading, the coherence bandwidth of the channel is greater than the bandwidth of the transmitted signal, f such that all frequency components of the signal will experience the same magnitude of fading. This means $f_0 > f \approx \frac{1}{T_s}$ where $\frac{1}{T_s}$ is the symbol rate and is nominally taken to be equal to f. Flat fading could also be viewed, in the time domain, to be the result of a multipath propagation whose excess delay , T_m is so small compared to the symbol duration, T_s that they add up to one undistorted signal by inter symbol interference (ISI).

In frequency selective fading, the coherence bandwidth of the channel is smaller than the bandwidth of the signal ($f_0 < \frac{1}{T_s}$) such that various frequency components of the signal will be affected differently by the channel. In the time domain, the multipath components of the signal will have significant time dispersion compared to the symbol period resulting in ISI.

- **Fast fading versus slow fading**

In wireless channels, the time-varying nature of the channel is caused by changes in the propagation path. Therefore, for a transmitted signal the destination sees variations in the signal's amplitude and phase. The time variant mechanism will be characterized in the time domain by the channel coherence timeT_c, which is a measure of the expected time duration over which the channel is essentially invariant [4].

The coherence time determines whether the channel can be described as slow fading or fast fading. In slow fading channel, the coherence time of the channel is greater than the symbol duration of the transmitted signal ($T_c >> T_s$). In this regime, the amplitude and the phase change imposed by the channel can be considered roughly constant over the period of channel use. In contrast, fast fading occurs when the coherence time of the channel is small relative to the symbol duration of the transmitted signal ($T_c < T_s$). In this regime, the amplitude and phase change imposed by the channel varies considerably over the period of channel use.

In fast fading channel, the source, using time diversity, may take advantage of channel variations. Although a deep fade may temporarily erase some of the transmitted codeword, use of channel coding coupled with successfully transmitted bits during other time instances may allow the erased bits to be recovered. In a slow fading channel, it is not possible to use time diversity because the transmitter sees only a single realization of the channel within its delay constraints (coherence time). A deep fade therefore lasts the entire duration of the transmission and cannot be mitigated using coding. [49].

The coherence time of the channel is related to a quantity known as the Doppler spread of the channel. When a user is moving, the user's velocity causes a shift in the frequency of the signal transmitted along each signal path. This phenomenon is known as the Doppler shift. Signals traveling along different paths can have different Doppler shifts. Such that when they add up at the destination, the resulting signal will have a broader bandwidth than the transmitted signal. This is known as Doppler spread f_d and measures this spectral broadening of the signal. In general, coherence time is inversely related to Doppler spread and typically expressed as $f_d \approx \frac{V}{\lambda} \approx \frac{k}{T_c}$ $\quad (2.6b)$

Where V is the relative velocity, λ is the signal wavelength, and k is a constant taking values in the range of 0.25 to 0.5.

2.1.2 RAYLEIGH FADING MODEL

In a multipath environment, an impulse at the transmitter reaches the receiver through multiple impulses at different height. Figure 2.4 illustrates this behavior. Let the transmit band pass signal be

$$x(t) = \mathcal{R}\{x_b(t)e^{j2\pi f_c t}\} \quad (2.7)$$

where $x_b(t)$ is the baseband signal, f_c is the carrier frequency signal and t is the time.

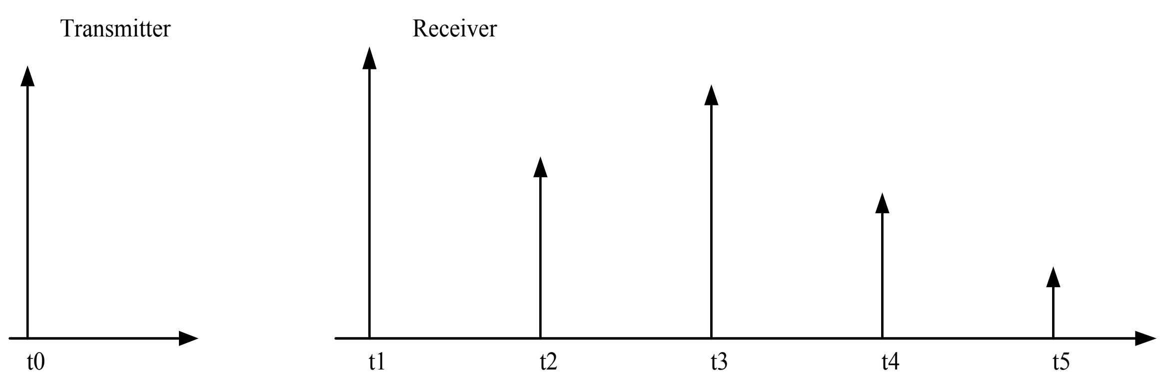


Figure 2.4 Impulse response of a multipath channel

As illustrated in Figure 2.4, the transmit signal reaches the receiver through multiple paths where the n^{th} path has attenuation $\alpha_n(t)$and delay $\tau_n(t)$. The received signal is

$$r(t) = \sum_n \alpha_n(t)\, x[t - \tau_n(t)] \tag{2.8}$$

Plugging in the equation for transmit baseband signal from the above equation

$$r(t) = \mathcal{R}\left\{\sum_n \alpha_n(t)\, x_b[t - \tau_n(t)] e^{j2\pi f_c[t-\tau_n(t)]}\right\} \tag{2.9}$$

The baseband equivalent of the received signal is

$$r_b(t) = \sum_n \alpha_n(t) e^{-j2\pi f_c \tau_n(t)}\, x_b[t - \tau_n(t)] = \sum_n \alpha_n(t) e^{-j\theta_n(t)}\, x_b[t - \tau_n(t)] \tag{2.10}$$

where $\theta_n(t) = 2\pi f_c \tau_n(t)$ is the phase of the n^{th} path.

The impulse response is

$$h(t) = \sum_n \alpha_n(t) e^{-j\theta_n(t)} \tag{2.11}$$

The phase of each path can change by 2π radian when the delay $\tau_n(t)$ changes by $1/f_c$. If f_c is relatively large, small motions in the medium can cause changes of 2π radians. Since the distance between the devices is much larger than the wavelength of the carrier frequency, it is therefore reasonable to assume that the phase in uniformly distributed between 0 and 2π radians and the phases of each path are independent [3].

When there are a large number of paths, applying Central Limit Theorem (CLT), each path can be modeled as circularly symmetric complex Gaussian random variable with time as variable. This model is called Rayleigh fading channel model.

A circularly symmetric complex Gaussian random variable is of the form

$$Z = X + jY \tag{2.12}$$

where real and imaginary parts are zero mean independent and identically distributed (i.i.d.) Gaussian random variables. For a circularly symmetric complex random variable Z,

$$E[Z] = E[X + jY] = E\left[e^{j\theta} Z\right] = e^{j\theta} E[Z] \tag{2.13}$$

The statistics of a circularly symmetric complex Gaussian random variable is completely specified by the variance

$$\sigma^2 = E[Z^2] \tag{2.14}$$

The magnitude $|Z|$which has a probability density function (PDF)

$$p(z) = \frac{z}{\sigma^2} e^{\frac{-z^2}{2\sigma^2}}, z \geq 0 \tag{2.15}$$

is called a Rayleigh random variable. Rayleigh Fading channel is practical for an environment where there is large number of reflectors. Figure 2.5 and 2.6 illustrate the PDF of Z and θ respectively.

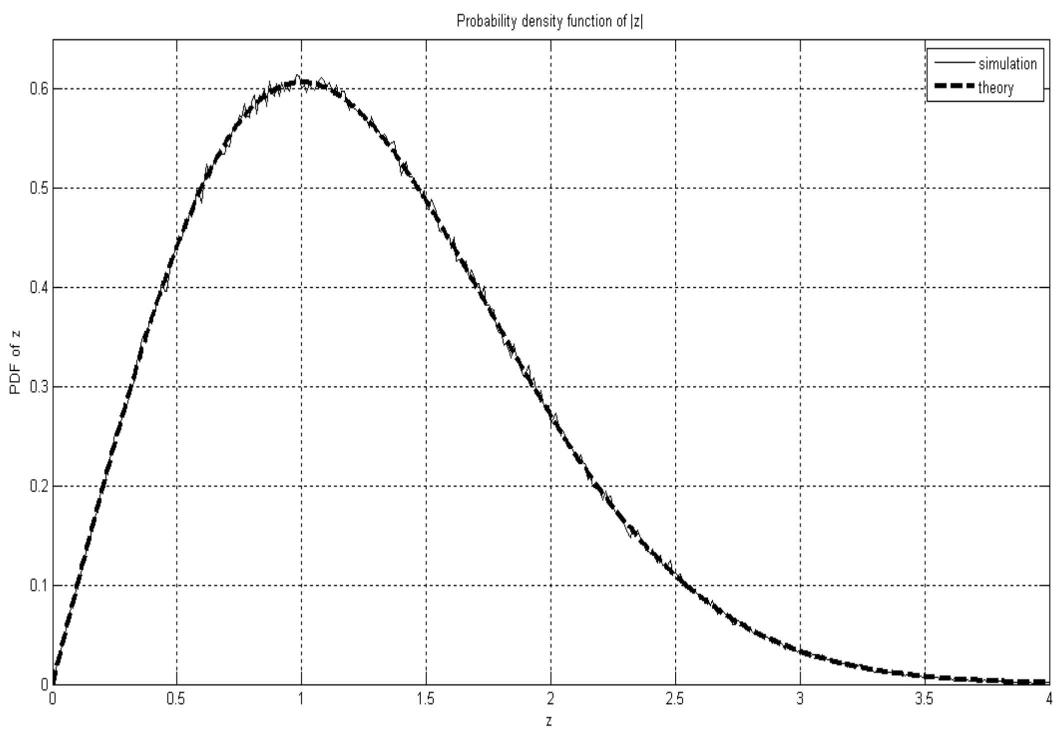


Figure 2.5 PDF of Rayleigh random variable

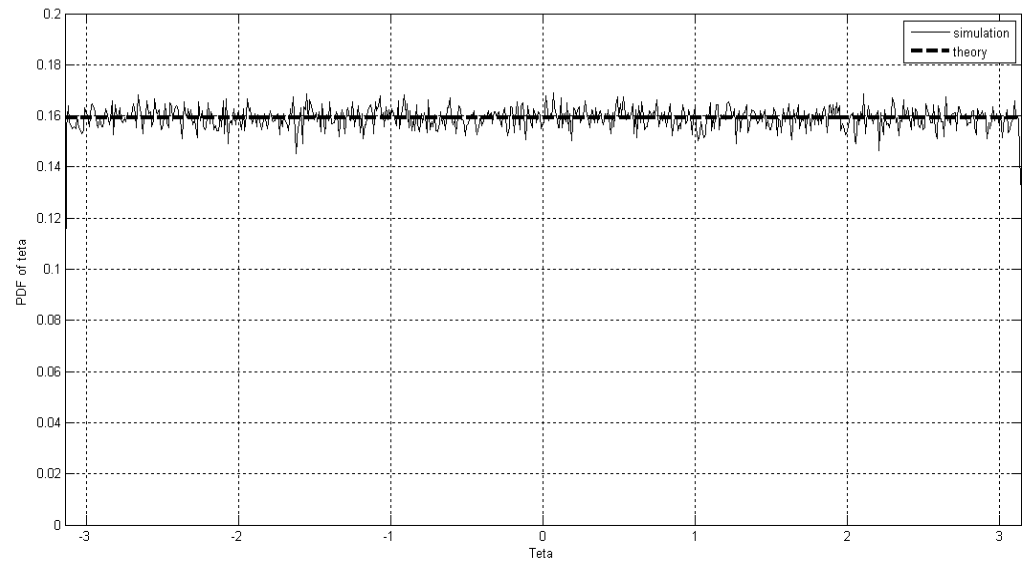


Figure 2.6PDF of uniformly distributed $\boldsymbol{\theta}$ random variable

2.1.3 PERFORMANCE ANALYSIS OF A SIMPLE COMMUNICATION SYSTEM

In this subsection, we derive the probability of error of a point to point communication system with Binary Phase Shift Keying (BPSK) modulation scheme in AWGN channel as shown in Figure 2.7 [47].

In BPSK, the binary bits 0 and 1 are mapped to the analog levels -$\sqrt{E_b}$ and+$\sqrt{E_b}$ respectively.

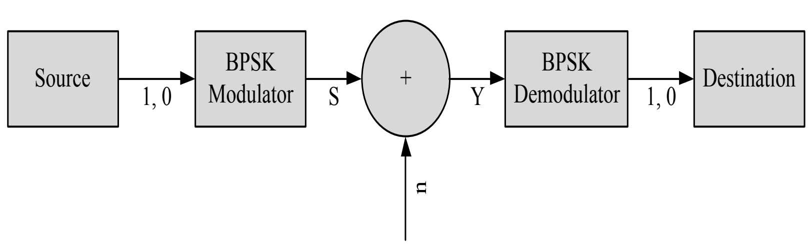


Figure 2.7 basic block diagram of a communication system with BPSK modulation

The transmitted received signal at the destination is given by

$$y(t) = s(t) + n(t) \tag{2.16}$$

where $s(t)$ is the transmitted signal that can have the values of s_0 or s_1 depending whether 0 or 1 was transmitted respectively. The noise $n(t)$ follows the Gaussian probability density function (PDF)

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{2.17}$$

With $\mu = 0$ and $\sigma^2 = \frac{N0}{2}$.

The conditional PDF of the received signal y when s_0 and $s_1$were transmitted are

$$p(y|s_0) = \frac{1}{\sqrt{\pi N_0}} e^{\frac{-(y+\sqrt{E_b})^2}{N_0}} \tag{2.18}$$

$$p(y|s_1) = \frac{1}{\sqrt{\pi N_0}} e^{\frac{-(y-\sqrt{E_b})^2}{N_0}} \tag{2.19}$$

Respectively and they are illustrated in Figure 2.8

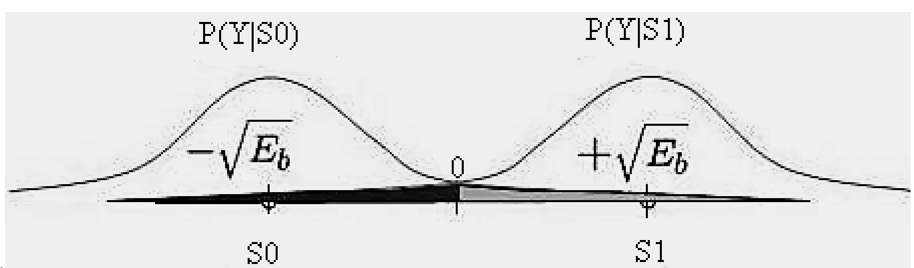


Figure 2.8 Conditional PDF with BPSK modulation

Assuming that both symbols are equally probable, thus, the optimal decision boundary is zero. If the received signal is greater than zero, then the receiver assumes that 1 was transmitted. If the received signal is less than or equal to zero then the receiver assumes that 0 was transmitted.

$$y > 0 \Rightarrow s_1$$

$$y \leq 0 \Rightarrow s_0$$

The probability of error given s_1 is transmitted is the area under the tail of the Conditional Gaussian PDF from $-\infty\ to$ 0 which is compute by

$$p(e|s_1) = \frac{1}{\sqrt{\pi N_0}} \int_{-\infty}^{0} e^{\frac{-(y-\sqrt{E_b})^2}{N_0}} dy = \frac{1}{\sqrt{\pi}} \int_{\sqrt{\frac{E_b}{N_0}}}^{\infty} e^{-z^2}\, dz = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \qquad (2.20)$$

where $erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-x^2}\, dx$ is the complementary error function.

Similarly, the probability of error given s_0 is transmitted is the area under tail of the Conditional Gaussian PDF from $0\ to\ \infty$ which is compute by

$$p(e|s_0) = \frac{1}{\sqrt{\pi N_0}} \int_{0}^{\infty} e^{\frac{-(y+\sqrt{E_b})^2}{N_0}} dy = \frac{1}{\sqrt{\pi}} \int_{\sqrt{\frac{E_b}{N_0}}}^{\infty} e^{-z^2}\, dz = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \qquad (2.21)$$

The total error probability is

$$P_b = p(S_1).\, p(e|S_1) + p(S_0).\, p(e|S_0) \qquad (2.22)$$

Given that $p(S_1) = p(S_0) = {}^{1}\!/_{2}$, the bit error rate (BER) is

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \qquad (2.23)$$

Next, we derive the BER for BPSK in flat Rayleigh block fading channel with average received signal to noise ratio $SNR = \frac{E_b}{N_0}$, the received signal is given by

$$y = hx + n \qquad (2.24)$$

where h is the complex channel coefficient corresponding to Rayleigh multipath channel, the real and the imaginary parts are Gaussian distributed having zero mean and variance ${}^{1}\!/_{2}$, x is the transmitted symbol taking values +1 and -1 and n is the AWGN with zero mean and variance ${N_0}/{2}$ per dimension. We assume that the channel characteristics h are known at the receiver.

The bit error probability for a given value of h is evaluated by the conditional PDF given by

$$P_{(b|h)} = \frac{1}{2} erfc\left(\sqrt{\frac{|h|^2 E_b}{N_0}}\right) = \frac{1}{2} erfc(\sqrt{\gamma}) \tag{2.25}$$

Where $\gamma = \frac{|h|^2 E_b}{N_0}$

To find the error probability over all random values of $|h|^2$, one must evaluate the conditional PDF function $P_{(b|h)}$ over the PDF of γ.

If h is a Rayleigh distributed random variable, then $|h|^2$ is chi-square distributed with two degrees of freedom. Since $|h|^2$ is chi-square distributed, γ is also chi-square distributed. The PDF of γ is given by

$$p(\gamma) = \frac{1}{{E_b}/{N_0}} e^{\frac{-\gamma}{{E_b}/{N_0}}} \text{ }, \gamma \geq 0 \tag{2.26}$$

Consequently, the error probability is

$$P_b = \int_0^\infty P_{(b|h)}. p(\gamma). d\gamma = \int_0^\infty \frac{1}{2} erfc(\sqrt{\gamma}). p(\gamma). d\gamma \tag{2.27}$$

The results of the above integration reduces to

$$P_b = \frac{1}{2}\left(1 - \sqrt{\frac{{E_b}/{N_0}}{{E_b}/{N_0} + 1}}\right) \tag{2.28}$$

For large ${E_b}/{N_0}$, the probability of error approximates to

$$P_b \approx \frac{1}{4\frac{E_b}{N_0}} \tag{2.29}$$

Figure 2.9 illustrates the system performance of BPSK modulation in AWGN and block fading channels. It is clearly shown that the system is severely degraded by the variations of the received signal strength. The error produced by the fading channel is because of the channel being in deep fade rather than the Gaussian noise being large [3]. The results show that the Bit Error Rate (BER) decays exponentially with the average SNR. On the other hand, similar system performance over block fading channel decays linearly with the average SNR. The large difference in terms of performance between both channels has been the industry research over the past years. This research has led to several solutions.

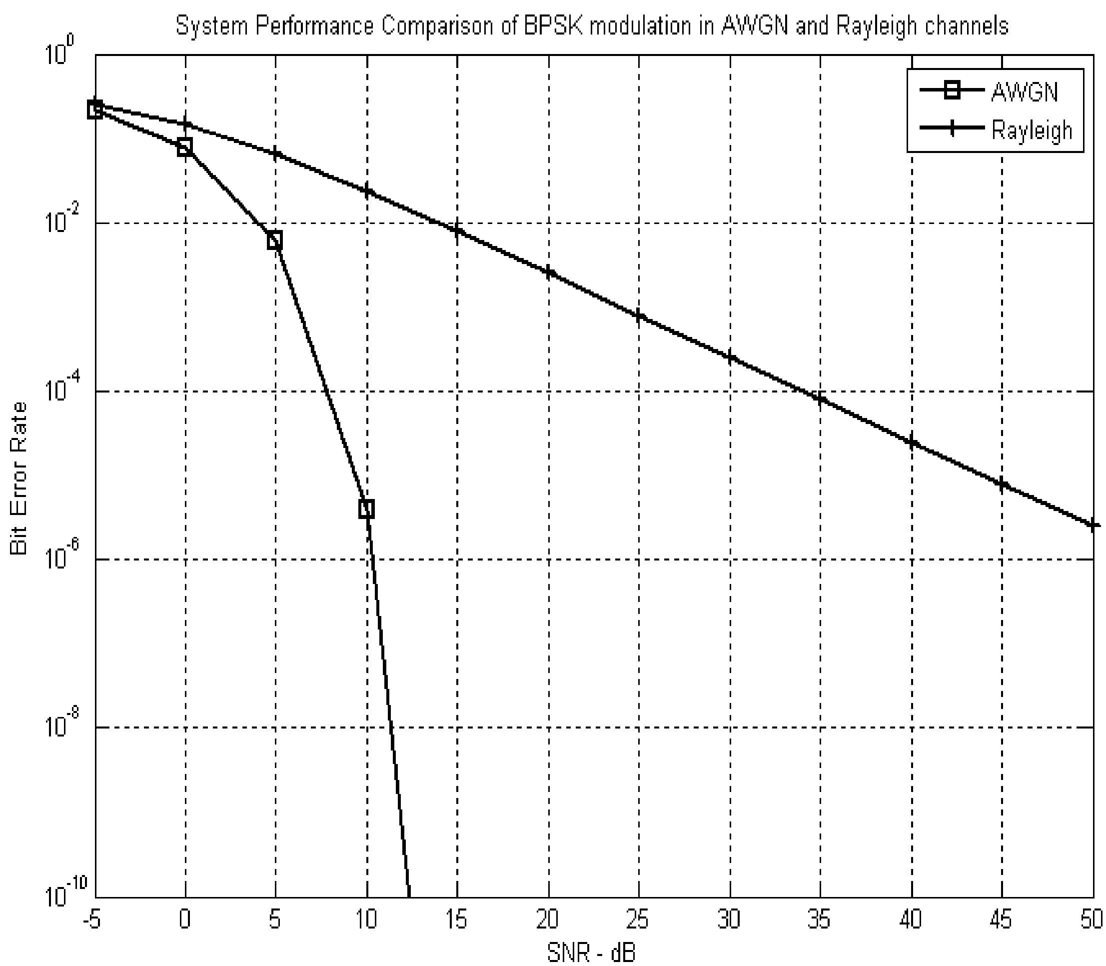


Figure 2.9 Comparison between AWGN and block fading channels

2.1.4 OUTAGE PROBABILITY IN FADING CHANNELS

The outage probability is used to evaluate the system performance when it is impossible to average the conditional error rate over all different fading coefficients. We consider the quasi static fading scenario where the channel coefficients are considered unchanged over the entire data frame. Assume that a specific FER is required for a particular application to work adequately. To achieve this FER, a minimum SNR γ_{min} is required. If the instantaneous SNR that varies with the fading coefficients falls below this level, the system is considered in outage.

The outage probability is given by [49]

$$P_{outage} = P[\gamma \leq \gamma_{min}] = \int_0^{\gamma_{min}} p(\gamma)d\gamma = \int_0^{\gamma_{min}} \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} d\gamma = 1 - e^{-\frac{\gamma_{min}}{\bar{\gamma}}} \tag{2.30}$$

where $\bar{\gamma}$ is the average received SNR.

At high SNR, equation (2.30) is approximated by

$$P_{outage} \approx \frac{\gamma_{min}}{\bar{\gamma}} \tag{2.31}$$

As illustrated in equation (2.31), the outage probability is inversely proportional to the average SNR. To reduce the outage probability, an extremely high transmission power is required which is intolerable for most applications.

2.2 CHANNEL CAPACITY

Shannon stated in his paper [1] “The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.” Consider the communication system illustrated in Figure 2.10. K information bits that constitute one symbol m are encoded into an n bits codeword X, appropriate for transmission over the noisy channel. The rate of the code is $r = {}^{k}/_{n}$.

Figure 2.10 – Communication model

The noisy channel coding theorem states that it is possible to achieve reliable communications over a channel if the transmission rate $R < C$. The capacity of an AWGN channel is given by

$$C_{AWGN} = \log(1 + \frac{E_b}{N_0}) \qquad (2.32)$$

Where $\frac{E_b}{N_0}$ is the information SNR. C is the channel capacity that represents the number of information bits per channel use that can be transmitted with an arbitrarily low error rate over a channel. The theorem proves the existence of good codes, but it does not specify which codes achieve channel capacity.

Equally important is the converse channel coding theorem which follows from Fano's inequality [5]. The converse theorem states that it is impossible to achieve a low error probability, regardless of the type of code used if $R > C$

In fading channels, the instantaneous received SNR γ varies with the channel gain; hence the instantaneous channel capacity is a function of the fading coefficient and is given by

$$C_{fading} = \log(1 + |h|^2 \frac{E_b}{N_0}) \qquad (2.33)$$

The outage probability as defined above can be written in terms of the instantaneous capacity C_{fading} as

$$P_{outage} = P[C_{fading} < R] \qquad (2.34)$$

2.3 INTERFERENCE CHANNELS

The interference channel (IC) models networks where two or more users (N users) are independently communicating their information to their respective N receivers through a common channel. Subsequently, the transmission of information from each source to its corresponding receiver interferes with the communication between the other transmitters and receivers. The interference channel can be regarded as a channel that is contained N principal links and $N(N-1)$ interference links.

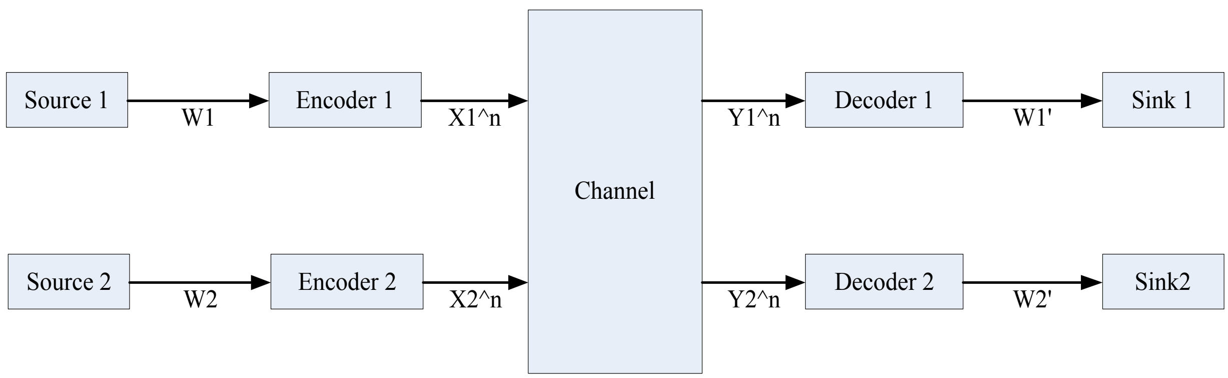


Figure 2.11 the Memoryless IC

The original information theoretic work on interference channel was introduced by Shannon [38] and followed further by Ahlswede [9]. Nevertheless, the specification of the rate region for the general IC is still an open problem. In this section, we review the basic results on Interference channels. A standard model for IC is illustrated in Figure 2.11 [9]. A discrete memoryless IC consists of two statistically independent sources W_k with $B_k$bits, $k = 1,2$. Encoder k maps $W_k$to a string of $X_k^n = X_{k1}, X_{k2}, \dots, X_{kn}$ of n input symbols that are transmitted over a memoryless channel$P_{Y_1,Y_2|X_1,X_2}(.)$ that has two inputs and two outputs. At the receiver k, Y_k^n is processed to obtain the message estimate $\widehat{W_k}$, $k = 1,2$.

The error probability is defined as

$$P_e = \ P_r\left[\left\{\widehat{W}_1 \neq W_1\right\} \cup \left\{\widehat{W}_2 \neq W_2\right\}\right] \tag{2.35}$$

A set of rate pairs (R_1, R_2) is said to be achievable on the interference channel if there exists a sequence of $(\lceil 2^{nR_1} \rceil, \lceil 2^{nR_2} \rceil, n)$ codes such that $P_e \to 0$as $n \to \infty$. The closure of this set is called the interference channel capacity region.

2.3.1 GAUSSIAN INTERFERENCE CHANNEL

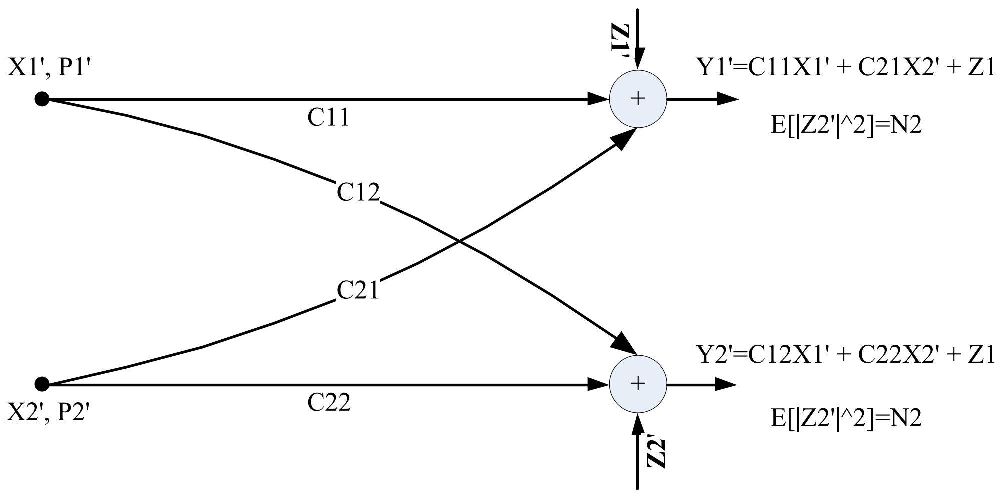


Figure 2.12 The Gaussian Interference channel

The Gaussian IC as illustrated in Figure 2.12 is not a broadcast channel since there is only one destined receiver for each sender, nor it is a multiple access channel because each receiver is only interested in the data transmitted by its corresponding source [5]

As Figure 2.12 shows, given channel inputs $X'_{ki}$and channel outputs Y'_{ki} with block power constraints

$$\sum_{i=1}^{n} |X'_{ki}|^2 \leq n \,.\, P'_k \,, \quad k = 1,2 \tag{2.36}$$

for some positive P'_1 and P'_2. The channel outputs at time I are given by

$$Y'_{1k} = C_{11}X'_{1i} + C_{21}X'_{2i} + Z'_{1i} \tag{2.37}$$

$$Y'_{2k} = C_{12}X'_{1i} + C_{22}X'_{2i} + Z'_{2i} \tag{2.38}$$

where Z'_{ki} is the Gaussian noise term, with $E[|Z'_{ki}|^2] = N_k, N_k > 0, k = 1,2$.

One can use elementary scaling transformations to convert the interference channel in Figure 2.12 into the IC that has the standard form with the same capacity region. The resulting channel has the following new parameters

$$X_1 = \frac{C_{11}}{\sqrt{N_1}} X'_1, \qquad Y_1 = \frac{1}{\sqrt{N_1}} Y'_1, \qquad Z_1 = \frac{1}{\sqrt{N_1}} Z'_1 \tag{2.39a}$$

$$X_2 = \frac{C_{22}}{\sqrt{N_2}} X'_2, \qquad Y_2 = \frac{1}{\sqrt{N_2}} Y'_2, \qquad Z_2 = \frac{1}{\sqrt{N_2}} Z'_2 \tag{2.39b}$$

and the new power constants and channel gains are

$$P_1 = \frac{C_{11}^2}{\sqrt{N_1}} P'_1, \qquad P_2 = \frac{C_{22}^2}{\sqrt{N_2}} P'_2 \tag{2.40a}$$

$$a_{12} = \frac{C_{12}^2}{C_{11}^2} \frac{N_1}{N_2}, \qquad a_{21} = \frac{C_{21}^2}{C_{22}^2} \frac{N_2}{N_1}, \tag{2.40b}$$

Note that, in the IC standard form, the direct links have unit gains and the noise has unit variance.

Next, we illustrate a table that classifies the interference.

IC Class	Parameters
No interference	$a_{12} = a_{21} = 0$
Very strong interference	$a_{12} \geq 1 + P_2$ and $a_{21} \geq 1 + P_1$
Strong interference	$a_{12} \geq 1$ and $a_{21} \geq 1$
Weak interference	$a_{12} \leq 1$ and $a_{21} \leq 1$
Z interference	$a_{12} = 0$ or $a_{21} = 0$
Degraded IC (does not have standard form)	$C_{11} = C_{22} = C_{12} = C_{21} = 0$

Table 2.2 the interference classes

The capacity region for the standard IC with NO interference is clearly known [5] (Capacity of the Gaussian channel with power constraint P and noise variance N). It is given by

$$C = \frac{1}{2}\log_2\left(1 + \frac{P}{N}\right) \quad \textit{bits per transmission} \tag{2.41}$$

Figure 2.13 illustrates the capacity plot of the Gaussian interference free channel for different types of modulation scheme.

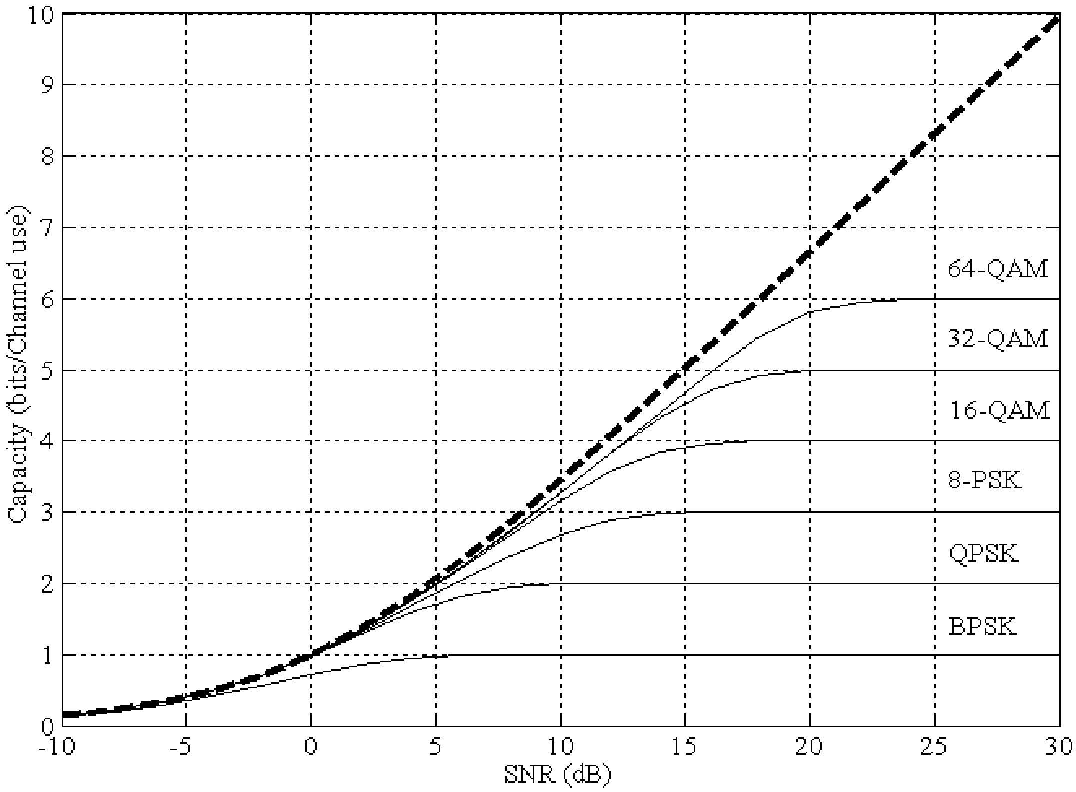


Figure 2.13 Capacity of Gaussian channel for various modulation schemes

The capacity region for the standard IC with very strong interference is the set of rate pairs(R_1, R_2) [40], such that

$$R_1 \leq \frac{1}{2}\log_2(1 + P_1) \tag{2.42a}$$

$$R_2 \leq \frac{1}{2}\log_2(1 + P_2) \tag{2.42b}$$

The capacity region for the standard IC with strong interference is the set of rate pairs (R_1, R_2) [39], such that

$$R_1 \leq \frac{1}{2}\log_2(1 + P_1) \tag{2.43a}$$

$$R_2 \leq \frac{1}{2}\log_2(1 + P_2) \tag{2.43b}$$

$$R_1 + R_2 \leq min \left\{\frac{1}{2}\log_2(1 + a_{21}P_2 + P_1), \frac{1}{2}\log_2(1 + a_{12}P_1 + P_2)\right\} \tag{2.43c}$$

Suppose that the set of rate pairs $(R_1, R_2) \in Capacity\ region\ of\ IC$, there are codes such that receiver 1 and 2 can reliably decode the respectiveW_1 and W_2 [10]. Consider receiver 1 that decodes W_1 and can generate $X_1^n(W_1)$ and

$$\tilde{Y}_1^n = \sqrt{a_{12}}X_1^n + X_2^n + \frac{1}{\sqrt{a_{21}}}Z_1^n. \tag{2.44}$$

Note that 2.44 is simply Y_2^n with a reduced noise variance so that receiver 1 can reliably decode W_2. Similarly, receiver 2 can reliably decode both W_1 and W_2. Therefore, we have a compound Gaussian multi-access channel (MAC) whose capacity region is the intersection of two MAC capacity regions.[9], [13], [39], [41].

It has been shown that strong interference is less harmful that weak interference and very strong interference is as good as no interference [39], [40] and [41].

Unfortunately, the capacity region for the standard IC with weak or moderate interference is still unknown.

2.3.2 THE HAN-KOBAYASHI ACHIEVABLE RATE REGION

The best achievable rate region for the general two user two receiver IC is known as the Han-Kobayashi (HK) region [13]. The original work was initiated by Carleial [11] who has developed two basic coding strategies for Gaussian IC. Their approach consists of splitting the data at each source into two parts private and public. The private part of the message (V_j at rateT_j) is only decoded by the corresponding receiver, while the public part of the message (U_j at rateS_j) is decoded by both receivers. Note that $j = 1,2$.

Carleial [11] proposed successive decoding technique at the receiver. However HK improved this approach by using a more powerful joint decoder. The resulting region has seven MAC-like bounds per receiver because every receiver decodes three messages.

Let $\mathcal{P}$ be the set or probability distributions $P(.)$ such that

$$P(q, v_1, u_1, x_1, v_2, u_2, x_2, y_1, y_2)$$
$$= P(q).P(v_1|q)P(u_1|q)P(x_1|v_1, u_1, q).P(v_2|q)P(u_2|q)P(x_2|v_2, u_2, q).P(y_1, y_2|x_1, x_2) \quad (2.45)$$

Suppose we fix $P(.)$.Consider receiver 1 and the set $\mathcal{R}_{HK}^{(1)}(P)$ of rate tuples (S_1, T_1, S_2, T_2) that satisfy

$$S_1 \leq I(V_1; Y_1|U_1, U_2, Q) \quad (2.46)$$

$$T_1 \leq I(U_1; Y_1|V_1, U_2, Q) \quad (2.47)$$

$$T_2 \leq I(U_2; Y_1|V_1, U_1, Q) \quad (2.48)$$

$$S_1 + T_1 \leq I(V_1, U_1; Y_1|U_2, Q) \quad (2.49)$$

$$S_1 + T_2 \leq I(V_1, U_2; Y_1|U_1, Q) \quad (2.50)$$

$$T_1 + T_2 \leq I(U_1, U_2; Y_1|V_1, Q) \quad (251)$$

$$S_1 + T_1 + T_2 \leq I(V_1, U_1, U_2; Y_1|Q) \quad (252)$$

Similarly, let the set $\mathcal{R}_{HK}^{(2)}(P)$be the set of (S_1, T_1, S_2, T_2) that satisfies the above equations (2.46-2.52) with indexes 1 and 2 swapped. For a set $\mathcal{S}$ of 4-tuples(S_1, T_1, S_2, T_2), let $\prod(\mathcal{S})$ be the set of (R_1, R_2) such that $(R_1 = S_1 + T_1)$ and $(R_2 = S_2 + T_2)$ for some$(S_1, T_1, S_2, T_2) \in \mathcal{S}$. We have the following result [13].

The set

$$\mathcal{R}_{HK} = \prod\left(\bigcup_{P\in\mathcal{P}}\left(\mathcal{R}_{HK}^{(1)}(P) \cap \mathcal{R}_{HK}^{(2)}(P)\right)\right) \quad (2.53)$$

is an achievable rate region for the memoryless IC.

2.3.3 RECENT ACHIEVABLE RATE RESULTS AND OUTER BOUNDS

HK region is the best available rate region. However, it is complex to compute. There has been a lot of research dedicated to computing outer bounds on the capacity of IC. Two outer bounds for the Gaussian IC were recently derived by Kramer [16], one using a genie aided approach and the other using the results for the degraded IC.

The following is the recent results derived by Kramer [16]

- The Capacity region of the Gaussian IC is contained within the set (R_1, R_2) satisfying

$$R_1 \leq \frac{1}{2}\log_2(1 + P_1) \tag{2.54a}$$

$$R_2 \leq \frac{1}{2}\log_2(1 + P_2) \tag{2.54b}$$

$$R_1 + R_2 \leq \frac{1}{2}\log_2\left[(P_1 + a_{21}P_2 + 1)\left(\frac{P_2 + 1}{\min(a_{21}, 1)\, P_2 + 1}\right)\right] \tag{25.4c}$$

for all values of a_{21}. Moreover, the sum rate bound obtained by swapping indexes 1 and 2 is also valid by symmetry.

- If $0 < a_{21} \leq 1$ then the rate region of the IC is contained within the set (R_1, R_2) satisfying

$$R_1 \leq \frac{1}{2}\log_2\left(1 + \frac{P_1'}{P_2' + {}^{1}/_{a_{21}}}\right) \tag{2.55a}$$

$$R_2 \leq \frac{1}{2}\log_2(1 + P_2') \tag{2.55b}$$

where $P_1' + P_2' = {}^{P_1}/_{a_{21}} + P_2$. If $0 < a_{12} \leq 1$, the inequalities obtained by swapping indexes 1 and 2 would also be valid.

For further recent achievable rate results, refer to [10].

Figure 2.5 illustrates the following five regions:

a. An outer bound due to Sato[43],
b. And outer bound due to Carleial [44],
c. A genie-aide outer bound from [16],
d. A broadcast out bound in [16] that uses ideas developed by Sato [45] and Costa [14],
e. An inner bound that combines FDM/TDM and rate splitting.

Figure 2.14 shows that reasonable improvements on either inner bounds or the outer bounds or both are still needed.

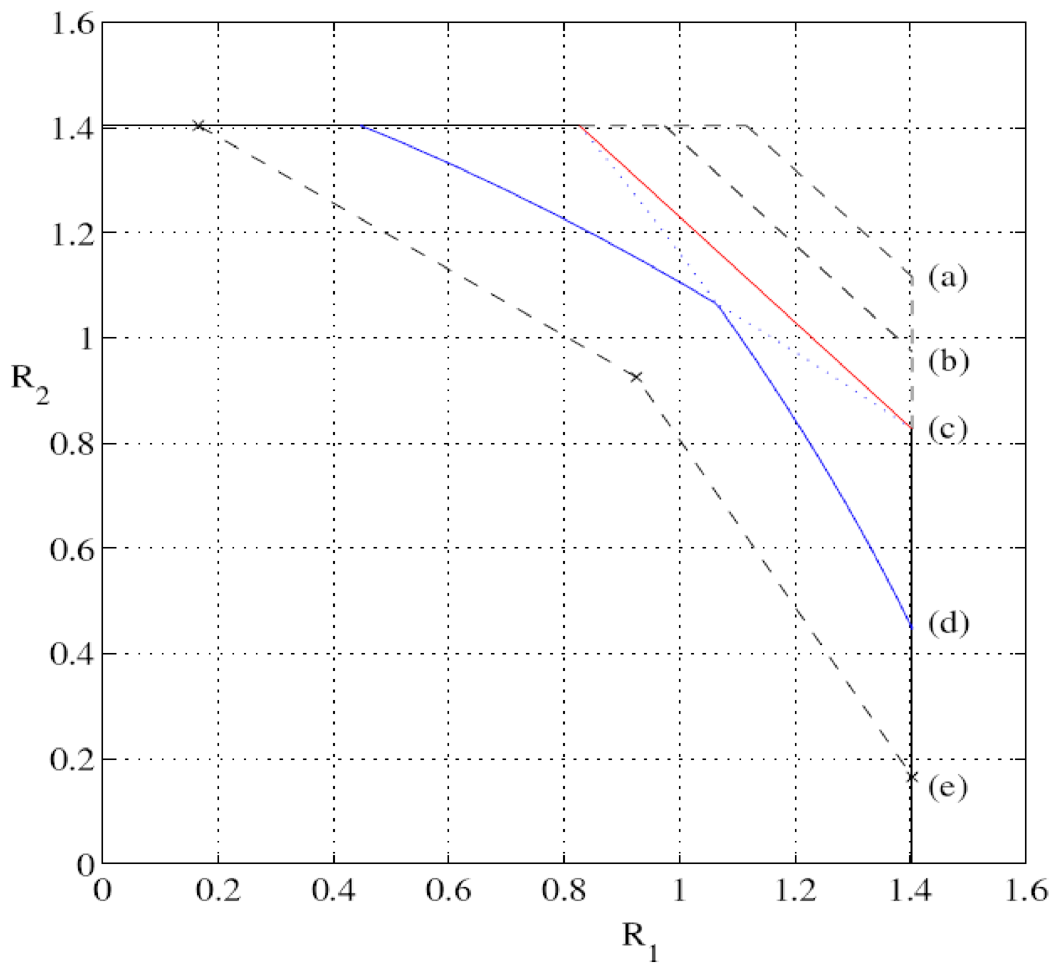


Figure 2.14 Capacity bounds for Gaussian IC with $P_1 = P_2 = 6$ and $a_{12} = a_{21} = 0.3$ the rate units are bits per channel use [10]

2.4 DIVERSITY TECHNIQUES TO COMBAT FADING

Diversity is introduced to effectively enhance the performance of a wireless communication system by providing redundant information over multiple independent branches with different characteristics. It is one of the main techniques to combat fading and co-channel interference and avoid error bursts. To increase system reliability, multiple versions of the same signal are transmitted / received and combined in the receiver.

One natural way to enhance the performance of a wireless system is to transmit the information through multiple signal paths, each of which fades independently which lead to possible reliable communications if at least one path is strong.

This technique which is called diversity [3], dramatically improves the system performance over fading channels. Figure 2.15 illustrates the error probability as a function of the SNR for different numbers of diversity branches L.

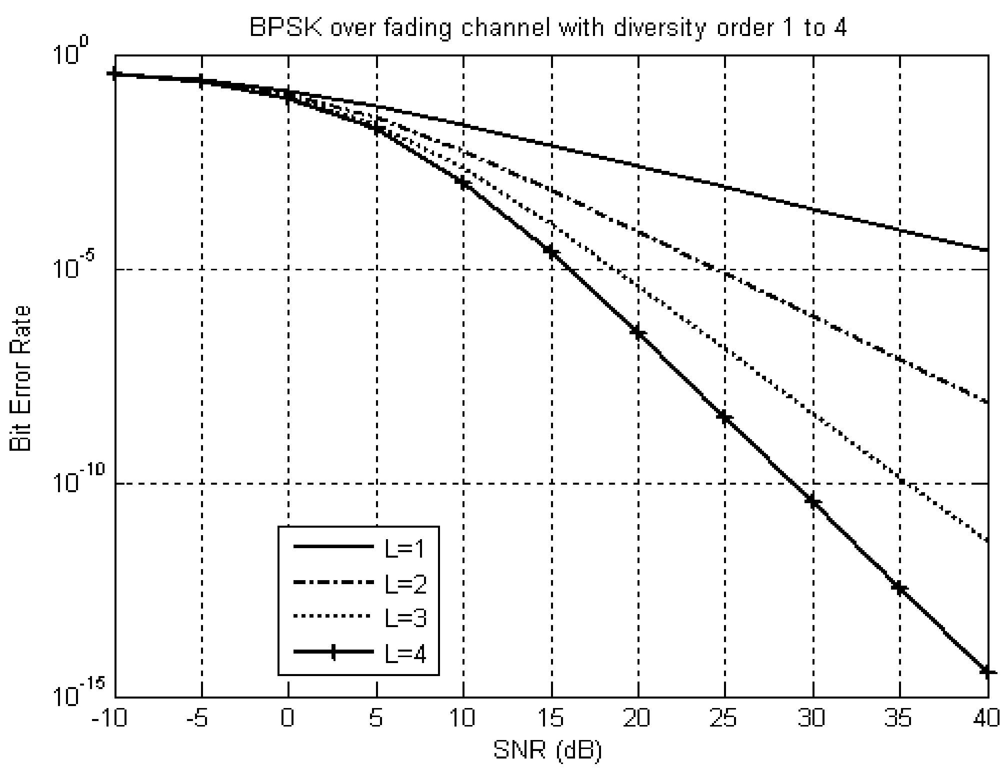


Figure 2.15 System performance for different diversity order

Figure 2.15 shows that the BER rapidly decreases as the number of diversity increases. By increasing the number of different paths through which the message is transmitted, the probability of correctly receiving the transmitted data block of information in one of the paths is higher.

The resulting symbol error probability can be approximated as [3]

$$p_e \approx \binom{2L-1}{L} \frac{1}{(4SNR)^L} \tag{2.56}$$

Where L denotes the number of independent transmission paths. Figure 2.56 shows that for a specific SNR, the symbol error probability is exponentially decreasing as the number of diversity is increasing. This can also be deduced from equation (2.56). Therefore, L is called the diversity order. In the coming subsections, we will briefly introduce the common diversity techniques.

2.4.1 FREQUENCY DIVERSITY

The signal is transmitted over multiple frequency channels or spread over a wide spectrum. It relies on the fact that the fading is different at different frequencies. Therefore, when there is a fade at one frequency, there may not be a fade at another one. At the transmitter, the same data signal is transmitted on two frequencies. At the receiver end, a combining approach is used to measure the Signal to Noise Ratio (SNR) in each receiver and automatically selects which is the best at any instant in time. The drawback of this method is the bandwidth inefficiency by transmitting the same information over two frequencies.

Orthogonal frequency division multiplex (OFDM) is a good example of frequency diversity where communication over a multipath channel is converted into communication over simpler narrowband sub channels.

2.4.2 TEMPORAL DIVERSITY

Multiple copies of the same signal are transmitted at different time instants. Time diversity is achieved by averaging the fading of the channel over time. Typically, the channel coherence time is of the order of tens to hundreds of symbols, and therefore the channel is highly correlated across the consecutive symbols. To ensure that the coded symbols are transmitted through independent fading gains, interleaving of code words is required.

Figure 2.16 illustrates an example of how time diversity is achieved after interleaving. We consider a flat fading channel, we transmit a code word$\mathbf{x} = [x_1, \dots, x_l]$ of length Lsymbols and the received signal is given by

$$y_l = h_l x_l + w_l\,, \qquad\qquad l = 1, \dots, L \tag{2.57}$$

Assuming perfect interleaving so that consecutive symbols x_l are transmitted sufficicently far apart in time, we can assume that the $\mathrm{h}_l's$ are independent. The parameter L is commonly called the number of diversity branches. The additive white Gaussian noises $\mathrm{w}_1, \dots, w_l$are i.i.d. $CN(0, N_0)$random variables.

Repetition coding is one simple time diversity achieving code, in which $\mathrm{x}_l = \mathrm{x}_1$ for $l = 1, \dots, L$.in vector form the overall channel becomes

$$\mathbf{y} = \mathbf{h}x_1 + \boldsymbol{w} \tag{2.58}$$

where $= [y_1, \dots, y_l]$, $\mathbf{h} = [h_1, \dots, h_l]$ and $\mathbf{w} = [w_1, \dots, w_l]$.

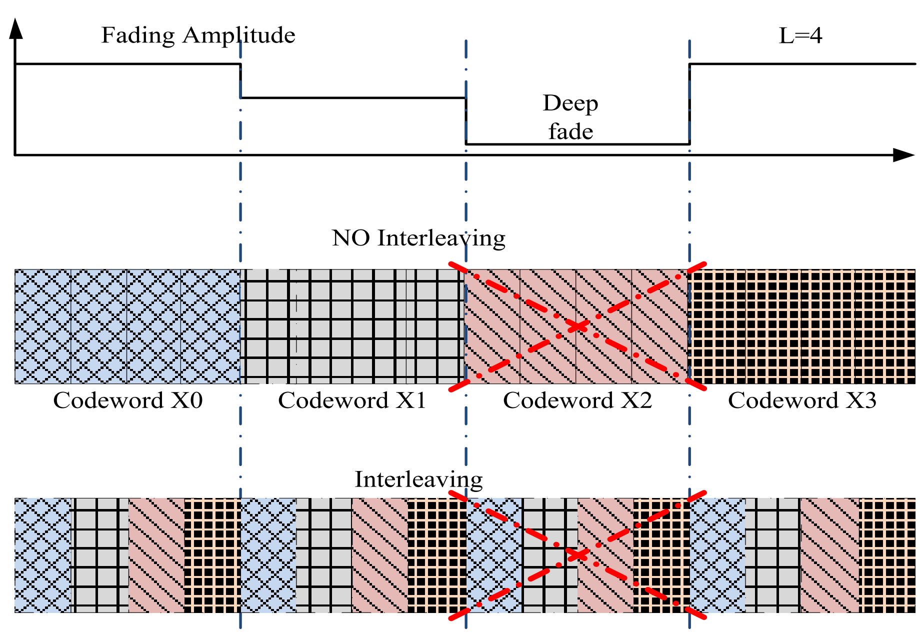


Figure 2.16code words are transmitted over consecutive and interleaved symbols.

2.4.3 SPATIAL DIVERSITY

The signal is transmitted over several different propagation paths. In wireless communication, space diversity is achieved by using a combination of multiple transmit / receive antennas. The antennas are sufficiently placed to each other in order to have the channel gains between different antenna pairs fade independently. Figure 2.17 illustrates the different types of diversity which are Transmit diversity, receive diversity and transmit and receive diversity.

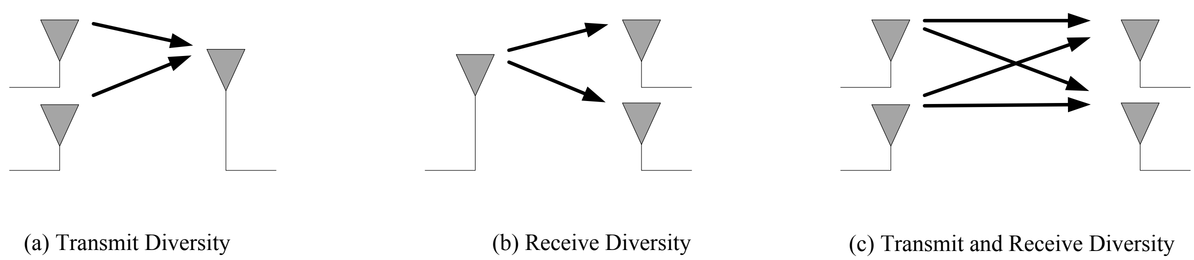


Figure 2.17 Spatial diversity illustrations

Consider the multiple input single output (MISO) case of Figure 2.17 to illustrate the possible benefits of this diversity approach. One simple way to obtain diversity order is to repeatedly transmit one symbol over L transmit antennas and over L symbol periods. During each symbol period, only one antenna is actively functioning and all others are down [3]. This is similar to repetition code. The drawback of this approach is the low bandwidth efficiency despite the fact that it provides a diversity order of L. Lately, this field of research is highly active especially in space time coding where transmit diversity is provided with high bandwidth efficiency. The most basic space time coding scheme is the Alamouti scheme which is adopted in most of the third generation cellular standards [28]. As shown in [3], the Alamouti scheme provides about 3 dB of power gain compared to the repetition code while bandwidth efficiency is maintained.

In theory, spatial diversity can be implemented at both transmitter and receiver ends. Nevertheless, installing multiple antennas at the mobile terminal is quite expensive and almost impossible due to size constraints. Cooperative diversity has been proposed as a new class of diversity which offers similar spatial diversity to multiple input multiple output (MIMO) systems.

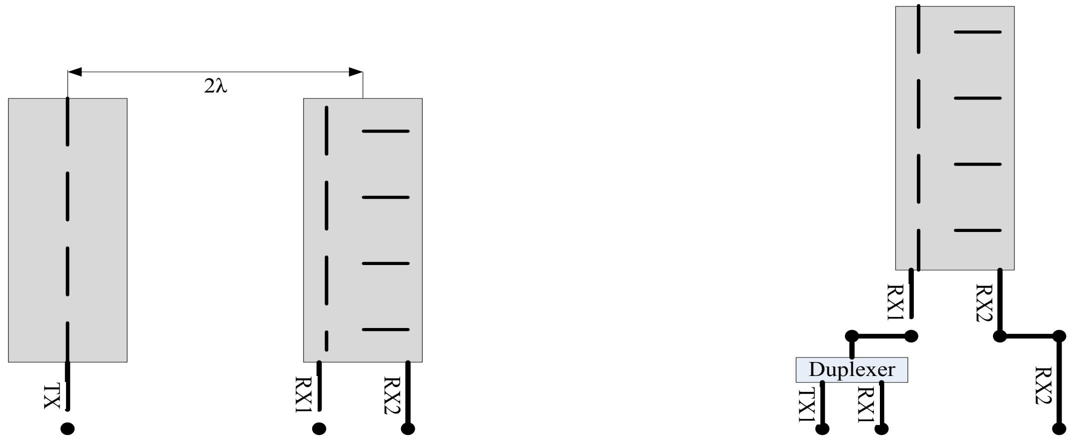
[6] and [50] independently derived the capacity of MIMO channels. They showed that the capacity of a wireless channel in a fading environment can be increased considerably by employing multiple transmitting and/or receiving antennas. Consider a MIMO system with N_t transmit and N_r receive antennas. It is shown that a MIMO system with independent fading between antenna pairs, one can design codes with probability of error that decays with $SNR^{-N_t N_r}$ which means that the system can achieve a diversity gain of $N_t N_r$.

2.4.4 POLARIZATION DIVERSITY

Multiple versions of a signal are transmitted and received via antennas with different polarization. Polarization diversity combines pairs of antennas with orthogonal polarizations. Reflected signals can undergo polarization changes based on the wireless channel model. This diversity technique demonstrates good performance at base stations because it is less vulnerable to near random orientations of transmitting antennas.

As a good practical example, consider the base station in a cellular network. It is quiet known that mobile phones have considerably lower transmittal power than the transmitters at the base stations. To compensate this difference, one can use polarization diversity systems at the base station via dual polarized antennas [29].

Figure 2.18 shows a sector antenna system with polarization diversity reception. The difference between both systems is in the space constraints. Some times in congested area, it is difficult to have more space for installing antennas. The system in (2.18b) can have receive and transmit antennas built-in in one antenna frame.



(a) Two antennas, three feeders

(b) One antenna, three feeders, one duplexer filter

Figure 2.18 Sector antenna system with polarization diversity reception

2.4.5 MULTIUSER DIVERSITY

Multiuser diversity is obtained by opportunistic user scheduling at either the transmitter or the receiver. Opportunistic user scheduling is as follows: the transmitter selects the best user among candidate receivers according to the qualities of each channel between the transmitter and each receiver. In frequency division duplexing (FDD) systems, the receiver must feedback the channel quality information to the transmitter with limited level of resolution. [3]

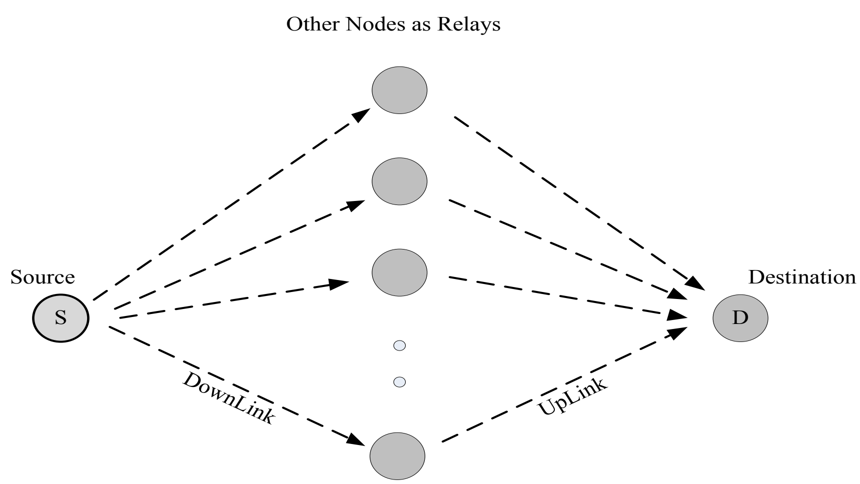


Figure 2.19 Multiuser illustrations using all other nodes as relays

One possible way of achieving multiuser diversity is via relaying. Figure 2.19 illustrates an example of multiuser diversity that is artificially created using all other nodes as relays. In this case, the channel variation changes from slow rather fast time scale fading. The relaying and destination nodes are not fixed at specific locations, they are moving. In first phase source to relays transmission, the source relays a packet to the nearest neighboring nodes. Different packets are distributed to the destination via different relay nodes. Communication is limited to the nearest neighbors but each packet goes at most two hops. In the second phase relays to destination transmission, all nodes have packets for the destination. Each relay node forwards packets to destination only when it gets close.

2.4.6 COOPERATIVE DIVERSITY

Cooperative diversity was originally introduced in 2003 [26, 27]. It exploits spatial diversity by letting user nodes to exchange information and emulate an array of distributed antenna [25]. In cooperative transmission, the information of a certain destination node may reach its destination via multiple transmit antennas each of which belongs to one node. The overall performance is based on the link quality through which the information passes from one node to another. Hence, each user link carries information for other nodes as well. It is clear that to mitigate error propagation from one node to another, it is important to correctly rebuild the received signal at each node prior to relay it.

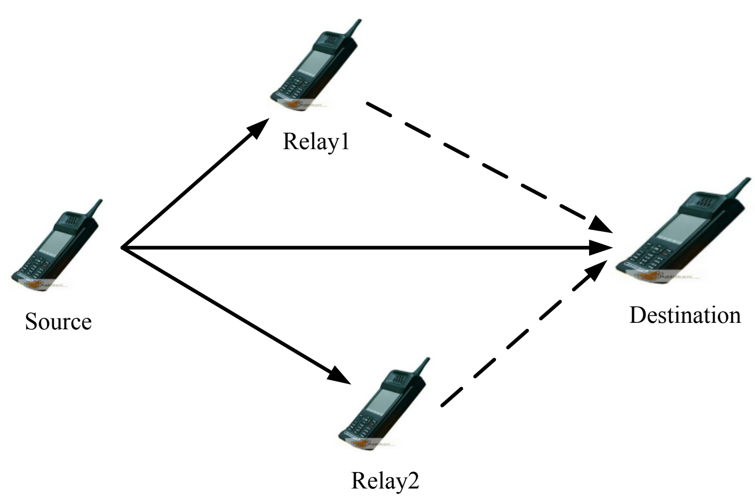


Figure 2.20 illustration of cooperative wireless transmission

As illustrated in Figure 2.20, the two relay nodes can receive signals from the source node transmission, process those received signals and transmit their own signals to increase capacity and reliability of end to end transmissions. Additionally, relaying can be performed in multiple stages so that relays and destinations benefit from spatial diversity.

The solid and dashed arrows indicate transmissions that occur in different time slots or frequency bands. The main advantage of cooperative communications resides when multiple transmissions experience fading and shadowing. For example, if the signal coming from the source node experiences a deep fade at the destination, there is a high chance that it is communicated to the destination via other neighboring relaying nodes.

2.5 TURBO CODES

Prior to turbo codes, the best performance one can get was based on an outer Reed-Solomon error correction code combined with an inner Viterbi-decoded convolutional code.

In 1993, Turbo coding was introduced by Berrou [2]. It was the first practical code to closely approach Shannon's channel capacity limits. Since its discovery, turbo code which is an energy efficient class of forward error correction codes, has progressed and reached a maturity state within just few years. Turbo coding is now in many standardized systems as Long Term Evolution (LTE).

2.5.1 ENCODER

Figure 2.21 shows the bloc diagram of the turbo encoding scheme that was originally proposed by Berrou [2]. It consists of a parallel concatenation of two recursive systematic convolutional (RSC) codes. The two rate $1/2$ RSC encoders are separated by an interleaver π. The information source is directly connected to the input of the first block encoder while it is connected via an interleaver to the second block encoder. $X_i^{(0)}$ is an exact copy of the information stream M_i which is called systematic output, $X_i^{(1)}$ and $X_i^{(2)}$ are the two parity outputs. The three output streams are multiplexed to form the codeword $X = \left\{X_i^{(0)}, X_i^{(1)}, X_i^{(2)}\right\}$. This leads to a turbo code of rate $1/3$. Though, other code rates are derived by systematically deleting bits from the output stream of an encoder. This is called puncturing. For instance, a rate $1/3$ Turbo code can be converted into a rate $1/2$ Turbo code by using the puncturing matrix

$$P_M = \begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{2.59}$$

where the two parity outputs are alternately punctured.

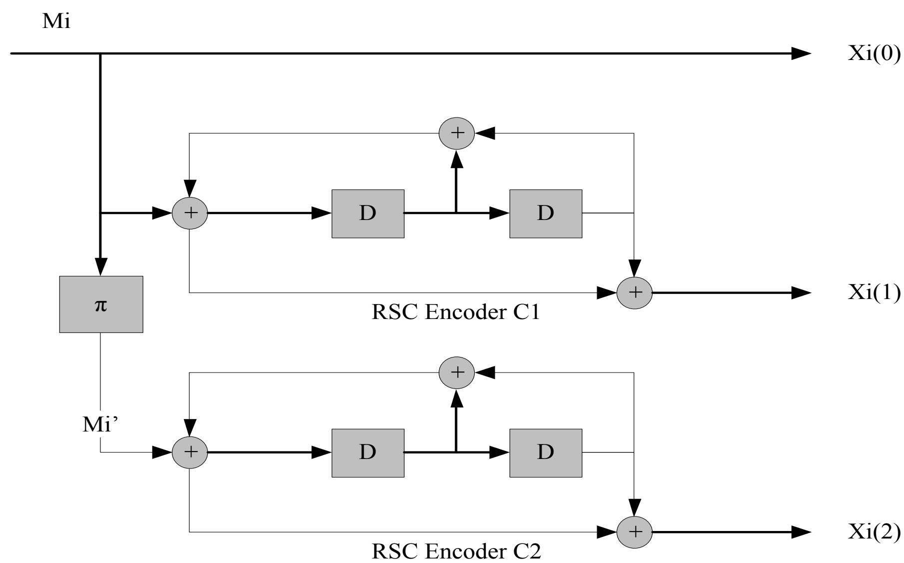


Figure 2.21 Rate $1/3$ turbo encoder

Interleaving is the process of rearranging bits according to a specific scheme or randomly. The interleaver plays an important role in achieving the highest performance possible in turbo codes. There has been lots of research on interleavers design and performance. However, the use of interleavers is mainly to ensure that the codewords produced by a turbo encoder have high Hamming distance. Some of the interleaver types are Block, semi-random and pseudo random interleavers.

An important issue that affects the performance of turbo codes is trellis termination. In principle, the larger the number of trellis transitions in which the two paths differ, the larger is the possible Hamming distance between the two corresponding codewords. In practice convolutional turbo odes are truncated at some point in order to encode the information sequence block by block. If no precautions are taken before truncation, each of the encoder states is a valid ending state and thus the shortest possible difference between the two trellis paths is made up of only one trellis transition. Naturally this procedure may result in very poor distance properties [8]. One approach to the problem is the tail biting. With tail biting the encoder is initialized to the same state that it will end up in, after encoding the whole block. The advantage of using tail-biting compared to trellis termination is that tail biting does not require transmission of tail bits.

2.5.2 DECODER

Figure 2.22 illustrates the block diagram of rate $1/3$ turbo decoder. The first constituent decoder D_1 receives the scaled systematic sequence$y^{(0)}$, the first scaled parity sequence $y^{(1)}$, and the a priori information Z_2 from the second constituent decoder D_2. It computes the log likelihood ratio (LLR). The extrinsic information is interleaved and used as the a priori information Z_1 by the second decoder.

Similarly, the second decoder D_2 receives the scaled systematic sequence$y-^{(0)}$, and the second scaled parity sequence $y^{(2)}$. After a certain number of iterations, the final estimate of the message sequence $\hat{m}$ is found by de-interleaving and hard limiting the output of D_2.

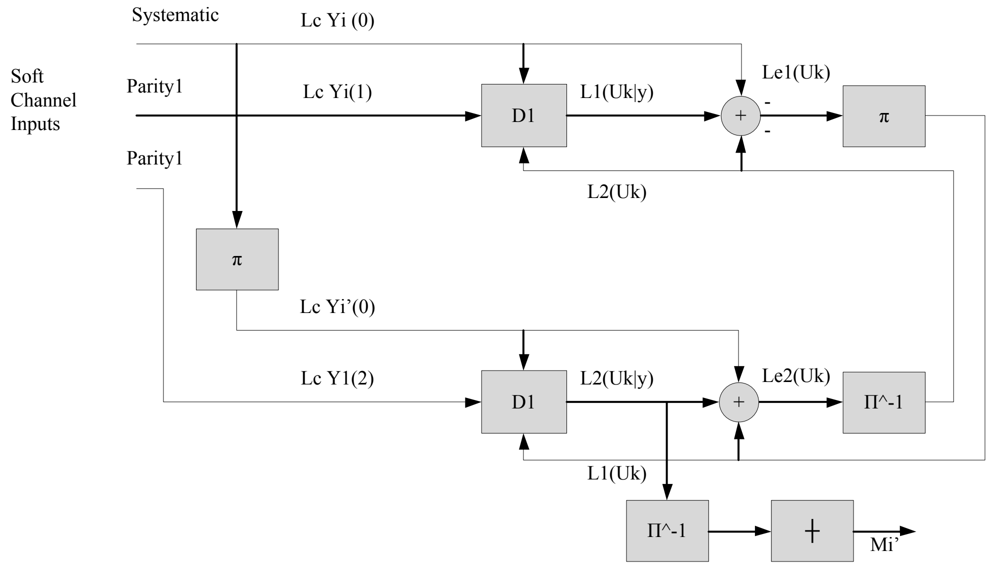


Figure 2. 22 Rate $1/3$ turbo decoder

2.6 NETWORK CODING

In various communication networks, files are divided into data packets and transmitted from the source node to other nodes by the traditional approach store and forward in which data packets received are stored and then forwarded to the next node. In network coding, intermediate nodes process combinations of previously received information, then create and transmit new packet to the next nodes. Network coding (NC) offers great benefits such as higher throughput, increased robustness and security.

2.6.1 CONCEPT OF NETWORK CODING

The concept of network coding was newly developed by Ahlswede in 2000 [31]. Ahlswede shows that network coding allows a source to multicast information a rate approaching the smallest minimum cut between the source node and the receiver node. In [32], Li shows that linear network coding with finite symbol size is sufficient for multicast connections. Koetter [33] presents an algebraic framework for linear network coding extending previous results to arbitrary networks, and prove the achievability with time-invariant solutions of the min-cut max-flow bound for networks with delay and cycles.

Due to its vast application, network coding has generated much interest in information theory, wireless communications and cryptography.

Figure 2.23 illustrates the butterfly network [34] which features a multicast from a single source to two destinations. Assume that the source node S multicasts two packets, X1 and X2, to both destination D1 and D2. In Figure 2.23a, every channel carries X1 or X2 and every intermediate node needs to replicate the received packet and then send them out. In Figure 2.23b, instead of copying and forwarding each single packet, the intermediate node 3 computes and outputs the bitwise XOR of X1 and X2. The channel from node 3 to node 4 is used to transmit X1+X2 which is then replicated at node 4 for passing on to nodes D1 and D2. The destination nodes decode by performing further decoding operations on the received packets. The node D1 can recover X2 by computing the XOR of the received packets X1 and X1+X2. Similarly, the node D2 can recover X1 by computing the XOR of X2 and X1+X2. As it shows in Figure 2.23b, it achieves the same results as Figure 2.23a with one less channel.

In wireless communications, network coding can be used to offer more benefits in terms of throughput, bandwidth and delay. It is mainly a good method to save on the number of time slots required to complete a communication round in cooperative communications. Figure 2.24 (a) illustrates the standard approach [35]. Nodes S and D send their packets to the relay R, and then R forwards each packet to the corresponding destinations. With network coding in Figure 2.24 (b), the relay creates a new packet X1+X2, and then sends it to both destinations. As in the above example, performing the bitwise XOR at the destination with its own message, the destination is able to decode the other node message. The advantage in Figure 2.24 (b) over Figure 2.24 (a) is that by using network coding, the complete transmission requires two time slots instead of three. This advantage has a great impact on throughput, delay and bandwidth.

This approach is adopted in one of the coding schemes in chapter four. It proves great gain over the other schemes which are detailed in chapter four.

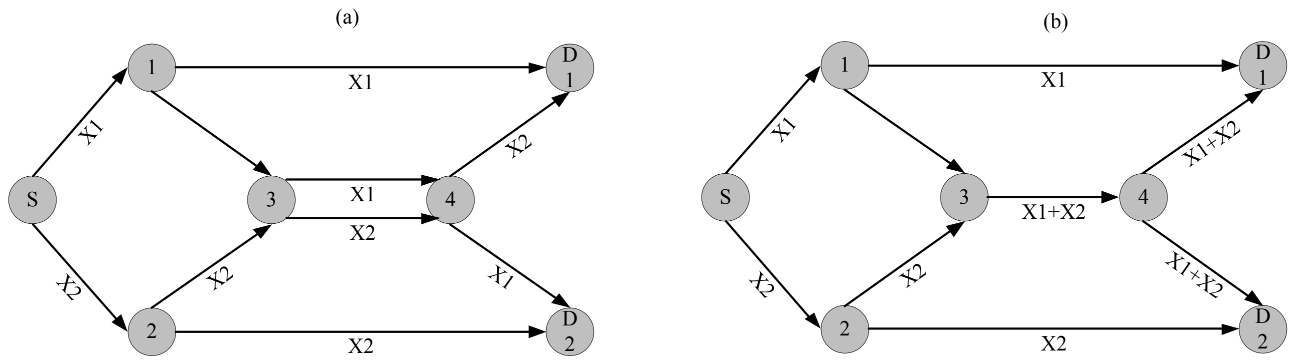


Figure 2.23 Multicasting in the butterfly network

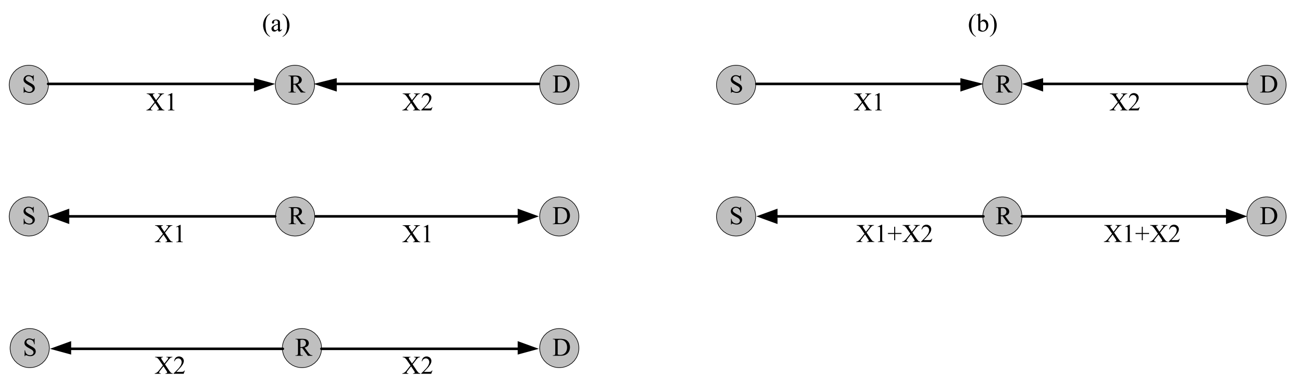


Figure 2.24 information exchange in wireless ad hoc network

2.6.2 BENEFITS OF NETWORK CODING

The main outcomes achieved in network coding are throughput and robustness.

The essential advantage out of network coding is possible throughput increase in certain network topologies [34, 36]. This is achieved by using fewer packets transmission to communicate more information in networks. Figure 2.23 illustrates how the butterfly network example using network coding can improve throughput for multicast in wired networks.

Similarly, Figure 2.24 demonstrates the saving in terms of the number of transmission at the relay node which therefore is translated a reduction of 50% of resource usage in the downlink bandwidth.

Network coding can also be used to improve robustness against network failures. This is achieved because of the linear combination of packets that is performed all over the network and not only at the source node. Thus the destination nodes can recover the original file with incomplete information they receive. Network coding can also provide protection against link failure. Koetter [33] investigated the problem of network recovery from link failure, and proved that there exist coding strategies that provide maximally robust networks for the multicast setup, and that there exists a static network coding solutions for network recovery under failure pattern without rerouting.

2.7 NESTED CODES

Xiao [37] proposes a joint channel and network coding approach called nested codes. In this coding scheme, multiple information packets are separately encoded and the resulting encoded packets are then XORed together at the physical layer prior to transmission. These encoded and XORed packets can be decoded in different ways depending on the prior information available to the receiver. If a receiver already knows the information in one or more of the packets, then the effect of known packets can be stripped away by regarding the known code words as a scrambling pattern; the net result is to decode the information that is not known to the receiver at lower effective rate (with more redundancy and thus more error protection). Alternatively, if a receiver has no prior information about any of the packets, then its decoder regards the XORed code words as being produced by a higher rate nested code. In this manner, the same codeword broadcast in a wireless medium is interpreted and decoded differently at different receivers depending on the receivers' prior knowledge of the broadcast information. Nested codes have different interpretations and can be decoded with variable rates at the receiver; this property makes nested codes an interesting coding strategy for collaborative communications.

Assume that there are N information packets of length k, each of which is going to be encoded at rate $R = {}^{k}/_{n}$. Let $G_1, G_2, .., G_N$be the generator matrices of rate $R = {}^{k}/_{nN}$. The resulting codeword can be represented as

$$c = i_1 G_1 \oplus i_2 G_3 \oplus \dots \oplus i_N G_N = [i_1, i_2, \dots i_N] \begin{bmatrix} G_1 \\ G_3 \\ \dots \\ G_N \end{bmatrix} \tag{2.60}$$

Note that if $G_1 = G_2 = \cdots = G_N$, then the resulting codeword becomes

$$c = i_1 G_1 \oplus i_2 G_3 \oplus \dots \oplus i_N G_N = [i_1 \oplus i_2 \oplus \dots \oplus i_N] G \tag{2.61}$$

The codeword in (2.57) represents the basic XOR in network coding. It is almost impossible to decode the original messages of more than one of the messages is unknown.

2.8 SUMMARY

In this chapter, we presented an overview on the wireless channel modeling. It was concluded that the variation of the received signal strength due to multipath transmission is the main reason for mediocre performance of the wireless communication systems. We also presented an overview on the achievable rate region for the interference channels. The capacity region for an interference channel is still an open problem. However; the best achievable region is the Han-Kobayashi achievable region. It has been shown that diversity is used to combat fading in wireless communications. We presented various diversity techniques. It has been shown that cooperative diversity achieves similar spatial diversity gain and throughput to the multiple input multiple output systems. We have also introduced Turbo codes, network coding and nested codes. It has been shown that turbo codes perform close to Shannon limits. Nested codes are promising and useful tools in the design of error control schemes in cooperative wireless networks.

3 2-USER DESTINATION COOPERATION IN INTERFERENCE CHANNELS

In this chapter, we consider 2-user cooperating in an interference channel. We evaluate the system performance before and after applying channel coding. We investigate a new cooperation scheme and various scenarios where the distances between nodes have different values. We first begin with the special case where all nodes are normalized at equal distances, then applying different cases that reflects real life scenarios

3.1 SYSTEM MODEL

We consider the similar model as the one presented in [7], where two sources (X_1, X_2) transmit independently to two destinations (Y_1, Y_2). We assume that all links experience flat block Rayleigh fading. Each destination receives both information from X_1 andX_2. The model is depicted in Figure 3.1.

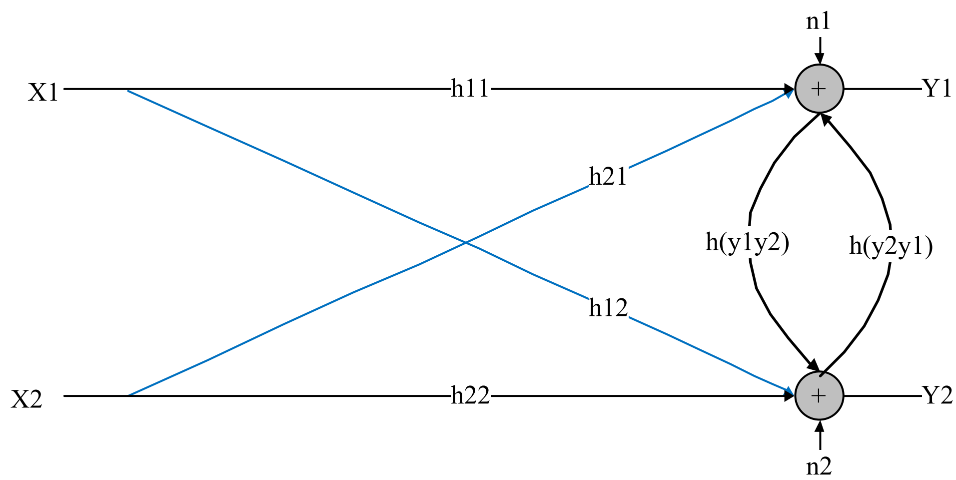


Figure 3.1 – System model

At first, transmitters X_1 and X_2 transmit and receivers try to decode both X_1 and X_2 (the received data). Then, if a receiver has successfully decoded X_1 and X_2, it cooperates with the other destination node by transmitting the information desired for it. For example: in the first cooperation scheme, if Y_1 can decode data from X_1 and X_2, in the second phase it transmits $X_2's$ data. This mode achieves at most a diversity of order 2.

Unlike [1], we assume that all terminals operate under the half duplex constraint. They can transmit or receive at any given time using the same frequency band. The overall transmission time period is divided into two phases: the broadcast phase and the cooperation phase as shown in Figure 3.2.

3.1.1 Broadcast Phase

In this stage (Transmission Slot), the source nodes use an (n,k) code to transmit k bits of information with rate $R = \frac{k}{n}$ to the destination nodes. We express the received signals at each destination as

$$Y_1 = \sqrt{pg_{X_1Y_1}}\, X_1 h_{11} + \sqrt{pg_{X_2Y_1}}\, X_2 h_{21} + n_1 \tag{3.1}$$

$$Y_2 = \sqrt{pg_{X_1Y_2}}\, X_1 h_{12} + \sqrt{pg_{X_2Y_2}}\, X_2 h_{22} + n_2 \quad (3.2)$$

where $n_1$and n_2 are independent identically distributed (i.i.d.), zero-mean, unit variance, complex Gaussian random variables.

h_{ij}, $i, j \in \{1,2\}, h_{Y_1Y_2}$ and $h_{Y_2Y_1}$: are complex channel coefficients which are assumed to be constant over one data transmission block and also assumed to be known at all destination nodes. The source nodes have no knowledge of the instantaneous channel characteristics.

$pg_{(ij)} = \frac{1}{d_{ij}^{\alpha}}$ represents the path gains on the link (i, j), where α is the path loss exponent andd_{ij} represents the distances between node i and node$j$.

3.1.2 COOPERATION PHASE

In this stage, the destination nodes assist each other by decoding, re-encoding and re-transmitting another copy of the correctly received message that is intended to the other destination.

3.1.2.1 COOPERATION SCHEMES

Depending on the correctly received information (X_1, X_2), we consider two cooperation schemes

- The basic scheme [55] considers cooperation at destination $Y_i$based only on receiving both information (X_i, X_j) correctly at destination Y_i, $i, j \in \{1,2\}$,(Case 4 in table 3.1).In this scheme, we express the received signal at Y_2 from Y_1 and vice versa as:

$$Y_{12} = \sqrt{pg_{Y_1Y_2}}\, \hat{X}_2 h_{Y_1Y_2} + n_3 \quad (3.3)$$

$$Y_{21} = \sqrt{pg_{Y_2Y_1}}\, \hat{X}_1 h_{Y_2Y_1} + n_4 \quad (3.4)$$

- The enhanced scheme considers the availability of more cases at the destination node Y_i (cases 2 or 3 in table 3.1) along with the basic scheme.

Hence, the cooperation at destination node i is only occurring when X_i is correctly received at node$i$. Furthermore, if X_j is also received correctly at node$i$ (Case 4), then cooperation is occurring by sending a correct copy of X_j to node$j(i \neq j)$.If X_j is not received correctly at node$i$ (Case 2 or case 3), then cooperation is happening by sending a correct copy of X_i to node$j(i \neq j)$. The enhanced idea behind this scheme is to increase the chance of correctly detecting X_j at node$j$. In other words, when receiving a correct copy of X_i at node$j$, this solid copy is used to again perform interference cancellation process at node j and detects X_j at node$j$ with higher certainty.

Subsequently, the destination node i is actively cooperating in 2 cases and remains silent (listening) in the other 2 cases. For example, cooperation at Y_1 is occurring if both X_1 and X_2 were correctly received (case 4) by sending a copy of X_2 to Y_2 or if just X_1 was correctly received (case 2) by sending a copy of X_1 to Y_2. Similarly, cooperation at Y_2 is happening during case 4 by sending a copy of X_1 to $Y_1$and during case 3 by sending a copy of X_2 to Y_1.

In the enhanced scheme, we express the received signal at Y_1 from Y_2 and vice versa as:

$$Y_{21} = \sqrt{pg_{Y_2Y_1}}\,\hat{X}_2 h_{Y_2Y_1} + n_4 \tag{3.5}$$

$$Y_{12} = \sqrt{pg_{Y_1Y_2}}\,\hat{X}_1 h_{Y_1Y_2} + n_3 \tag{3.6}$$

$\hat{X}_1$ and $\hat{X}_2$ represent the decoded messages at Y_1 and Y_2 respectively.n_3 and n_4 are independent identically distributed (i.i.d.), zero-mean, unit variance, complex Gaussian random variables. $h_{Y_2Y_1}$and $h_{Y_1Y_2}$ are the channel complex coefficients between destination nodes.

At each destination node, there are 4 possible situations as shown in table 3.1

All possibilities at each destination			
Case 1 No Cooperation	Case 2 Cooperation	Case 3 cooperation	Case 4 Cooperation
$\overline{X}_1$ incorrect $\overline{X}_2$ incorrect	X_1 correct $\overline{X}_2$ incorrect	$\overline{X}_1$ incorrect X_2 correct	X_1 correct X_2 correct

Table 3.1 possible situations available at all destinations

3.2 2-USER ORTHOGONAL CHANNEL

Time Division Multiple Access (TDMA) technique which is the baseline scheme divides the channel into two time slots (TS). Only one user transmits over the channel during any given TS.

Destination cooperation in interference channels (DC-IC) allows all users to transmit at the same time. The major advantage of DC-IC over the baseline scheme is the cooperative mode where both users are joining efforts to increase reliability and throughput. We will show that DC-IC has higher spectral efficiency than the baseline scheme. Figure 3.2 shows 2-user TS frames. It is obvious that for the 2-user orthogonal channel scheme X_1 and X_2 require 2 TS to be independently transmitted interference free. While for the DC-IC, we use the first TS to transmit both messages and the second TS to cooperate.

X1, Transmission	X2, Transmission	TDMA
X1, X2, Transmission	Cooperation	DC-IC

Figure 3.2 2-user orthogonal channels vs. DC-IC schemes

3.3 SUCCESSIVE INTERFERENCE CANCELLATION (SIC)

SIC is an iterative process that starts with the strongest signal first, decodes and re-encodes it. The second step is to subtract the decoded message from the original received signal. Then apply the same algorithm on the second strongest signal and so on until all received signals are decoded [21]. Figure 3.3 illustrates the SIC scheme for 2-user IC.

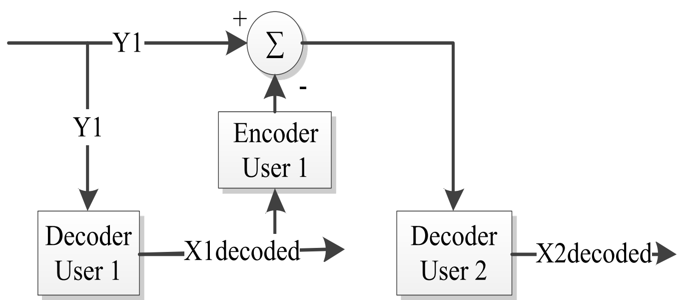


Figure 3.3 Successive Interference Cancellation scheme

From equation 3.1, we can express at node Y_1: Assume $h_{11} > h_{21}$, detect X_1:

$$decode\ \frac{Y_1}{h_{11}}\ to\ get\ \hat{X}_1$$

Subtract the decoded message from the received signal to detect X_2:

$$decode\,\frac{Y_1 - \sqrt{pg(x_1y_1)}\,\hat{X}_1 h_{11}}{h_{21}}\,to\ get\ \hat{X}_2$$

3.4 SIMULATION

In this section, we assume that$\alpha = 2$. The Binary Phase Shift Keying (BPSK) modulation is implemented with constellation points at -1 and 1. The channel code that is used at all nodes is Turbo code [8]. We first present an overview of the turbo encoder/decoder, and then we present the simulation results for two scenarios: the special case (upper bound) where all nodes are located at equal distances from each other and the more realistic scenario where nodes are located at different distances from each other.

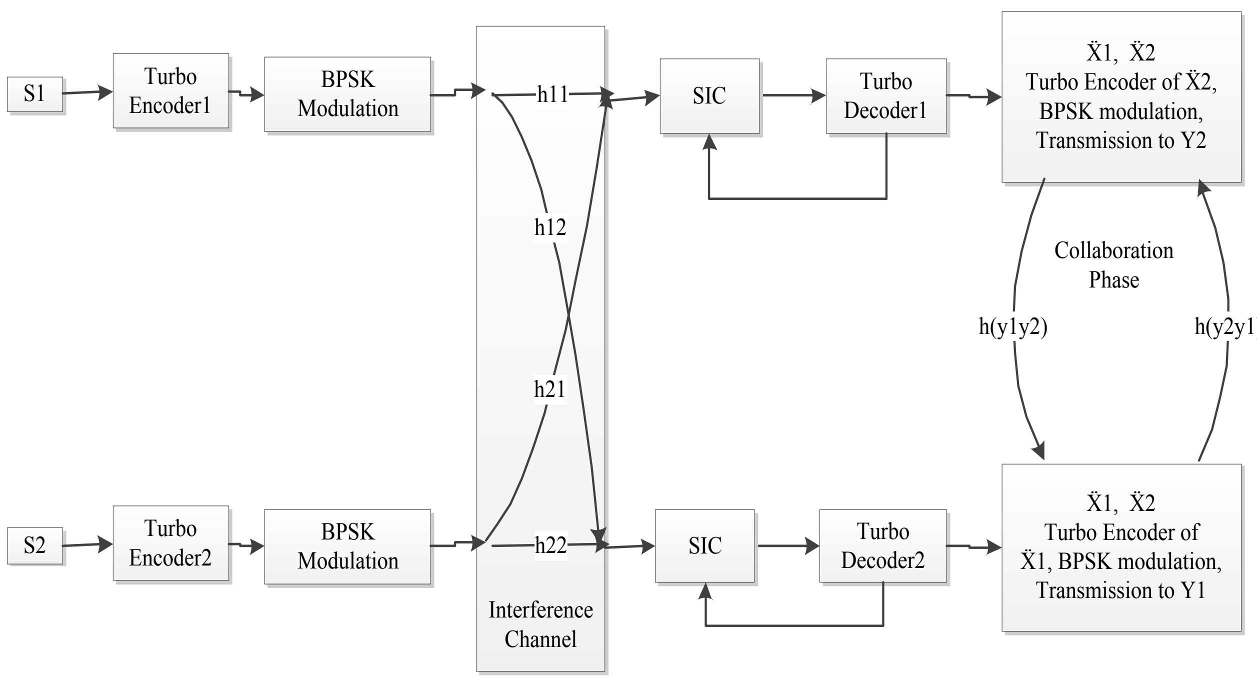


Figure 3.4 DC-IC channel coded system model

Figure 3.4 illustrates the coded DC-IC block diagram based on which we constructed our simulation algorithm.

Note that the Total SNR is the SNR taking into account the power consumed at both sources and destinations.

3.4.1 TURBO ENCODER / DECODER

The Turbo Encoder uses two Recursive Systematic Convolutional (RSC) component codes with generator polynomials $[7\ 5]_8$ and constraint length $K = 3$ [2].The best performance is achieved with relatively long interleavers. However, for our simulation, we assume a data block length of 1504 Bits (188 Bytes) which is the size of MPEG transport stream packet in DVB.

The Turbo decoder assumed in this simulation is the suboptimal Log-MAP algorithm [8]. It is an implementable version of the MAP algorithm that works in the Log domain. We assume that the code rate is ${}^1/_3$ and the number of decoding iteration is 4.

The equations to compute the branch transition probabilities ${\gamma_k}^{LM}$, forward ${\alpha_k}^{LM}$ and backward ${\beta_k}^{LM}$ recursions are as follows:

$$ {\gamma_k}^{LM}(s', s) = \ln \gamma_k(s', s) = \frac{1}{2} L_c \,.\, y_{k,1} \,.\, u_k + \frac{1}{2} \sum_{v=2}^{n} L_c \,.\, y_{k,v} \,.\, x_{k,v} + \frac{1}{2} u_k \,.\, L(u_k) \tag{3.7} $$

$$ {\alpha_k}^{LM}(s) = ln\, \alpha_k(s) = ln(\sum_{s'} e^{\gamma_k^{LM}(s',s)} \,.\, e^{\alpha_{k-1}^{LM}(s)}) = ln(\sum_{s'} e^{\gamma_k^{LM}(s',s) + \alpha_{k-1}^{LM}(s)}) \tag{3.8} $$

$$ {\beta_{k-1}}^{LM}(s') = ln\, \beta_{k-1}(s') = ln(\sum_{s} e^{\gamma_k^{LM}(s',s)} \,.\, e^{\beta_k^{LM}(s')}) = ln(\sum_{s} e^{\gamma_k^{LM}(s',s) + \beta_k^{LM}(s')}) \tag{3.9} $$

The Log-likelihood ratio is given by

$$L(\hat{u}_k) = ln\frac{\sum_{u_k=+1}^{(s',s)} e^{\gamma_k^{LM}(s',s)} \, . \, e^{\alpha_{k-1}^{LM}(s)} \, . \, e^{\beta_k^{LM}(s')}}{\sum_{u_k=-1}^{(s',s)} e^{\gamma_k^{LM}(s',s)} \, . \, e^{\alpha_{k-1}^{LM}(s)} \, . \, e^{\beta_k^{LM}(s')}} = ln\frac{\sum_{u_k=+1}^{(s',s)} e^{\gamma_k^{LM}(s',s)+\alpha_{k-1}^{LM}(s)+\beta_k^{LM}(s')}}{\sum_{u_k=-1}^{(s',s)} e^{\gamma_k^{LM}(s',s)+\alpha_{k-1}^{LM}(s)+\beta_k^{LM}(s')}}$$

$$= ln(\sum_{u_k=+1}^{(s',s)} e^{\gamma_k^{LM}(s',s)+\alpha_{k-1}^{LM}(s)+\beta_k^{LM}(s')})$$

$$- ln(\sum_{u_k=-1}^{(s',s)} e^{\gamma_k^{LM}(s',s)+\alpha_{k-1}^{LM}(s)+\beta_k^{LM}(s')}) \tag{3.10}$$

where

$$L_c = 4 \, . \, h_{ij} \, . \frac{E_s}{N_o}$$

3.4.2 SCENARIO 1 – SPECIAL CASE

In this scenario, all nodes are positioned at equal distances to each other$d_{ij} = 1$. We present a comparable analysis between coded and uncoded for both 2-user orthogonal channel and 2-user DC-IC systems.

3.4.2.1 FRAME ERROR RATE (FER)

Figure 3.5 illustrates the FER; it is shown that the system is achieving a diversity order of 2. Figure 3.5 also shows a change in FER curve indicating diversity gain. The 2-user DC-IC system requires two times slots to complete one full transmission.

From Figure 3.5, it can be seen that in the coded and cooperation case, the gain is more than 12dB at FER of 10^{-4} (case 4) and even larger at lower FER's. Furthermore, the additional gain out of the enhanced scheme is about 2dB (cases 2 or 3 and 4).

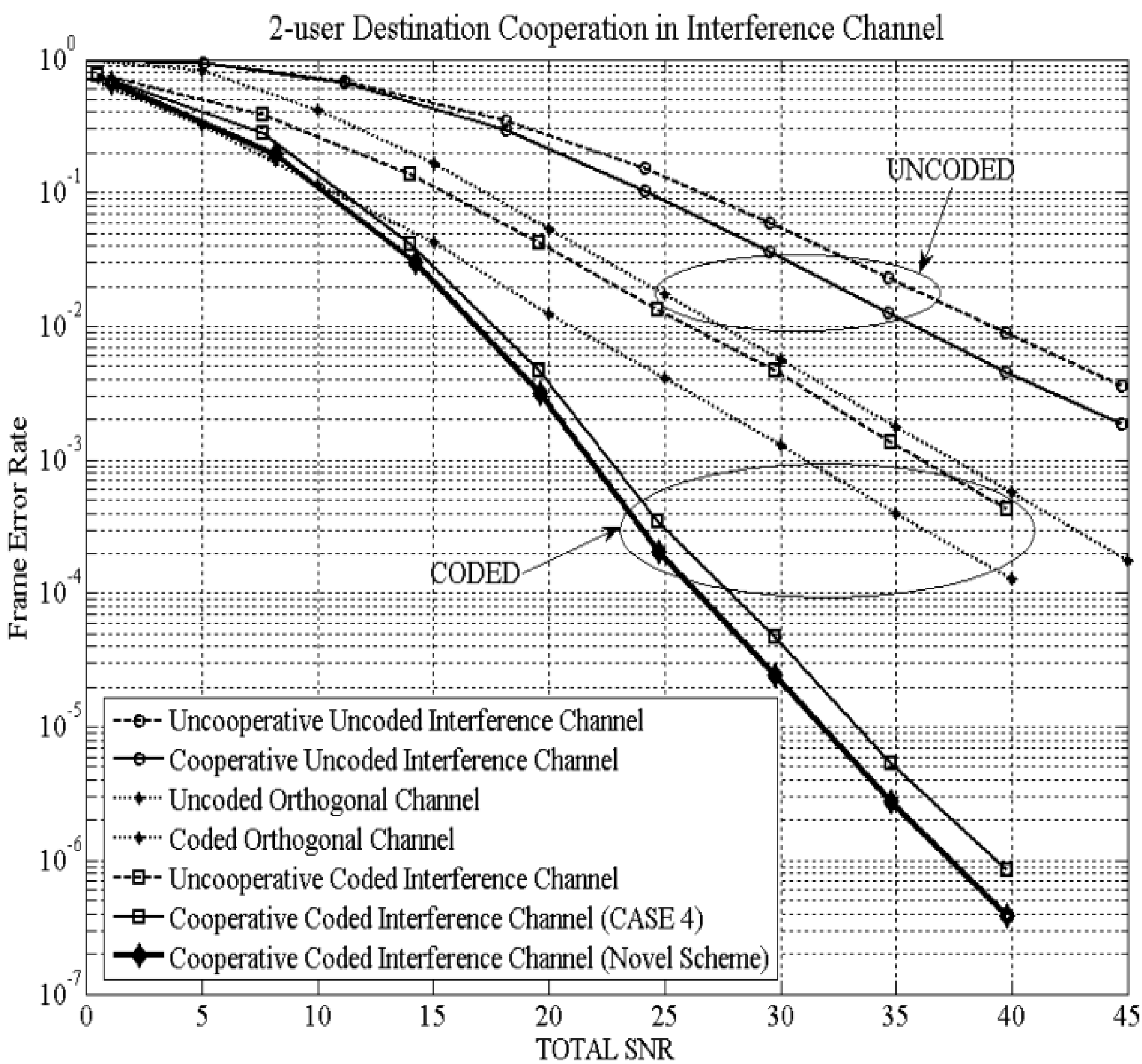


Figure 3.5 – Frame Error Rate – scenario 1

3.4.2.2 Cooperation Rate

Figure 3.6 shows the probability that the destination nodes can cooperate. Cooperation rate increases with the SNR and saturates at large values of SNR. This is due to the fact that at high SNR both receiver nodes receive the data from both source nodes correctly with high probability. Of course, this is the probability that the destination nodes are able to cooperate.

It is different from the actual rate of useful cooperation since if both receive the two pieces of data then there is little need for cooperation.

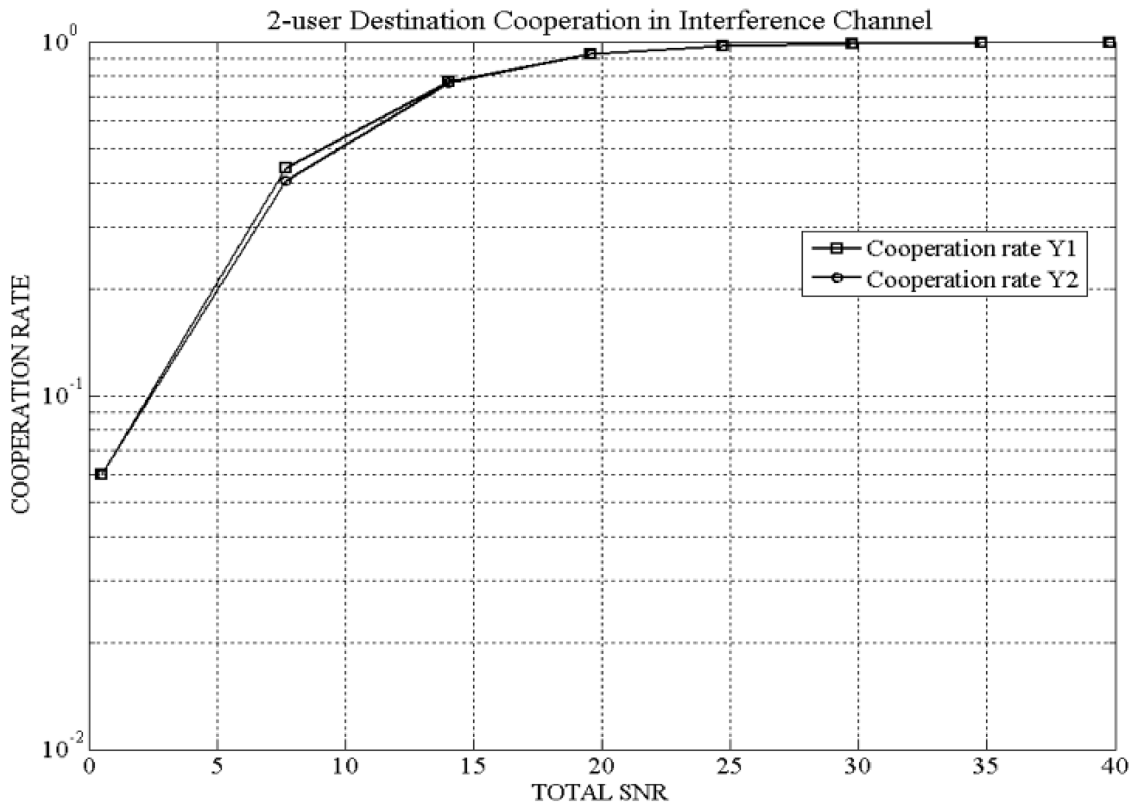


Figure 3.6 – Probability that destinations can cooperate – Scenario1

3.4.2.3 USEFUL COOPERATION

Figure 3.7 illustrates the rate of useful cooperation at both destinations. It is shown that the need for cooperation decreases as the SNR grows. It is reasonable that at very low SNR, useful cooperation is occurring more than at high SNR's due to the fact that at high SNR cooperation may not be needed. That is, it is a waste of energy to send data from Y_1 to Y_2 when Y_2 has already decoded X_2 correctly and vice versa.

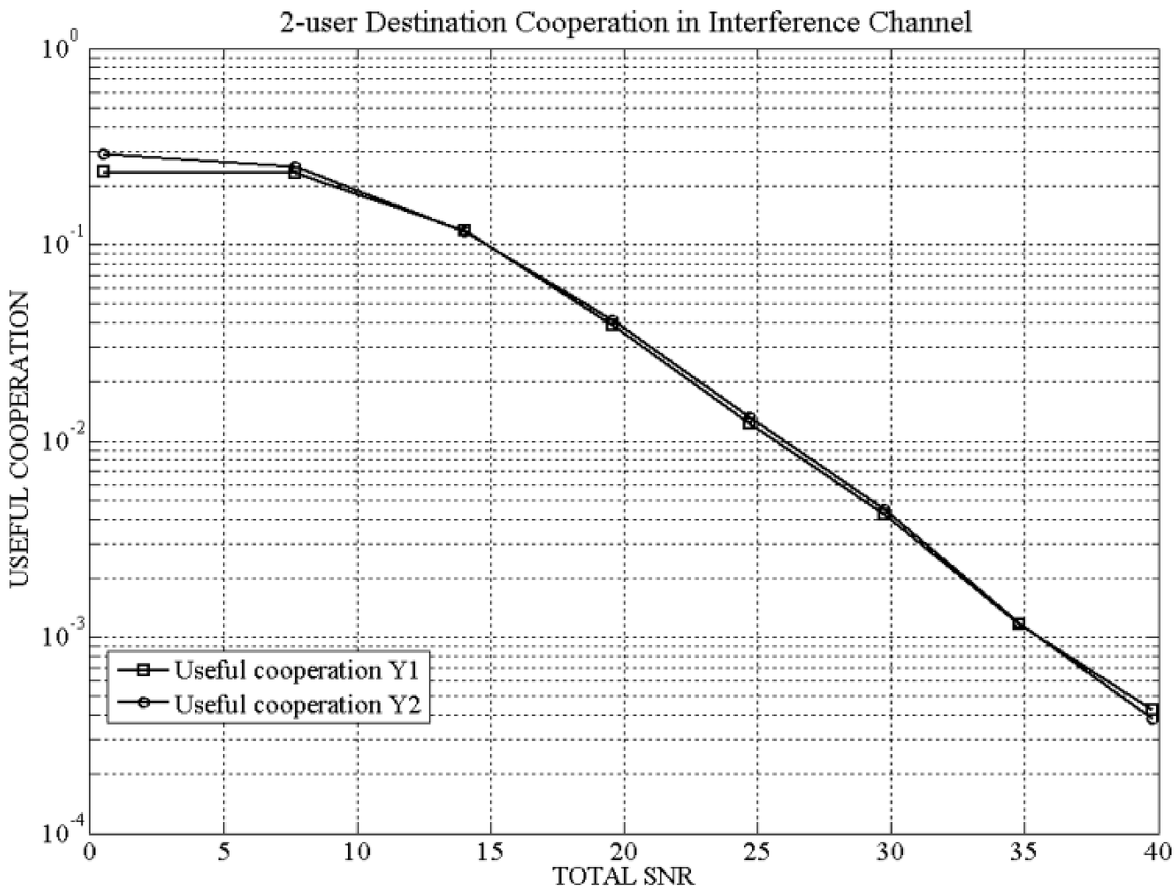


Figure 3.7 – Useful cooperation – Scenario1

3.4.2.4 EFFECT OF THE NUMBER OF DECODING ITERATIONS ON THE FER

In this simulation, we study the performance of the system for different values of decoding iterations considered for the turbo codes decoding process. This shows clearly the impact of the number of decoding iterations on the coding gain and illustrates the tradeoff between the coding gain and the time required to fully complete the decoding process. Figure 3.8 illustrates the curves of the FER for 1, 2, 4, 8 and 16 decoding iterations.

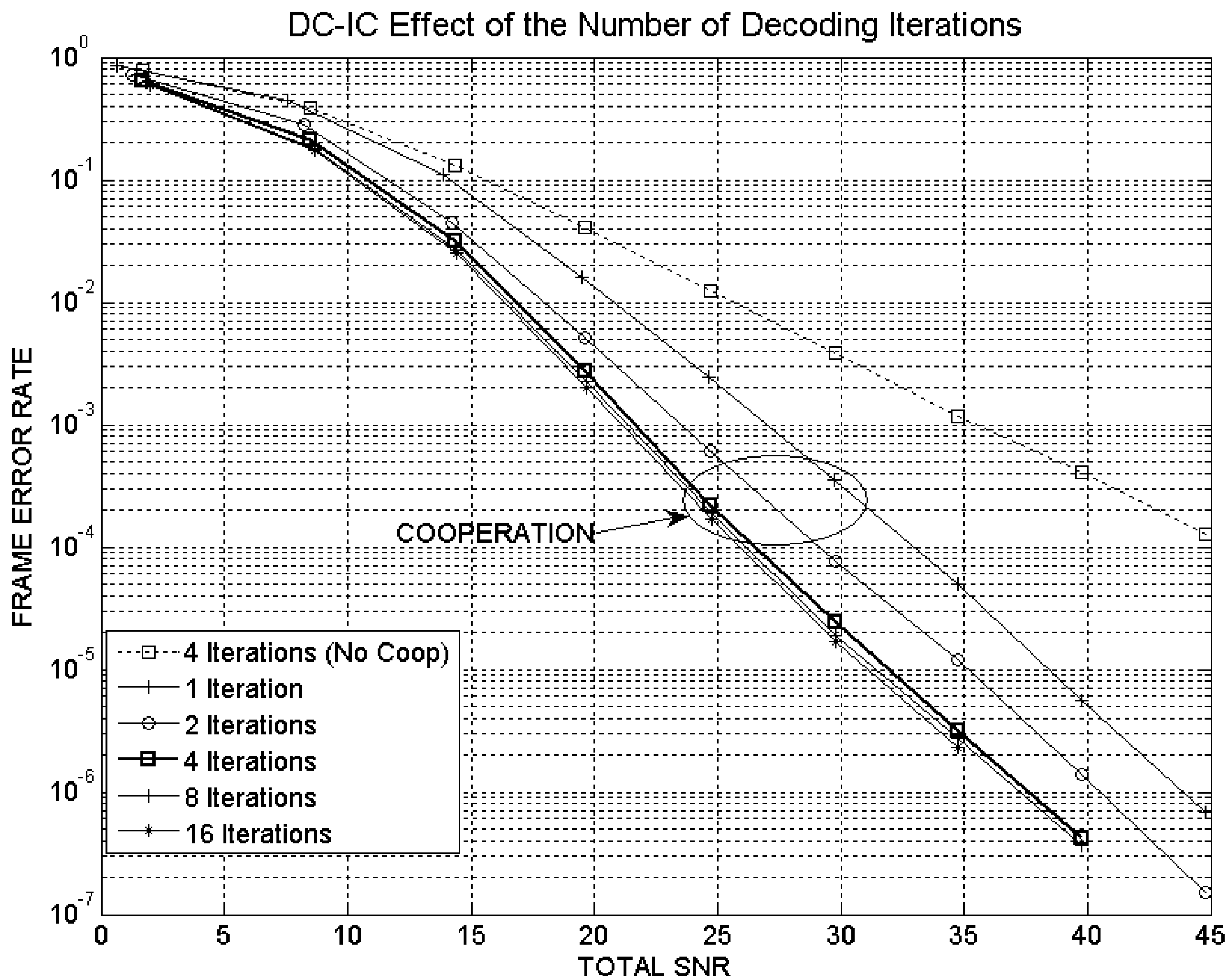


Figure 3.8FER - Effect of the number of decoding iterations – Scenario1

As the number of iterations increases, the turbo decoder performs considerably better. However after 6 iterations, there is little improvement achieved by using further iterations. Figure 3.8 shows that using 8 and 16 iterations rather than 4 gives an improvement of only about 0.25 and 0.4 dB respectively. Throughout our simulations, we used four iterations. In the next section, we consider the effects of puncturing.

3.4.2.5 EFFECT OF PUNCTURING ON THE FER

In turbo encoder, two component encoders are used for generating parity information from the data source. Throughout our simulations, we used two RSC component encoders having in $^1/_3$ code rate. Typically, in order to generate a $^1/_2$ code rate, half the parity bits from each component encoder are punctured [12].

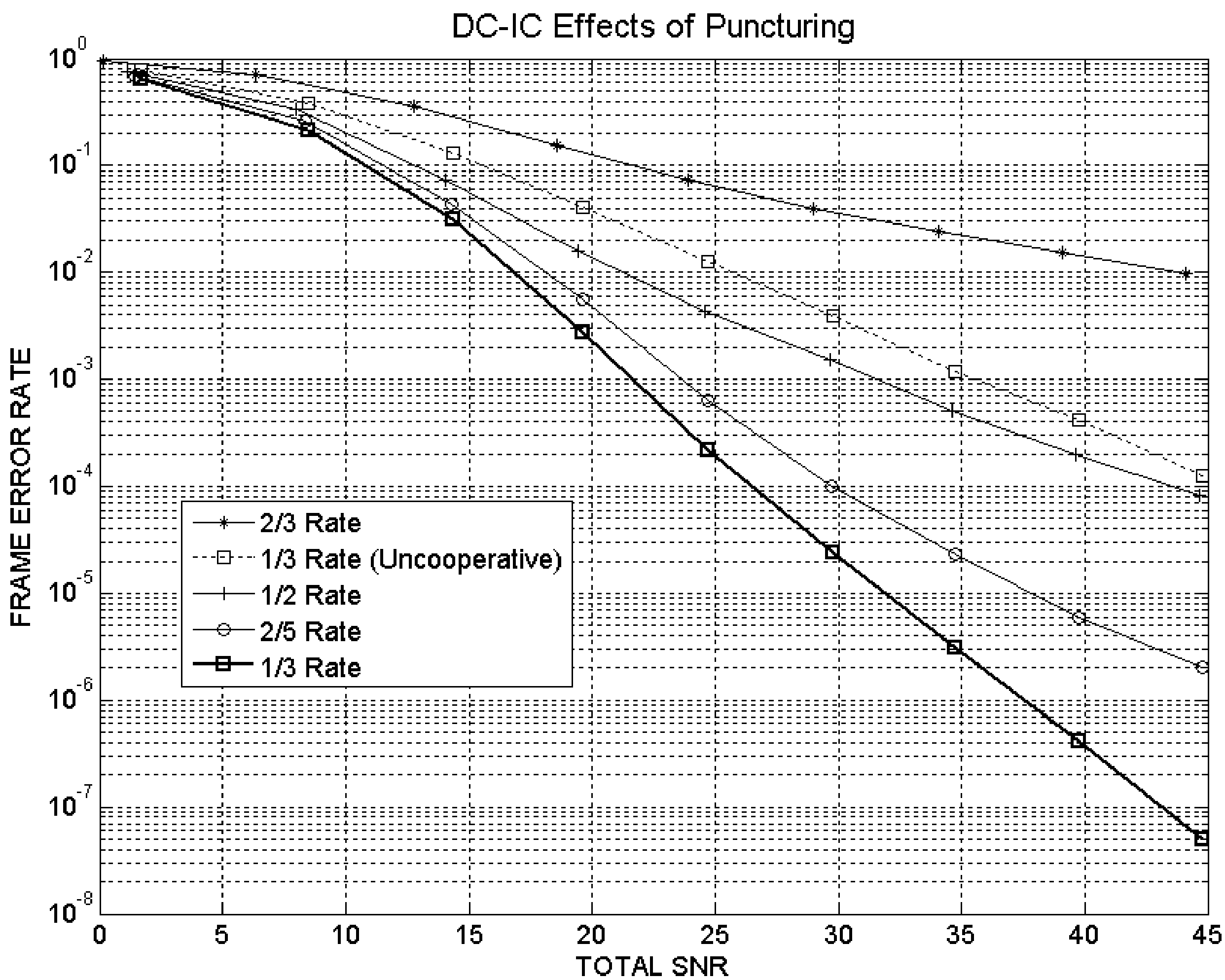


Figure 3.9 FER - Effect of puncturing – Scenario1

Figure 3.9 shows the FER of the system for several puncturing schemes resulting in some rates such as $^2/_5$, $^1/_2$ and $^2/_3$ compared with the no puncturing model of rate $^1/_3$. From Figure 3.9, it can be seen that the performance of the system degrades dramatically with puncturing due to the Rayleigh Fading channel characteristics.

3.4.2.6 EFFECT OF THE DATA BLOCK LENGTH ON THE FER

In most of the simulation algorithms used in this chapter, we consider the data block length (DBL) of 1504 bits (188 bytes). In this section, we show the impact of variable frame length on the system performance. Figure 3.10 illustrates the FER for various data block length; 169 bits (for voice transmission), 188 bytes which is the size of MPEG transport stream packet in DVB and 4096 bits. It shows that the performance is almost similar for both DBL of 1504 bits and 4096 bits at 10^{-5} of FER at low SNR, and then as SNR increases, the DBL of 4096 bits outperforms slightly the DBL of 1504 bits. On one hand, the more the DBL increases the performance of the pseudo random interleaver enhances, but on the other hand, it increases the FER. When it comes to increasing the DBL, there is a tradeoff between the FER and the interleaver performance which affects the overall performance.

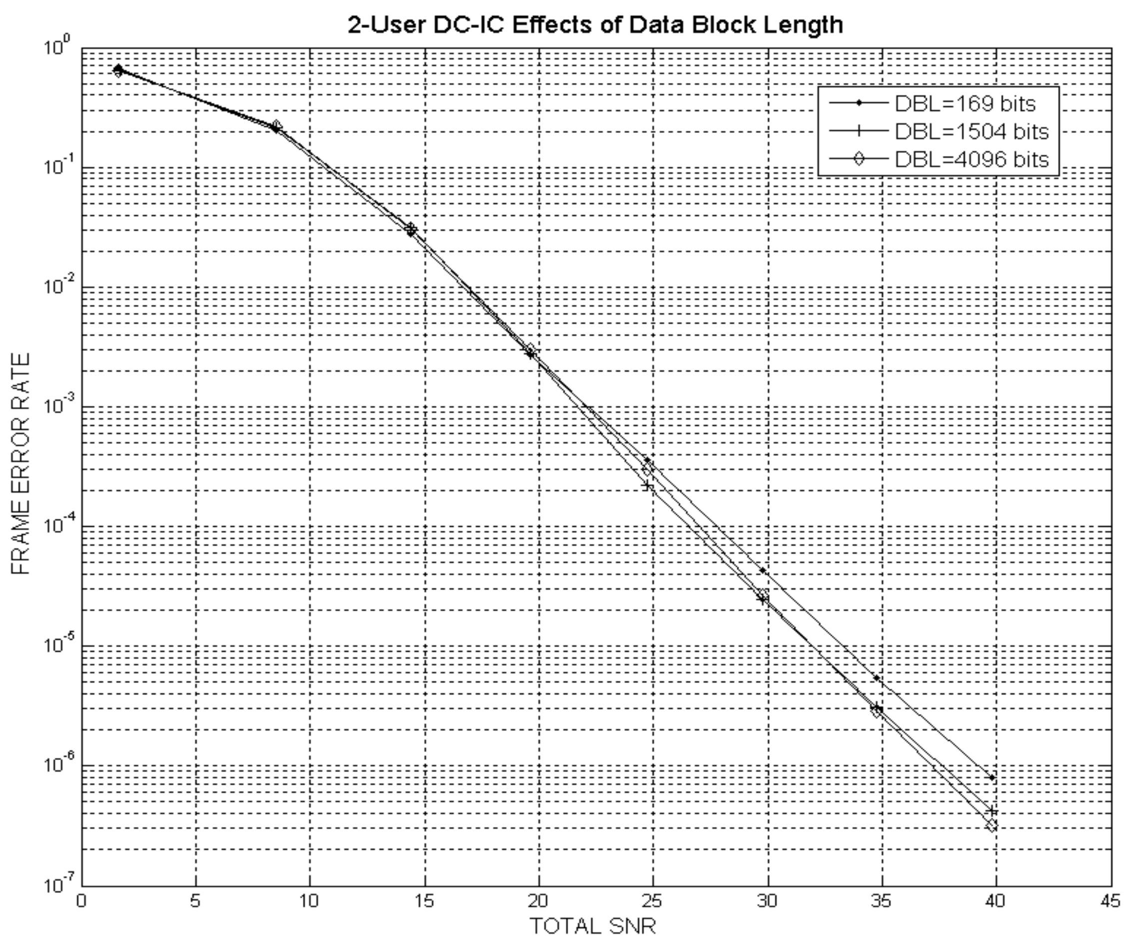


Figure 3.10 FER - Effect of Frame Length – Scenario1

3.4.2.7 EFFECT OF THE INTERLEAVER ON THE FER

The interleaver has a great impact on the performance of Turbo codes. The interleaver design along with the generator polynomials used in the component codes and the puncturing at the encoder have dramatic effect on the free distance of the resultant turbo code. Several algorithms have attempted to select a good interleaver based on maximizing the minimum free distance of the code. In this section, we compare the impact of the interleaver on the performance of the system. Figure 3.11 shows the FER for Row-Column (Block) [23], Circular shift interleaver [22] and pseudo random interleaver. It shows that the pseudo random interleaver has better performance than the others.

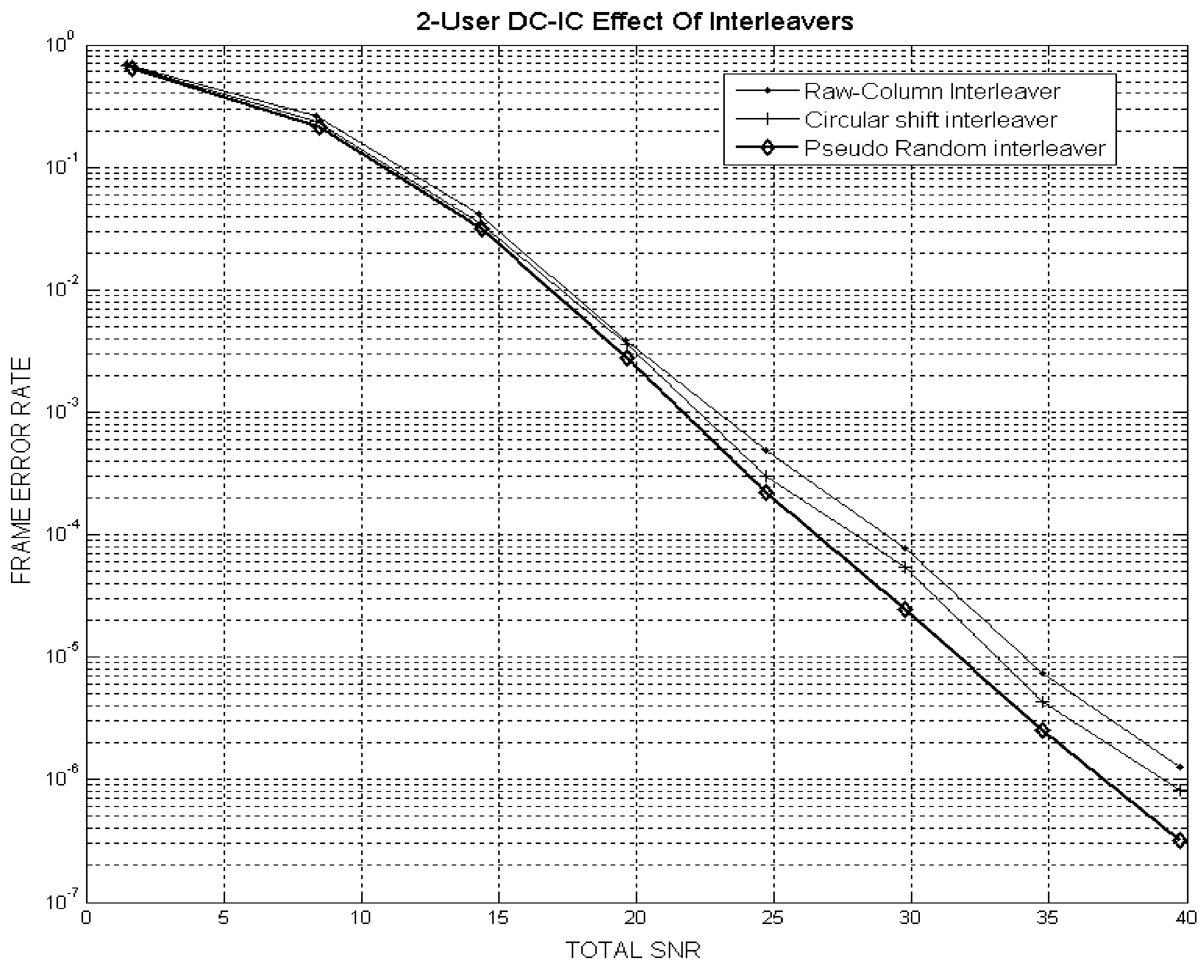


Figure 3.11 FER - Effect of Interleaver – Scenario1

3.4.3 Scenario 2 – 2-Adjacent cell case

In this scenario, we consider the 2-adjacent cell practical model where the nodes are located at different normalized distances from each other.

$$d_{11} = 0.916666666, \quad d_{12} = 0.6666666, \quad d_{21} = 0.75, \quad d_{22} = 1, \quad d_{Y_1Y_2} = 0.25$$

Figure 3.12, shows the 3-cell model and the optimal cooperation boundaries

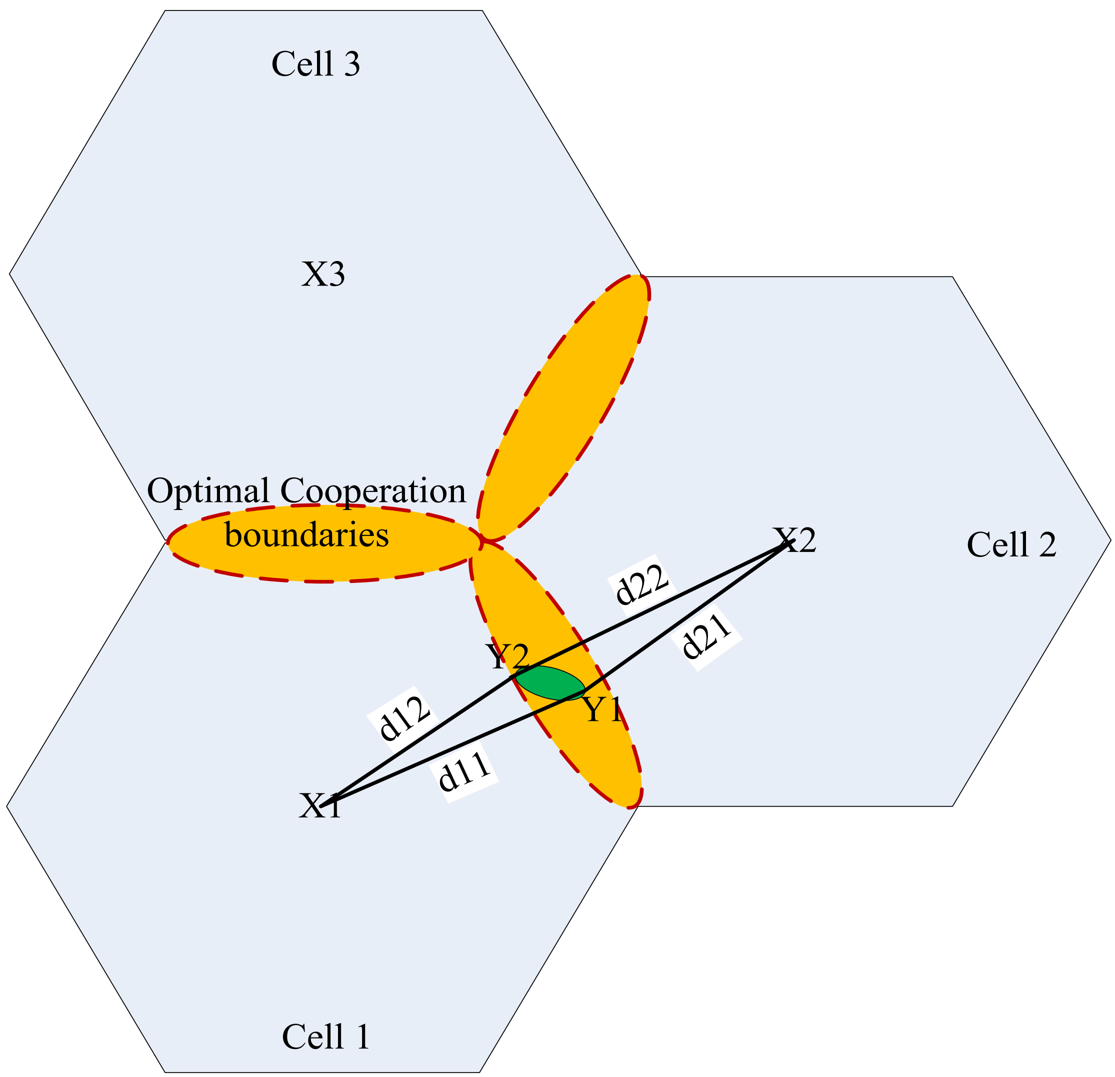


Figure 3.12 3-adjacent cells in cellular network

Figure 3.13 illustrates the FER. It is shown that the system is achieving better performance due to the fact that the distances are realistically chosen (destination nodes are at closer distance from each other.) $d_{11} = 0.916666666 \; and \; d_{Y_1 Y_2} = 0.25$

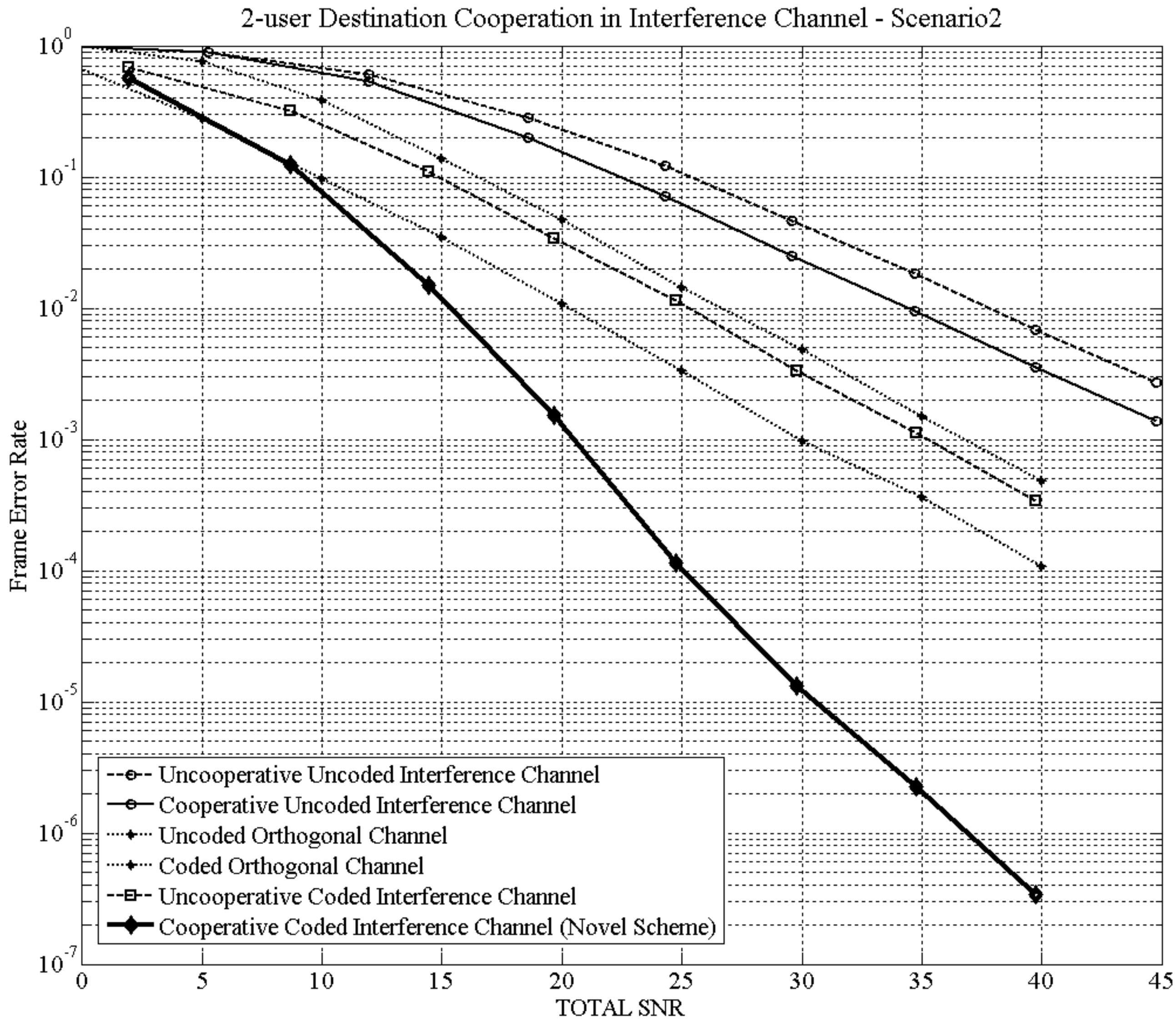


Figure 3.13Frame Error Rate of scenario 2

Figure 3.14 illustrates the SNR as a function of the distance between both destinations $d(Y_1 Y_2)$ at BER of 10^{-5}. Consider the case where both destinations are in the common region of cell1 and cell2 (Optimal cooperation zone) as explained in Figure 3.12. First, set Y_2 in the central of the cooperation sphere, and then move Y_1along the X axis then along the Y axis.

Figure 3.14 shows that the SNR gain between cooperative and uncooperative modes varies between 12.5 and 14.5 dB depending on the distance between both destinations. The maximum gain is when both destinations are at no distance from each other.

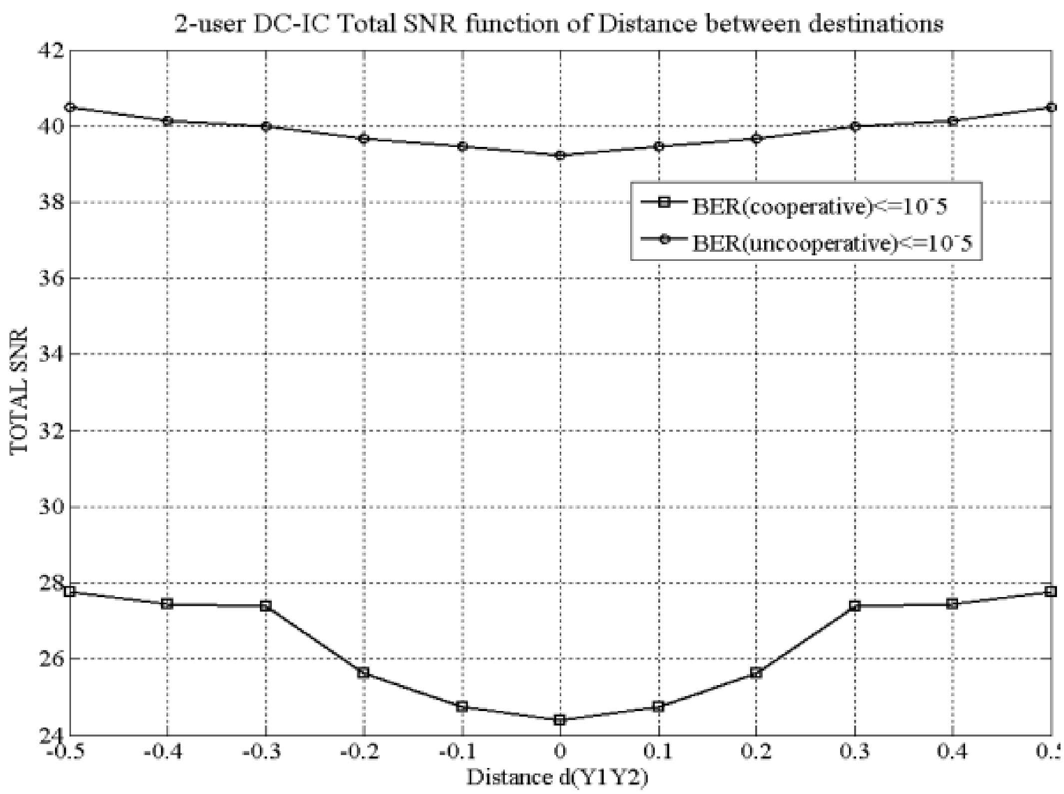


Figure 3.14 SNR functions of distances between destinations

3.5 SUMMARY

In this chapter, we have studied the performance of a 2-user DC-IC scheme. In phase one; both destinations decode the received superposed messages using the interference cancellation technique. In the second phase, the two destination nodes try to cooperate with each other.

For the special case and at FER of 10^{-4}, both cooperation schemes achieve a diversity order of 2 and a coding gain of about 13dB. The main advantage is in the cooperation phase that sends out another copy of the message that is experiencing different fading coefficients and therefore can assist in correctly decoding the messages at the final destinations. Moreover, another lead is the second cooperation scheme that exploits the available situations (case 2 & 3) at both destinations and not only case 4.

For the second scenario, it achieves a higher gain because the distances $d_{ij} < 1$. Therefore, the system performance varies based on the location of each nodes pair and it is upper bounded by the special case.

4 3- User Destination Cooperation in an Interference Channel with Network Coding

In this chapter, we extend the work in the previous chapter to 3-user Model. This model has three times slots in each communication cycle. The introduction of the enhanced cooperation scheme improves the outage probability. Furthermore, with the introduction of network coding, the number of cooperation phase reduces; consequently, the outage probability reduces as well. We present the performance analysis of several scenarios to show how the performance changes with each case. We also present a comparable analysis between the 3-user model on one hand and the 2-user model and the baseline scheme on the other hand.

4.1 System Model

We consider the model as illustrated in Figure 4.1, where three sources (X_1, X_2, X_3) transmit independently to three destinations (Y_1, Y_2, Y_3). We assume that all links experience flat block Rayleigh fading. Each destination node receives all information from X_1, X_2 andX_3.

Firstly, transmitters X_1, X_2 and X_3 transmit and receivers try to decode X_1, X_2 and X_3 (the received data). Secondly, if one receiver has successfully decoded all or some of the data from sources, it cooperates with the other destination nodes by transmitting the information desired for it. In this model, each destination node is only interested in its information i.e. destination node Y_i is only concerned about information coming from source node X_i, $i \in \{1,2,3\}$.

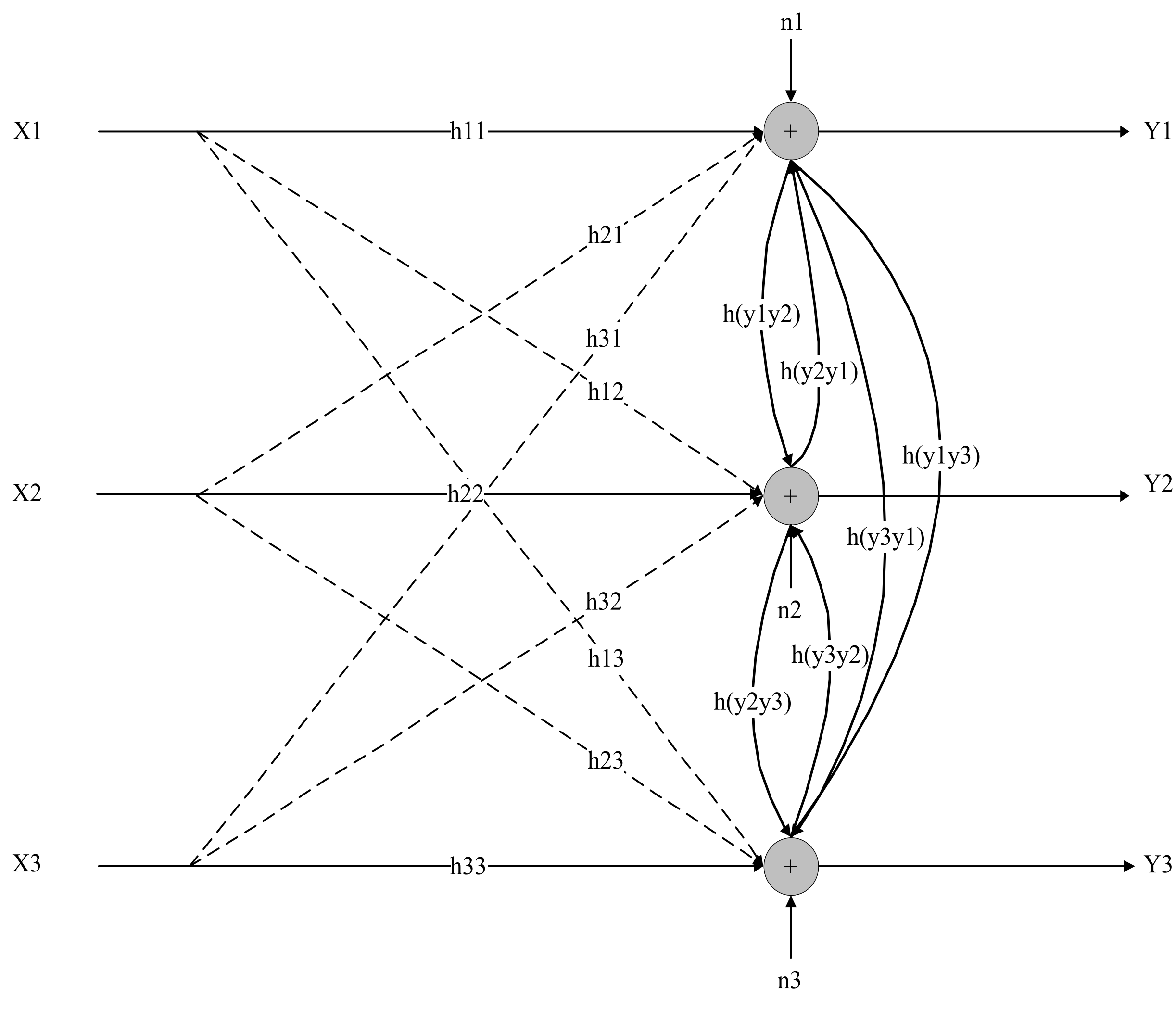


Figure 4.1 – System model

4.2 PROTOCOL DESCRIPTION

In the broadcast phase, all sources transmit their information to all receiving nodes. At the destination nodes, the cooperation is occurring based on the state in which each destination node is in after receiving the information.

In a recently accepted paper [55] on Destination cooperation in Interference channels, a simple cooperation scheme is introduced. In this 2-user model, the cooperation between the two destination nodes occurs in one situation where one destination node has received its own information and has the other user information. Cooperation is happening by sending this information to the other destination node. In the other situations, it remains silent. It is shown that this model achieves a diversity order of 2 and a coding gain of more than 12dB at 10^{-4} of FER.

In this chapter, we consider basic and enhanced cooperation schemes for the 3-user model. In the basic cooperation scheme, the information intended to a specific destination node which was not received in the broadcast phase, can be pulled out from another destination node if it is available. In the enhanced cooperation scheme, there is a high chance that this information intended for a specific destination node which was not received at any of the other destination nodes can be correctly decoded at any destination node during the cooperation phase by repeating the SIC process with higher certainty about the other nodes' information.

The idea behind this cooperation scheme is to perform further processing at some nodes trying to decode the missing information intended for node Y_i at node Y_j. This further processing is normally executed after exchanging some available information at other destination nodes in the first cooperation time slot. The last step in this scheme is to decide whether the newly decoded information is only required at destination node Y_j or further transmission is required in the second cooperation phase to relay the missing information at the other destination nodes $Y_i,\ Y_k$.

4.2.1 BROADCAST PHASE

In the broadcast stage, the source nodes use an (n, k) code to transmit k bits of information at rate $R = \frac{k}{n}$ to the destination nodes. We express the received signals at each destination as

$$Y_1 = \sqrt{pg(X_1Y_1)}\, X_1 h_{11} + \sqrt{pg(X_2Y_1)}\, X_2 h_{21} + \sqrt{pg(X_3Y_1)}\, X_3 h_{31} + n_1 \tag{4.1}$$

$$Y_2 = \sqrt{pg(X_1Y_2)}\, X_1 h_{12} + \sqrt{pg(X_2Y_2)}\, X_2 h_{22} + \sqrt{pg(X_3Y_2)}\, X_3 h_{32} + n_2 \tag{4.2}$$

$$Y_3 = \sqrt{pg(X_1Y_3)}\, X_1 h_{13} + \sqrt{pg(X_2Y_3)}\, X_2 h_{23} + \sqrt{pg(X_3Y_3)}\, X_3 h_{33} + n_3 \tag{4.3}$$

where n_1, n_2 and n_3 are independent identically distributed (i.i.d.), zero-mean, unit variance, complex Gaussian random variables.$h_{ij} i, j \in \{1,2,3\}$ are complex channel coefficients which are assumed to be constant over one data transmission block and are also assumed to be known at all destination nodes. The source nodes have no knowledge of the instantaneous channel characteristics. $pg_{(ij)} = \frac{1}{d_{ij}^{\alpha}}$ represents the path gains on the link (i, j), where α is the path loss exponent and d_{ij} represents the distances between node i and node$j$.

4.2.2 COOPERATION PHASE

This stage consists of two time slots at the most. The link between destination nodes is generally at closer distance than the link between source and destination nodes. Furthermore, the inter-destination nodes link is considered interference free and therefore there is a higher chance of achieving reliable communication in each cooperation time slot. We express the received signal at destination node j from destination node i as

$$Y_j = \sqrt{pg(Y_iY_j)}\, \hat{X}_j h_{Y_iY_j} + n_j \tag{4.4}$$

where $h_{Y_1Y_2}$, $h_{Y_1Y_3}$, $h_{Y_2Y_1}$, $h_{Y_2Y_3}$, $h_{Y_3Y_1}$, $h_{Y_3Y_2}$are complex channel coefficients which are assumed to be constant over one data transmission block and also assumed to be known at all destination nodes. The source nodes have no knowledge of the instantaneous channel characteristics

In the basic cooperation scheme, $\hat{X}_j$ is always the missing information at destination node Y_j that is being transmitted from destination nodeY_i.In the enhanced scheme, $\hat{X}_j$can also take the value of other information that was not intended for node $j$but it may help in decoding node X_j with more certainty whether at destination node j or at other destination nodes.

The destination nodes assist each other by decoding, re-encoding and re-transmitting another copy of the message of interest to the other destinations. With three sources transmitting to one destination, we have 2^3=8 possible cases at each destination node, then with three destination nodes, the overall scenarios presented at the destination nodes are$(2^3)^3 = 512$.This is due to the fact that there are three messages and three destination locations, making an overall 3x3=9 message-location pairs. Presence or absence of a message at a given location results in $2^9 = 512$ cases.Table 4.1 illustrates those possibilities

The state at each destination node after each time slot is represented in binary form as shown in table 4.1. Those bits are exchanged between destination nodes. This exchange of bits allows each node to know its next state whether to remain silent or to transmit some information.

Destination node Y_1	Destination node Y_2	Destination node Y_3	Binary representation at each destination node
$\overline{X}_1\overline{X}_2\overline{X}_3$	$\overline{X}_1\overline{X}_2\overline{X}_3$	$\overline{X}_1\overline{X}_2\overline{X}_3$	000
$\overline{X}_1\overline{X}_2X_3$	$\overline{X}_1\overline{X}_2X_3$	$\overline{X}_1\overline{X}_2X_3$	001
$\overline{X}_1X_2\overline{X}_3$	$\overline{X}_1X_2\overline{X}_3$	$\overline{X}_1X_2\overline{X}_3$	010
$\overline{X}_1X_2X_3$	$\overline{X}_1X_2X_3$	$\overline{X}_1X_2X_3$	011
$X_1\overline{X}_2\overline{X}_3$	$X_1\overline{X}_2\overline{X}_3$	$X_1\overline{X}_2\overline{X}_3$	100
$X_1\overline{X}_2X_3$	$X_1\overline{X}_2X_3$	$X_1\overline{X}_2X_3$	101
$X_1X_2\overline{X}_3$	$X_1X_2\overline{X}_3$	$X_1X_2\overline{X}_3$	110
$X_1X_2X_3$	$X_1X_2X_3$	$X_1X_2X_3$	111

Table 4.1 possible scenarios at the destination nodes

Once the broadcast phase is completed, the three destination nodes are in one of the 512 states. Those cases can be categorized into four groups which are No-cooperation, One-Cooperation TS, Two-Cooperation TS, and Outage. Table 4.2 illustrates the distribution of these cases over each group in both cooperation schemes.

	No-Cooperation	One-Cooperation	Two-Cooperation	Further processing	Outage
Basic scheme	64	156	103	0	189
Enhanced scheme	64	156	103	182	7

Table 4.2 the distribution of each group of cases in both cooperation schemes

4.2.2.1 BASIC COOPERATION SCHEME

Table 4.3 illustrates an example on the basic cooperation scheme. In this example which is randomly selected out of the one-cooperation group of cases, Y_1 cooperates with Y_2 by sending X_2. After the transmission of this cooperation time slot, all destination nodes may have received their envisioned information.

Situation	Destination node Y_1	Destination node Y_2	Destination node Y_3
One-Cooperation	$X_1X_2\overline{X}_3$	$X_1\overline{X}_2\overline{X}_3$	$X_1\overline{X}_2X_3$
Two-Cooperation	$\overline{X}_1\overline{X}_2\overline{X}_3$	$\overline{X}_1X_2X_3$	$X_1\overline{X}_2\overline{X}_3$
Outage	$\overline{X}_1\overline{X}_2X_3$	$X_1\overline{X}_2\overline{X}_3$	$\overline{X}_1X_2\overline{X}_3$

Table 4.3 Example on the basic cooperation scheme

Whereas, in the two-cooperation mode, Y_3 cooperates with Y_1 by sending X_1 and Y_2 cooperates with Y_3 by sending X_3. After the transmission of these two cooperation time slots, the destined information to each node may have successfully been received. Figure 4.2 illustrates this example. The dashed-line represents the second cooperation phase

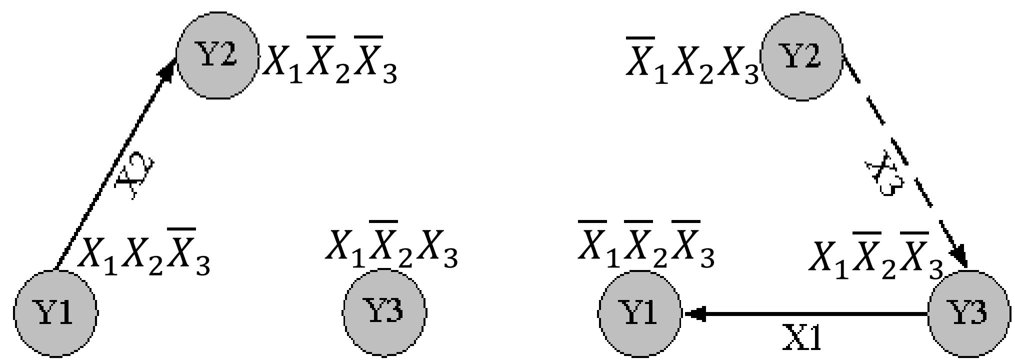


Figure 4.2 Basic scheme, (a) One-cooperation mode (b) Two –cooperation mode

4.2.2.2 ENHANCED COOPERATION SCHEME

In this cooperation scheme, we develop the basic cooperation scheme to include cases that were previously considered outages. The main focus of this scheme is on the outage cases. It tries to minimize the outage probability of each transmission by performing more processing at some destination nodes in the aim of finding the missing data. Note that, in general, most of the cases that require further processing fall under the group of two-cooperation with further processing i.e. most of these cases need the full cooperation cycle which is consisting of two cooperation time slots, but there are very few cases that only require one cooperation time slot. Table 4.4 illustrates the distribution of the cases that require further processing over one-cooperation and two-cooperation modes.

Further processing	
One-Cooperation	Two-Cooperation
37	145

Table 4.4 Distribution of cases that require further processing

Table 4.5 illustrates an example on the enhanced cooperation scheme. In this example, we consider three cases, the first one(One-cooperation) is the case that was considered as an outage in the basic cooperation scheme in table 4.3, the second case (Two cooperation mode) is randomly selected from Table 4.4 and the third case is an outage case randomly selected out of the 7 remaining cases in outage. In the case that requires One-cooperation mode, X_2 is not available at any of the destination nodes. In one cooperation time slot, Y_3 cooperates with Y_2 by sending X_3 to Y_2, if X_3 is correctly received at destination node Y_2 then SIC is performed again with more known information X_3. This leads to a higher chance of correctly decoding X_2.

Situation	Destination node Y_1	Destination node Y_2	Destination node Y_3
One-Cooperation with further processing - Randomly selected from table 4.4	$X_1\overline{X}_2\overline{X}_3$	$X_1\overline{X}_2\overline{X}_3$	$\overline{X}_1\overline{X}_2X_3$
Two-Cooperation with further processing - Outage case from Table 4.3	$\overline{X}_1\overline{X}_2X_3$	$X_1\overline{X}_2\overline{X}_3$	$\overline{X}_1X_2\overline{X}_3$
Outage - Randomly selected from table 2.1	$\overline{X}_1\overline{X}_2\overline{X}_3$	$\overline{X}_1\overline{X}_2\overline{X}_3$	$\overline{X}_1\overline{X}_2\overline{X}_3$

Table 4.5 Example on the Enhanced cooperation scheme

In the second case (Two-cooperation mode), X_1 is not available at Y_1, $X_2$is not available at Y_2 and X_3 is not available at Y_3. One way of cooperation is to send X_1 from Y_2 to Y_1 and Y_3in the first cooperation time slot, and then to send X_2 from $Y_3$to Y_2 in the second cooperation time slot. The key in this scheme, if X_1 is correctly received at destination node 3, is to use both correct information X_1 and X_2 available at destination node 3 to repeat the SIC process with just one unknown message X_3. Assuming that,X_1 is correctly received at both destination Y_1 and Y_3 after the first cooperation time slot, X_3 is correctly decoded by repeating the SIC process at destination node 3, and X_2 is correctly received from destination node 3 at destination node 2 after the second cooperation time slot. This whole process guarantees that similar cases are no longer considered as an outage.

Figure 4.3 illustrates this example. The dashed-line represents the second cooperation phase

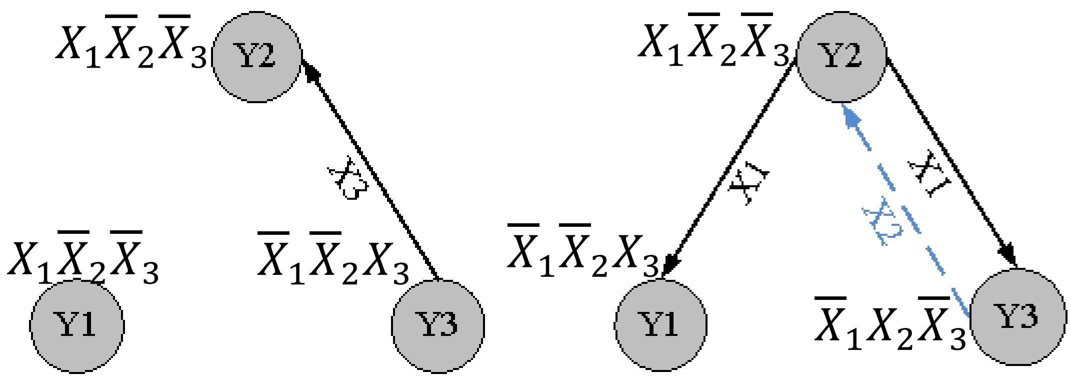


Figure 4.3 Enhanced scheme, (a) One-cooperation mode (b) two-cooperation mode

4.3 COMPARISON OF 3-USER DESTINATION CCOPERATION IN IC WITH 3-USER ORTHOGONAL CHANNEL

To maintain the same bandwidth and transmission time allocated for an orthogonal channel, one way to increase the spectral efficiency and system performance is to broadcast all the information in one time slot and try to cooperate in the remaining time slots. This approach proves to be efficient in the 2-user model presented in the previous chapter. However, in 3-user model other challenges may be introduced especially at high SNR where interference is enormous.

The major difference between 3-user DC-IC with 3-user orthogonal channel is that in the number of time slots require to send the information from the source nodes to the destination nodes. In the 3-user DC-IC, one time slot is required to broadcast all information, the other 2 time slots are used for cooperation between destination nodes. Whereas in the 3-user orthogonal channel, each user has its time slot to transmit its information interference free.

The advantage in the 3-user DC-IC is the cooperative diversity that is mainly used to combat fading in mobile communications. This model can achieve a diversity order 3 maximum. Another advantage the 3-user DC-IC has which is higher spectral efficiency compared with the baseline. For example, in the multicasting application where all information is required at all destination nodes, the 3-user model is efficient and has higher throughput. In the case of three users and above, network coding is more useful to implement.

X1 Transmission	X2 Transmission	X3 Transmission	TDMA
X1,X2,X3 Transmission	Cooperation	Cooperation	DC-IC

Figure 4.4 3-user orthogonal channels vs. 3-user DC-IC

Figure 4.4illustrates the number of time slots required to complete one communication cycle for both proposed and baseline schemes. It is clear that to independently transmit X_1, X_2, X_3 in interference free environment, one require three time slots. Whereas in the 3-user DC-IC, one time slot is used to broadcast all the information from different source nodes and the other two time slots are used for cooperation. This technique which is called cooperative communication has proven to be very efficient in fading channels. This is due to the fact that the same information is being sent to the same destination via multiple paths, each of which undergoes different fading characteristics.

4.3.1 SUCCESSIVE INTERFERENCE CCANCELLATION AT DESTINATION NODE $\boldsymbol{Y_1}$

From equation 4.1, we can express the following at nodeY_1:

Assume $h_{11} > h_{21}$ and$h_{11} > h_{31}$, detect X_1:

$$decode\ \frac{Y_1}{h_{11}}\ to\ get\ \hat{X}_1$$

Assume $h_{21} > h_{31}$, detect X_2: Subtract the decoded message from the received signal to detect X_2:

$$decode \frac{Y_1 - \sqrt{pg(x_1 y_1)}\, \hat{X}_1 h_{11}}{h_{21}} to\ get\ \hat{X}_2$$

Subtract the decoded message from the received signal to detect X_3:

$$decode \frac{Y_1 - \sqrt{pg(x_1 y_1)}\, \hat{X}_1 h_{11} - \sqrt{pg(x_2 y_1)}\, \hat{X}_2 h_{21}}{h_{31}} to\ get\ \hat{X}_3$$

4.4 SIMULATION

In this section, we assume that$\alpha = 2$. The Binary Phase Shift Keying (BPSK) modulation is implemented with constellation points at -1 and 1. The channel code that is used at all nodes is Turbo code [8].

We present the simulation results for 4 scenarios: the special case (upper bound) where all nodes are located at equal distances from each other and the other three scenarios in which the source node X_3 is fixed, the source nodes X_1 and X_2 are moving towards the destination nodes. The destination nodes Y_i form an equilateral triangle in the common area between the 3-adjacent cells. In the next subsections, we first show the performance analysis of the special case, and then followed by the other scenarios.

Figure 4.5 illustrates the coded DC-IC block diagram based on which we constructed our simulation algorithm. Note that the Total SNR is the SNR taking into account the power consumed at all source and destination nodes.

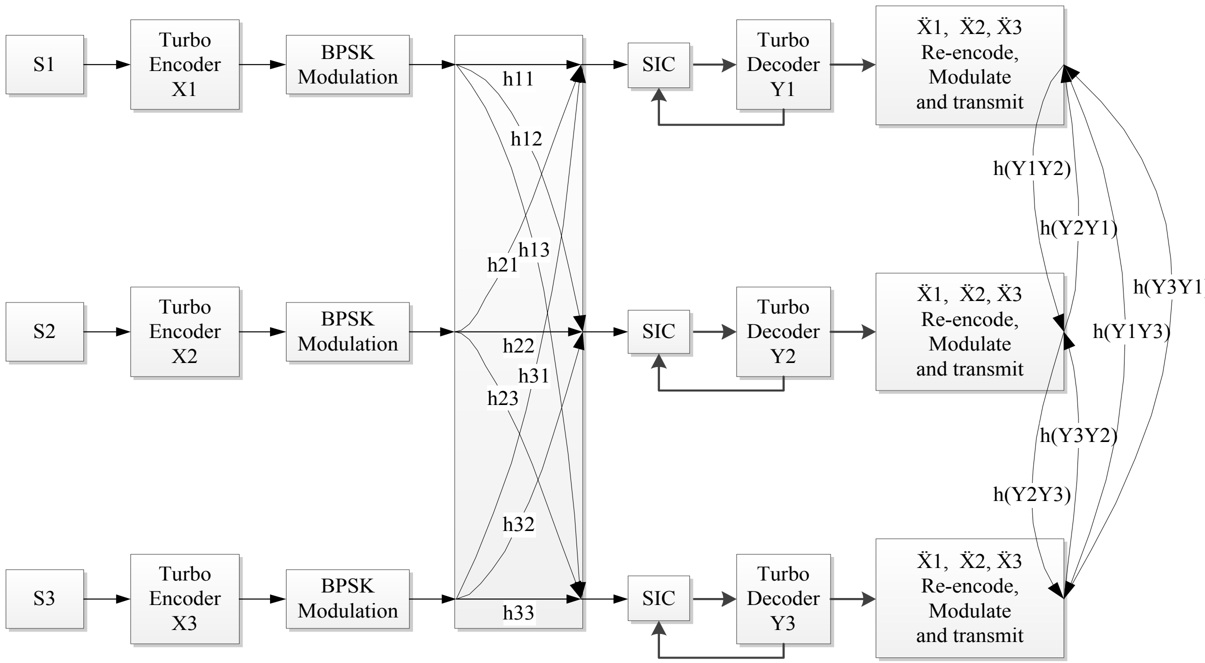


Figure 4.5 3-DC-IC channel coded system model

4.4.1 SCENARIO 1 – SPECIAL CASE

In this scenario, all nodes are positioned at equal normalized distances to each other$d_{ij} = 1$. We present a comparable analysis between coded and uncoded for both 3-user orthogonal channel and 3-user DC-IC systems.

4.4.1.1 FRAME ERROR RATE (FER)

Figure 4.6 illustrates the FER; it is shown that the system is achieving a diversity order 2.85 maximum when SNR is between 8 and 16 dB, 2.22 when SNR is between 16 and 25.5dB and 1.45 when SNR is above 26dB. Figure 4.4 also shows a change in FER curve indicating diversity gain. Figure 4.6 also shows the noticeable gain between cooperative and uncooperative coded schemes.

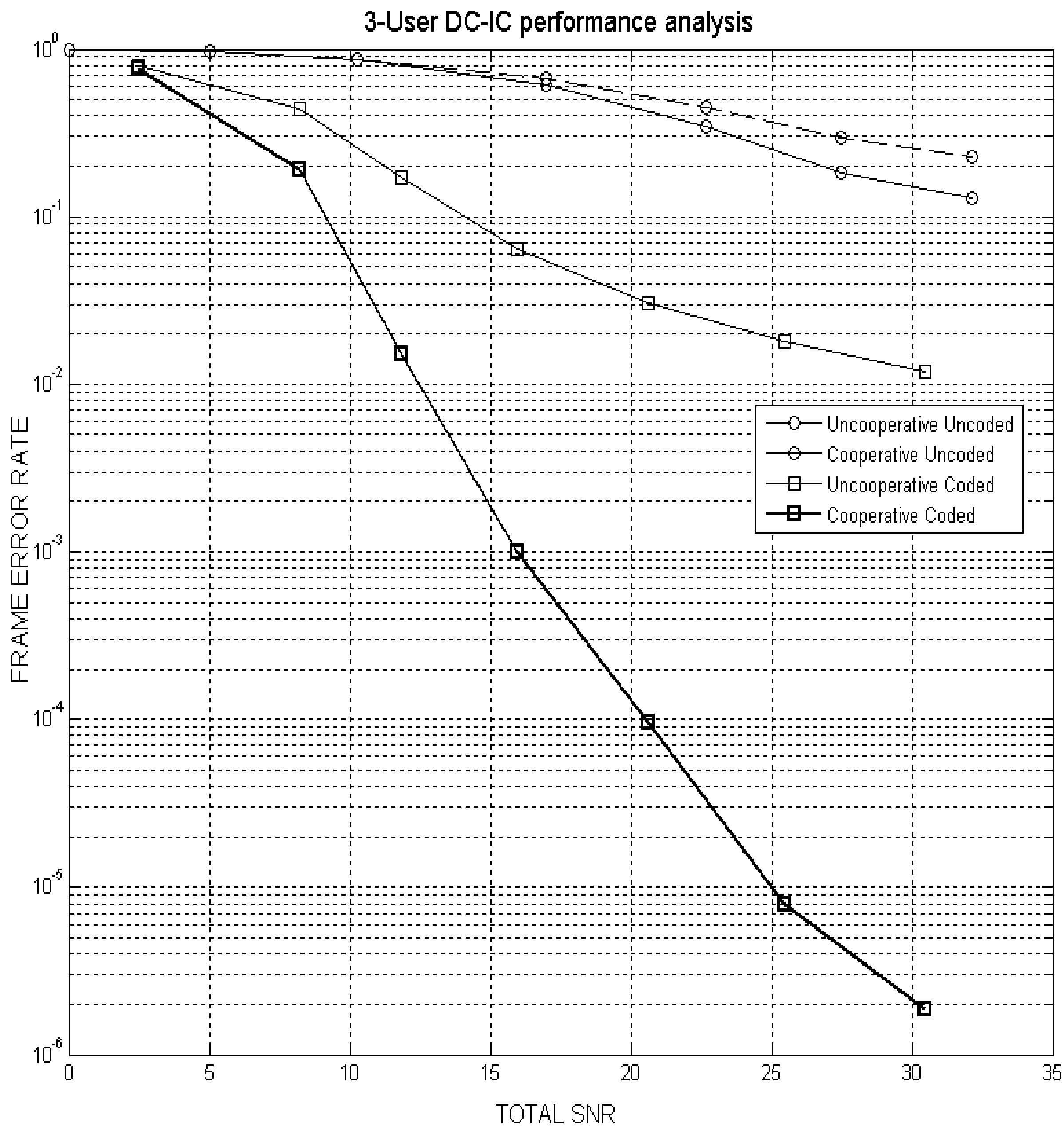


Figure 4.6 – Frame Error Rate – scenario 1

4.4.1.2 COOPERATION LINK PERFORMANCE ANALYSIS

Figure 4.7 shows the performance of the cooperation link between destination nodes

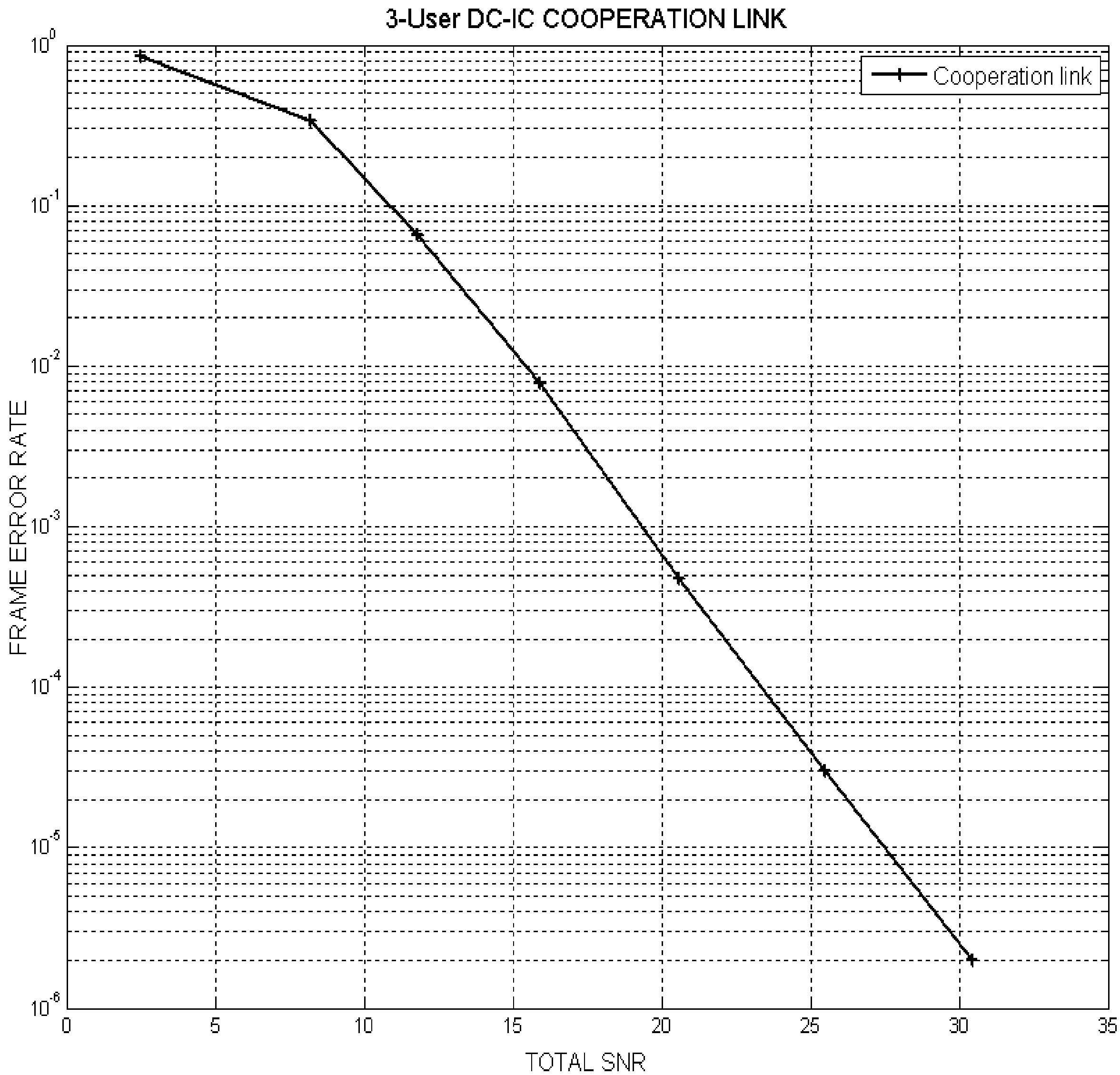


Figure 4.7– Cooperation link Frame Error Rate– scenario 1

4.4.1.3 COOPERATION RATE

Figure 4.8 shows the probability that the destination nodes are able to cooperate. At low SNR, Cooperation rate increases proportionally with SNR to a certain point where it drops as SNR increases. This is due to the fact that at higher SNR receiver nodes receive the data from their respective source nodes correctly with higher probability; therefore cooperation will not be useful at this stage. Of course, this is the probability that the destination nodes are able to cooperate. It is different from the actual rate of useful cooperation since if destination nodes receive all information then there is no need for cooperation. Since the destination nodes are handheld devices, it is one of the main challenges to use their energy very efficiently and therefore cooperation is only on demand and this is how it is considered in this scheme

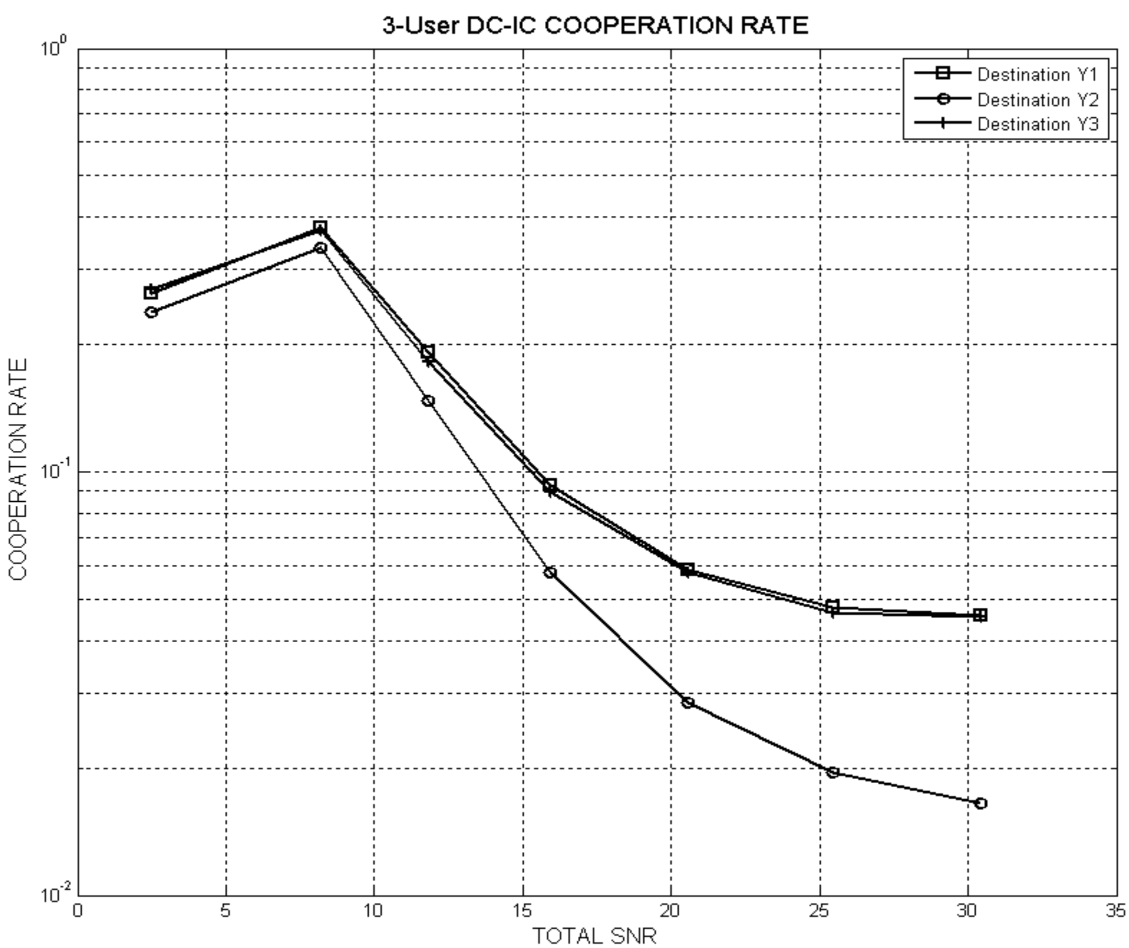


Figure 4.8 – Probability that destinations can cooperate – Scenario1

4.4.1.4 SUCCESSFUL COOPERATION

Successful cooperation is the probability of the correctly receiving frames from cooperation nodes. Figure 4.9 illustrates the rate of successful cooperation at destination nodes. It is shown that the cooperation increases with SNR until some point where it saturates. This is due to the performance of the link between destination nodes. At low SNR, the cooperation link is not very reliable, whereas at higher SNR, it becomes almost error free link.

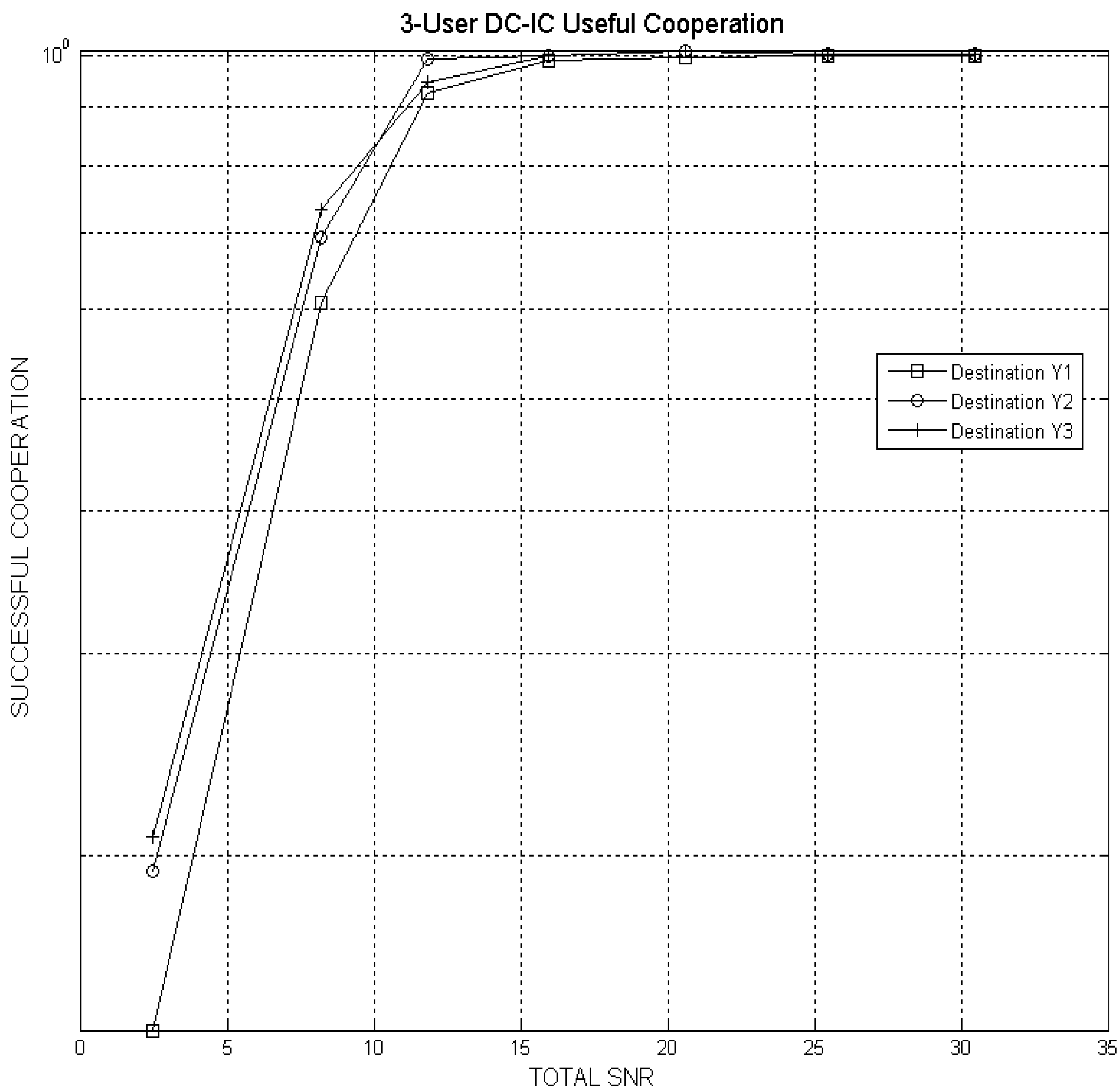


Figure 4.9 – successful cooperation – Scenario1

4.4.1.5 OUTAGE PROBABILITY

The outage probability is defined as when at least one of the destination nodes did not receive its respective information after the complete communication cycle, i.e. if X_i was not received at Y_i after the second cooperation time slot, the system is considered in outage. Figure 4.10 illustrates the outage probability versus the FER. As shown in Figure 4.10, the outage probability is considered as the lower bound of the FER

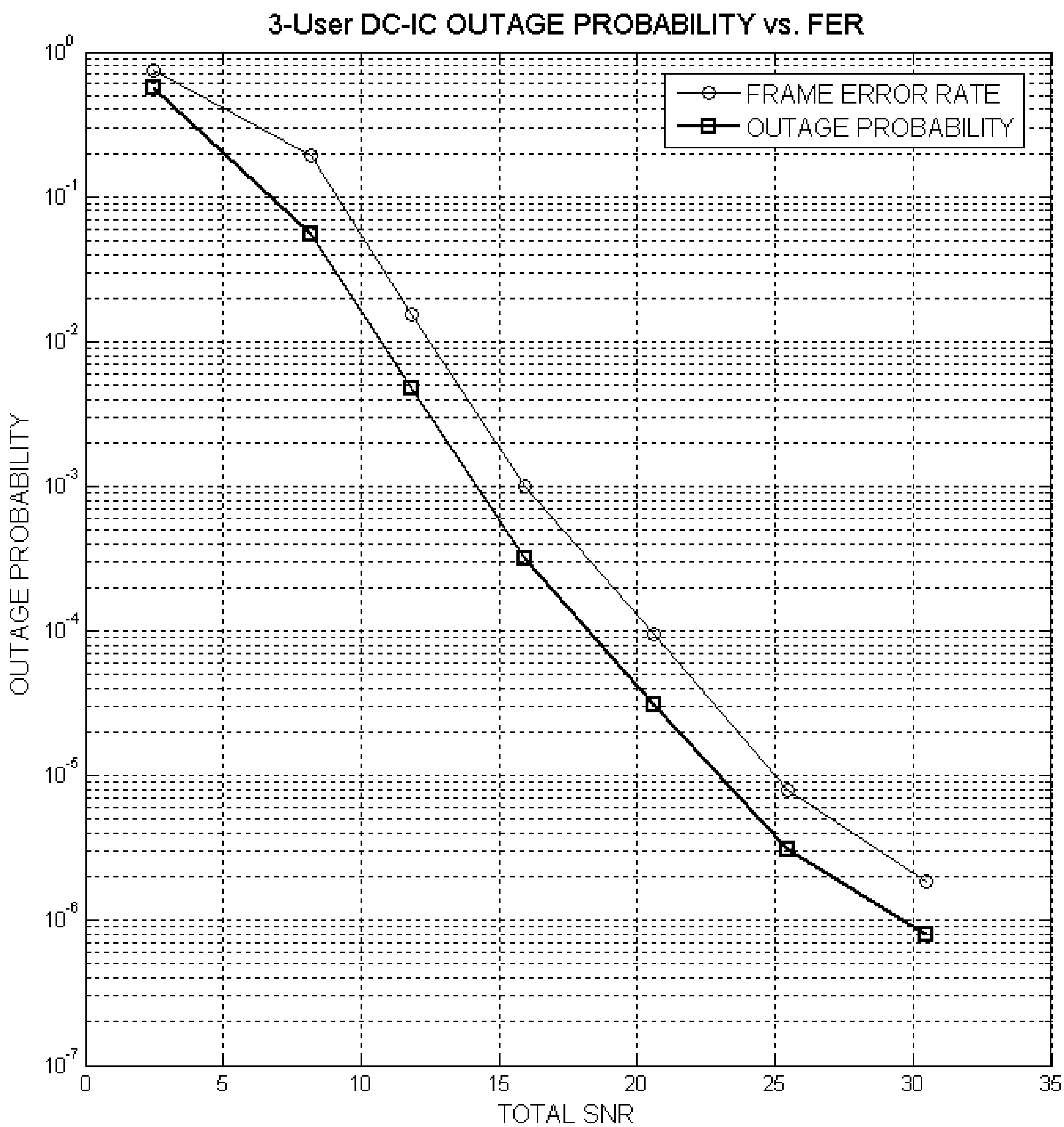


Figure 4.10 Outage Probability vs. FER - scenario 1

4.4.1.6 EFFECT OF NETWORK CODING

In this simulation, we study the performance of the system without network coding and we compare it with the previous results (case with network coding). This shows clearly the impact of network coding in cooperative communication especially when the number of cooperating users is greater than two. Figure 4.11 shows about 5.5 dB of gain at 10^{-4} of FER and it is even more at lower FER.As the number of users' increases, the system performance improves; this is due to the network coding benefits and the degree of freedom when adding more user nodes in the cooperative scheme.

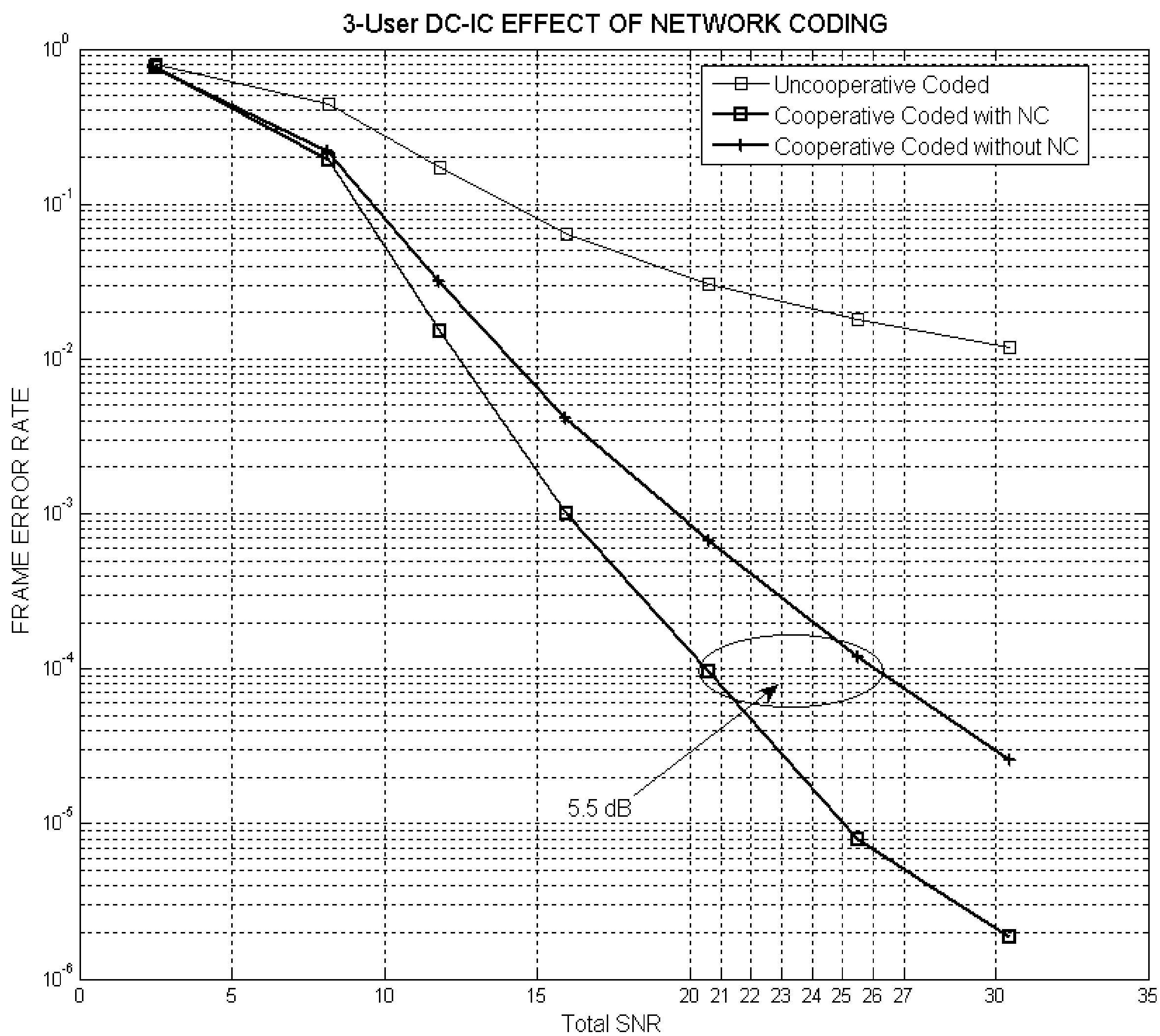


Figure 4.11 FER - Effect of the network coding – Scenario1

4.4.2 SCENARIO 2 – 3-ADJACENT CELL CASE

In this scenario, we consider the 3-adjacent cell model where the nodes are located at different normalized distances from each other. Figure 4.12, shows this model.

$$d_{11} = 0.483,\ d_{12} = 0.517,\ d_{13} = 0.484,\ d_{21} = 0.483,\ d_{22} = 0.449,\ d_{23} = 0.451,\ d_{31} = 0.966,\ d_{32} = 1,\ d_{33} = 0.967, d_{Y_1Y_2} = d_{Y_1Y_3} = d_{Y_3Y_2} = d_{Y_3Y_1} = d_{Y_2Y_1} = d_{Y_2Y_3} = 0.038$$

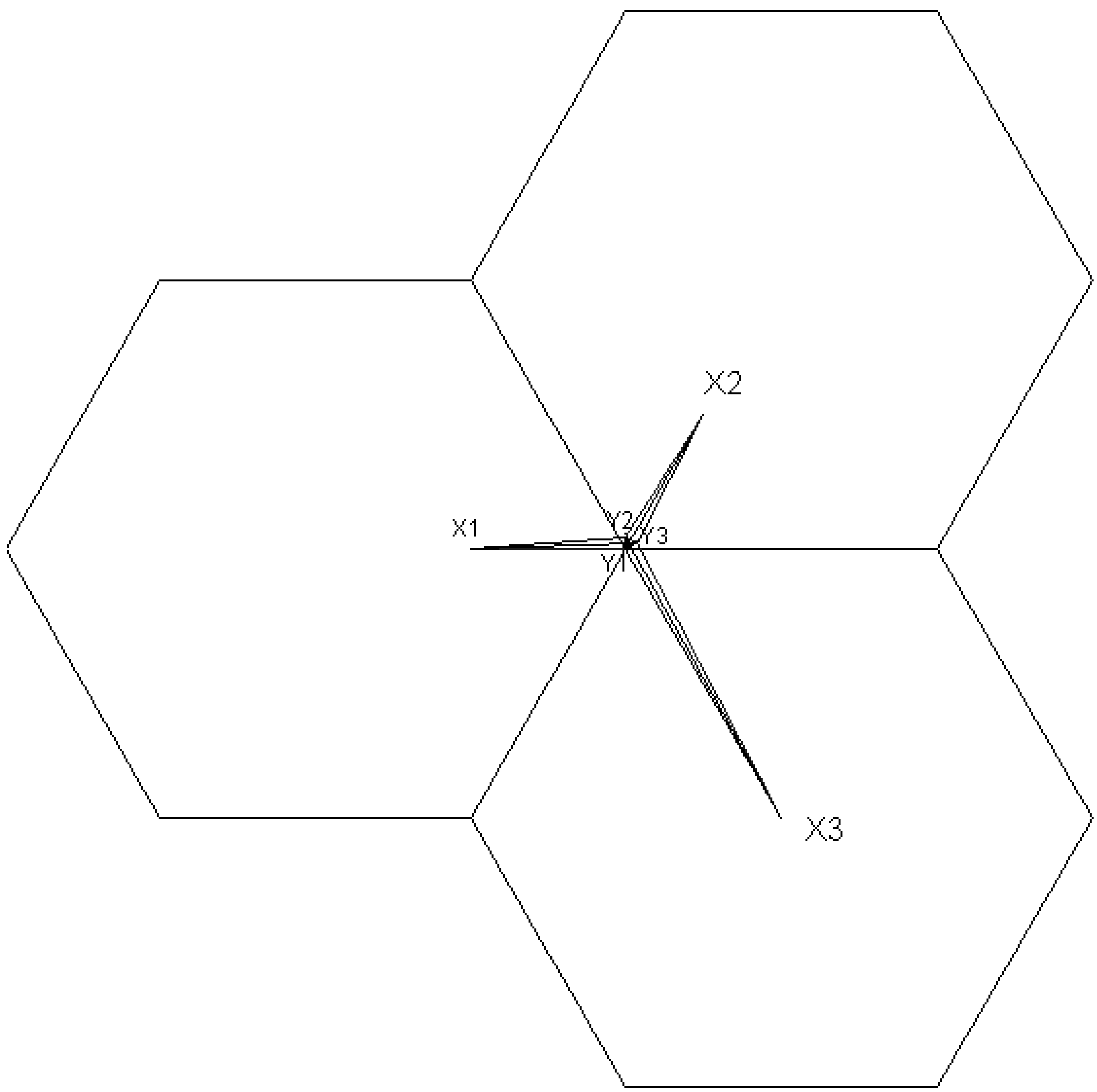


Figure 4.12 3-adjacent cells in cellular network – Scenario 2

Figure 4.13 illustrates the FER. It is shown that the system is achieving better performance due to the fact that the distances are shorter which results in better SNR.

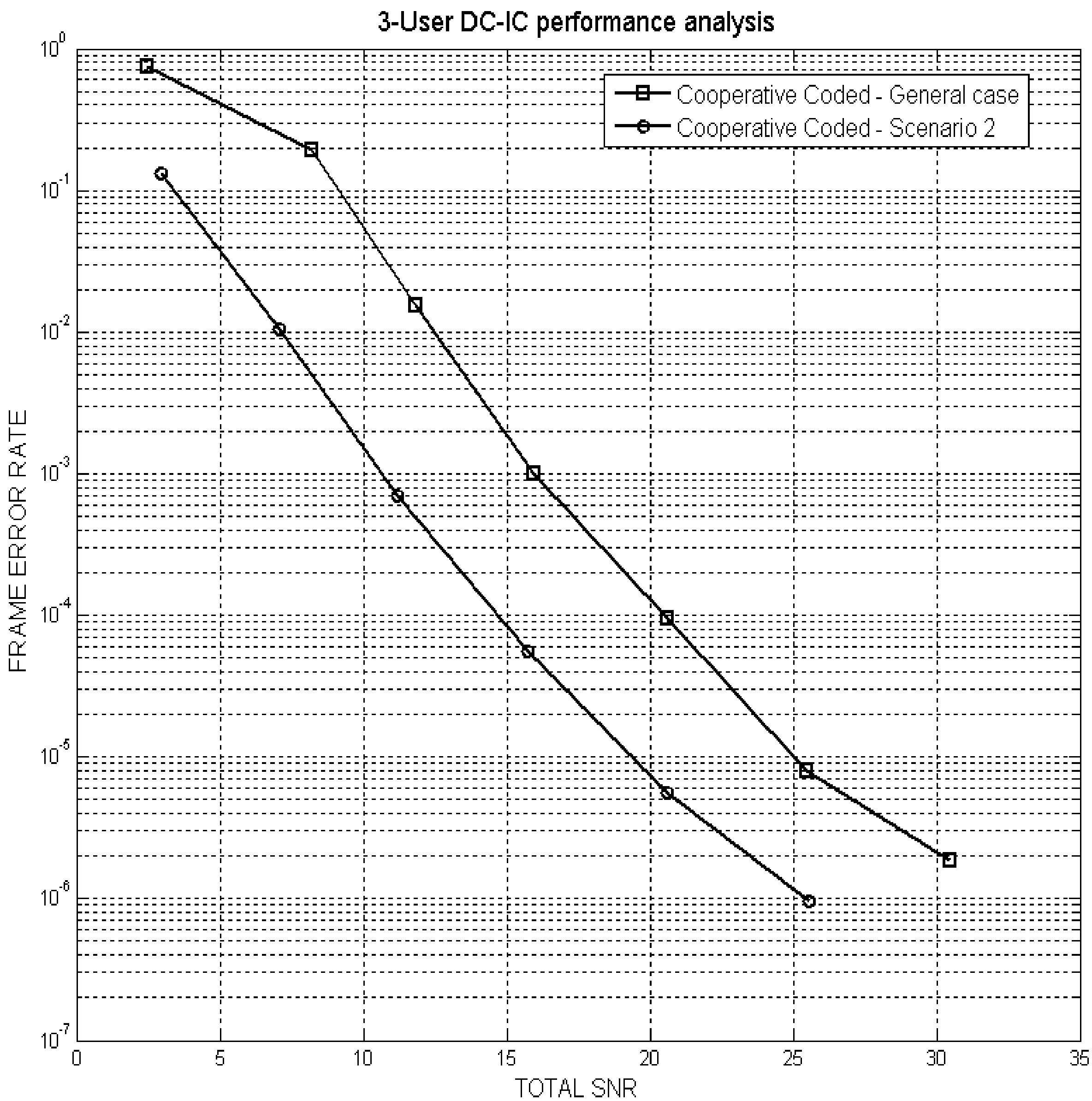


Figure 4.13 Frame Error Rate - scenario 2

4.4.3 SCENARIO 3 – 3-ADJACENT CELL CASE

In this scenario, we consider the 3-adjacent cell model where the nodes are located at different normalized distances from each other. Figure 4.14 illustrates this mode. $d_{11} = 0.241$, $d_{12} = 0.244$ $d_{13} = 0.275$, $d_{21} = 0.483$, $d_{22} = 0.449$, $d_{23} = 0.451$, $d_{31} = 0.966$, $d_{32} = 1$, $d_{33} = 0.967, d_{Y_1Y_2} = d_{Y_1Y_3} = d_{Y_3Y_2} = d_{Y_3Y_1} = d_{Y_2Y_1} = d_{Y_2Y_3} = 0.038$

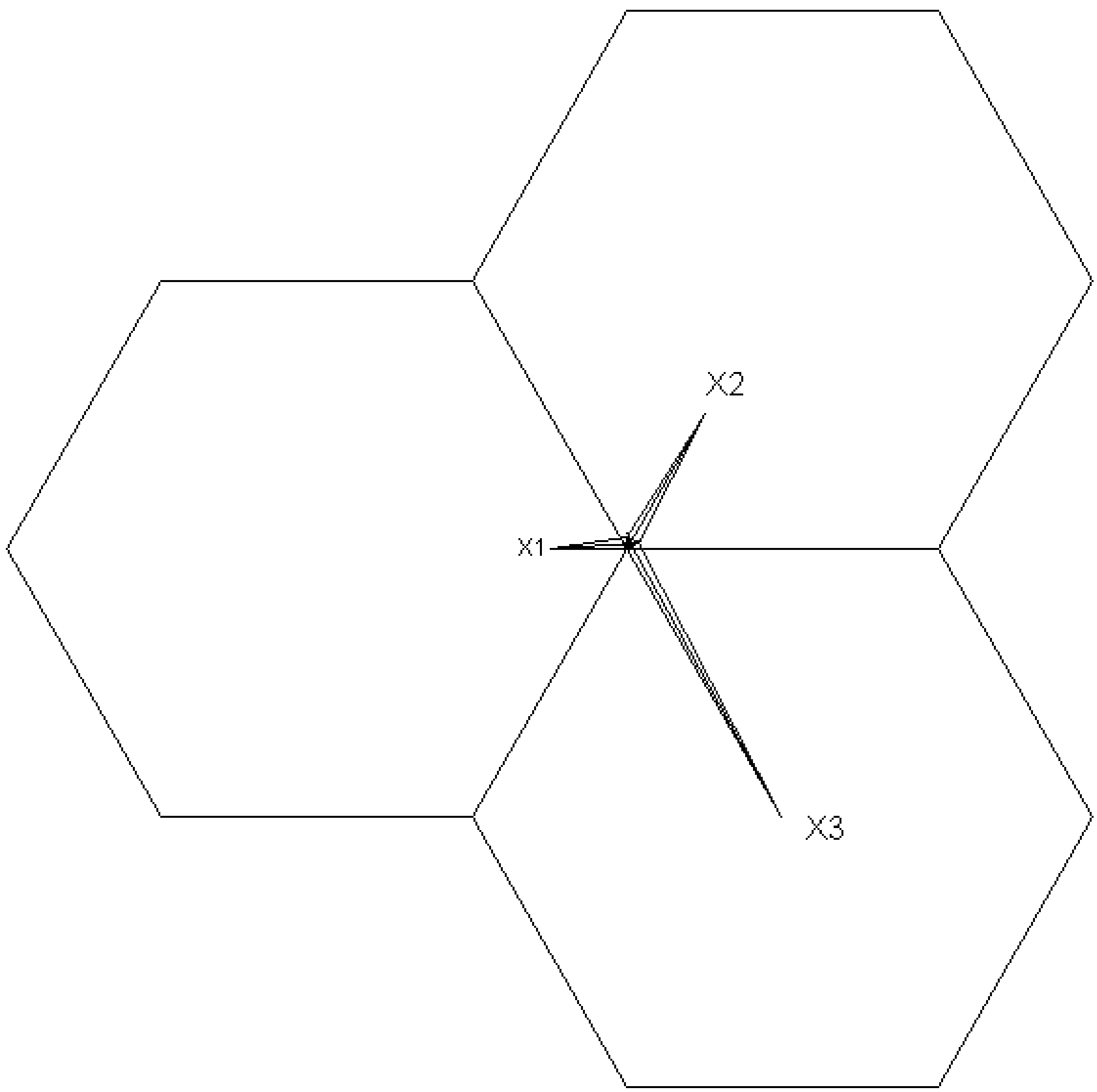


Figure 4.14 3-adjacent cells in cellular network – scenario 3

Figure 4.15 illustrates the FER. It is shown that the system is achieving better performance due to the fact that the distances are shorter which is resulting in higher SNR

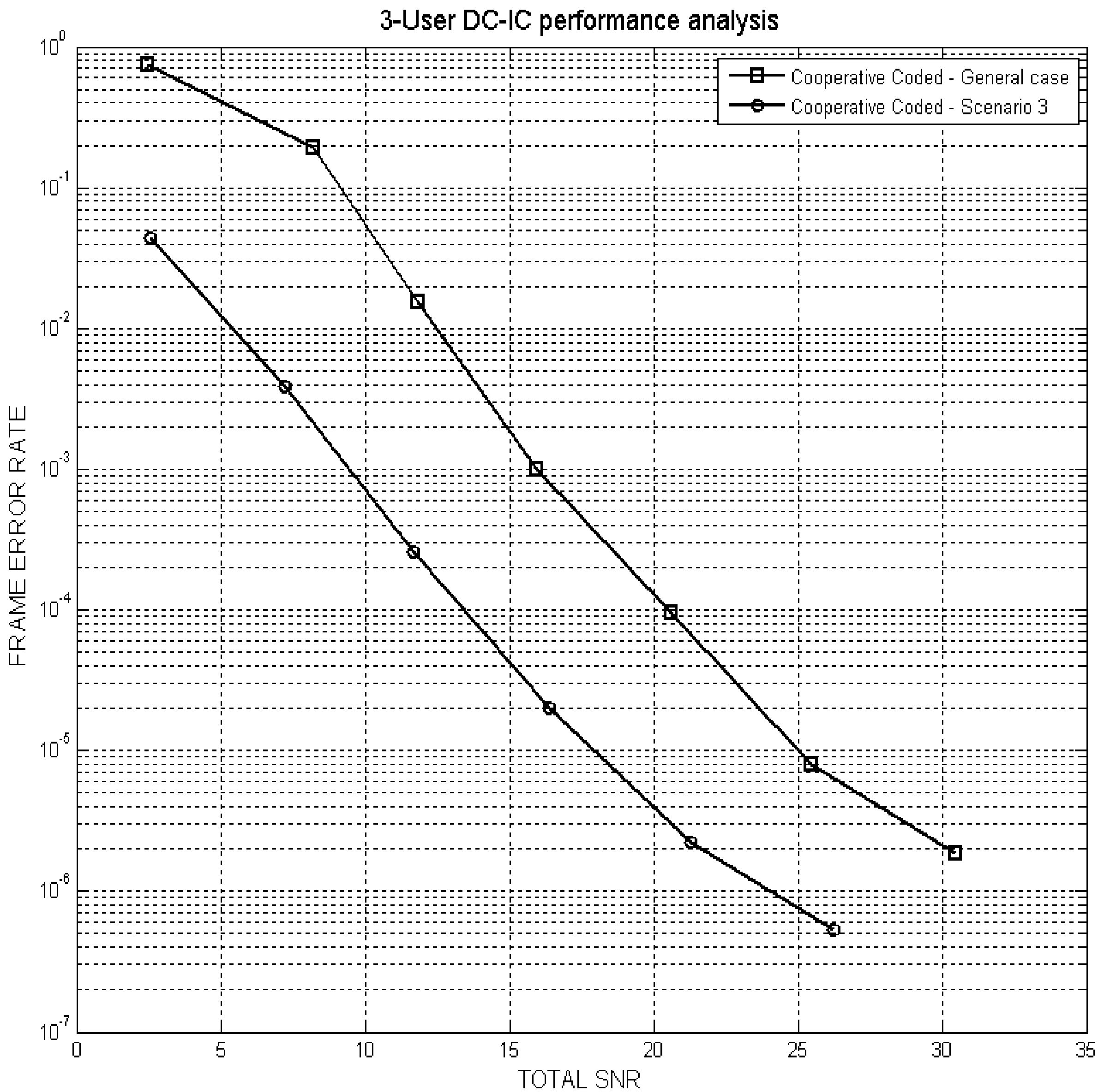


Figure 4.15 Frame Error Rate - scenario 3

4.4.4 SCENARIO 4 – 3-ADJACENT CELL CASE

In this scenario, we consider the 3-adjacent cell model where the nodes are located at different normalized distances from each other. Figure 4.16 illustrates this model. $d_{11} = 0.096$, $d_{12} = 0.104$ $d_{13} = 0.131$, $d_{21} = 0.483$, $d_{22} = 0.449$, $d_{23} = 0.451$, $d_{31} = 0.966$, $d_{32} = 1$, $d_{33} = 0.967$, $d_{Y_1Y_2} = d_{Y_1Y_3} = d_{Y_3Y_2} = d_{Y_3Y_1} = d_{Y_2Y_1} = d_{Y_2Y_3} = 0.038$

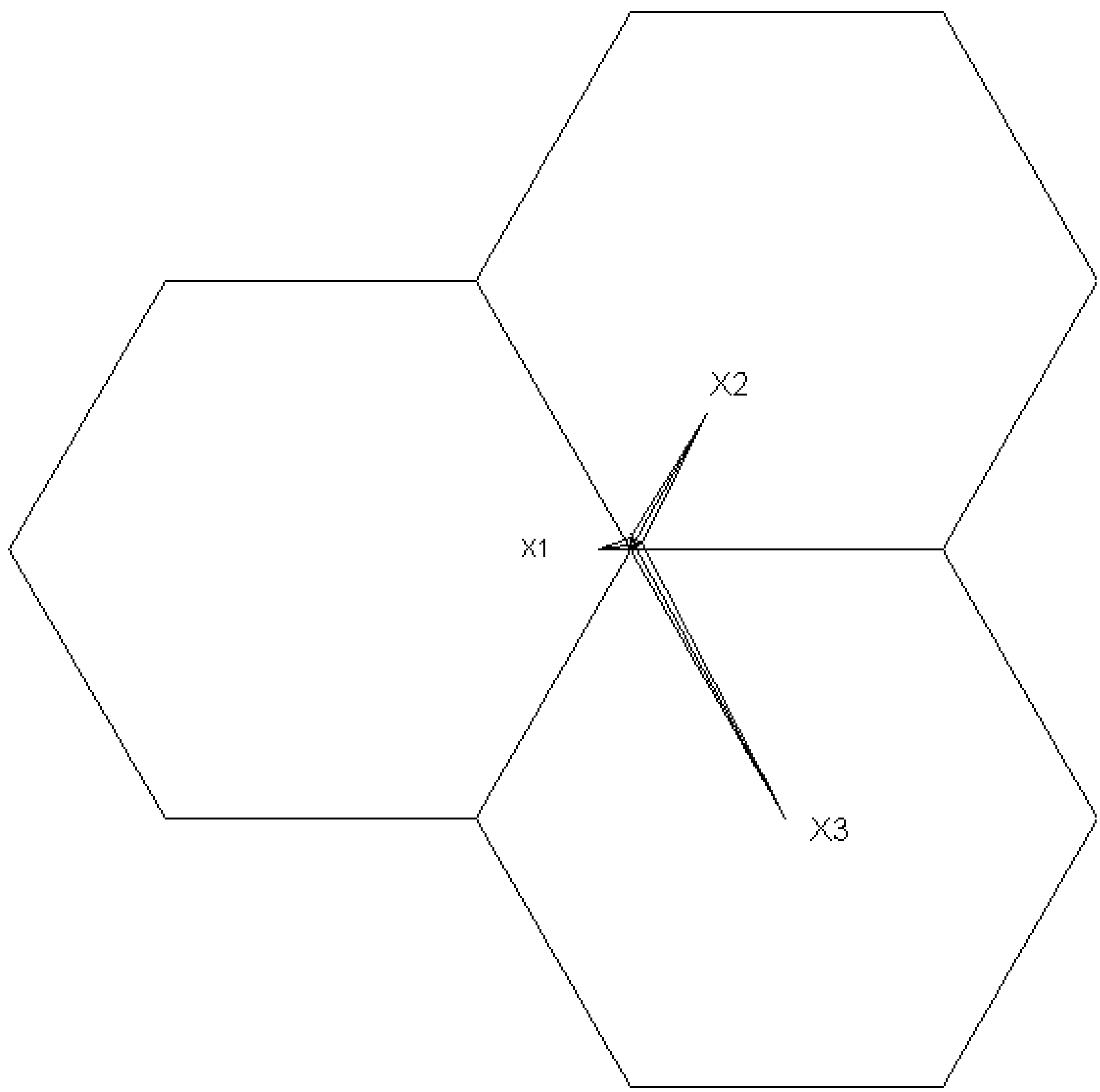


Figure 4.16 3-adjacent cells in cellular network – scenario 4

Figure 4.17 illustrates the FER. It is shown that the system is achieving better performance due to the fact that the distances are shorter which is resulting in higher SNR

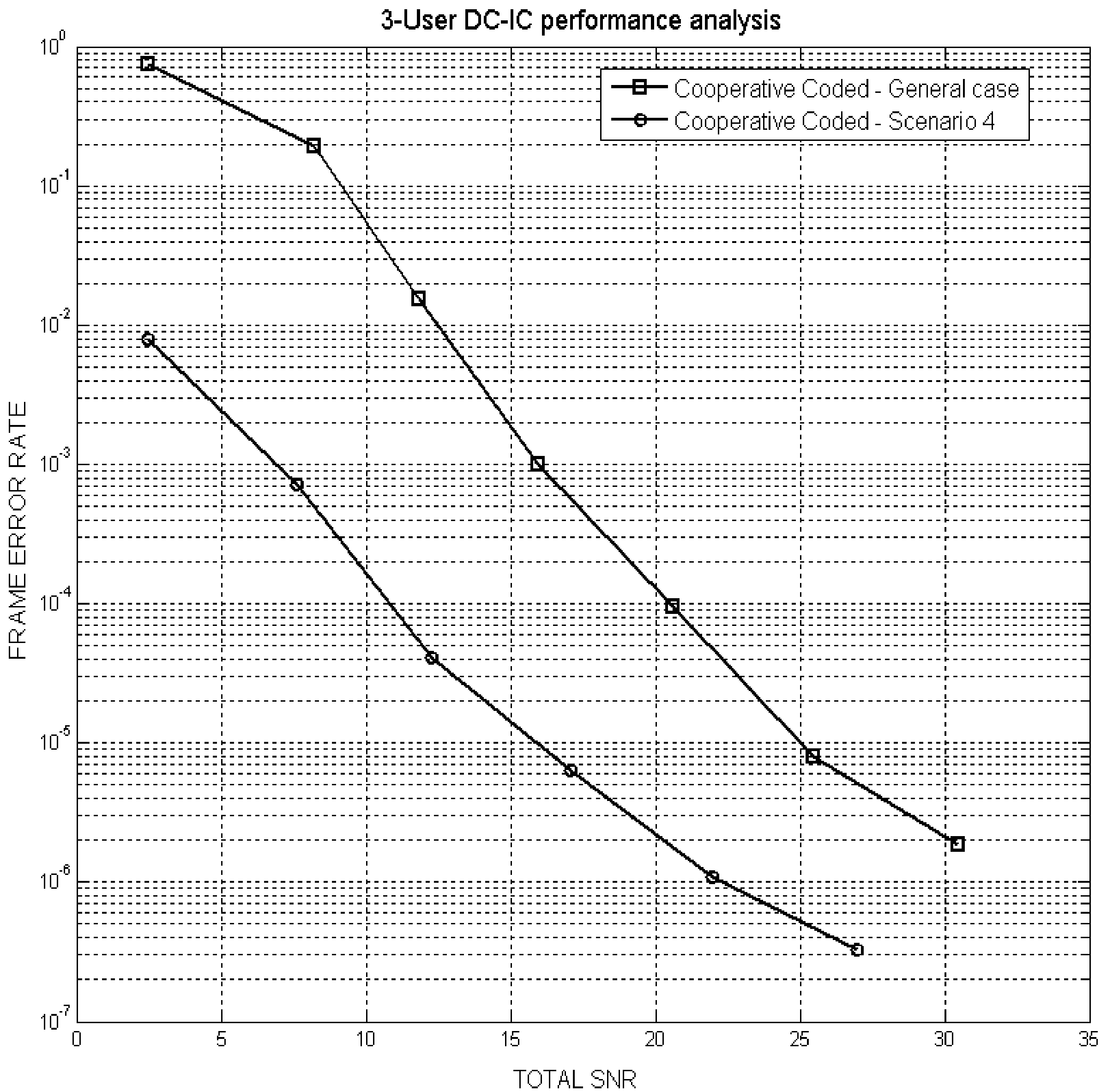


Figure 4.17 Frame Error Rate - scenario 4

4.4.5 COMPARISON ANALYSIS BETWEEN ALL SCENARIOS

We illustrate in Figure 4.18 the FER of all scenarios to show a comparison analysis. It is clear that all FER curves are upper bounded by the special case where the distance between all nodes is equal to one. In practical situations, possible scenarios fall at any distance below the special case distances. Those scenarios were randomly selected for illustration the functionalities of the system and for presentation purposes. However, there exists specific range of distances depending on the application type.

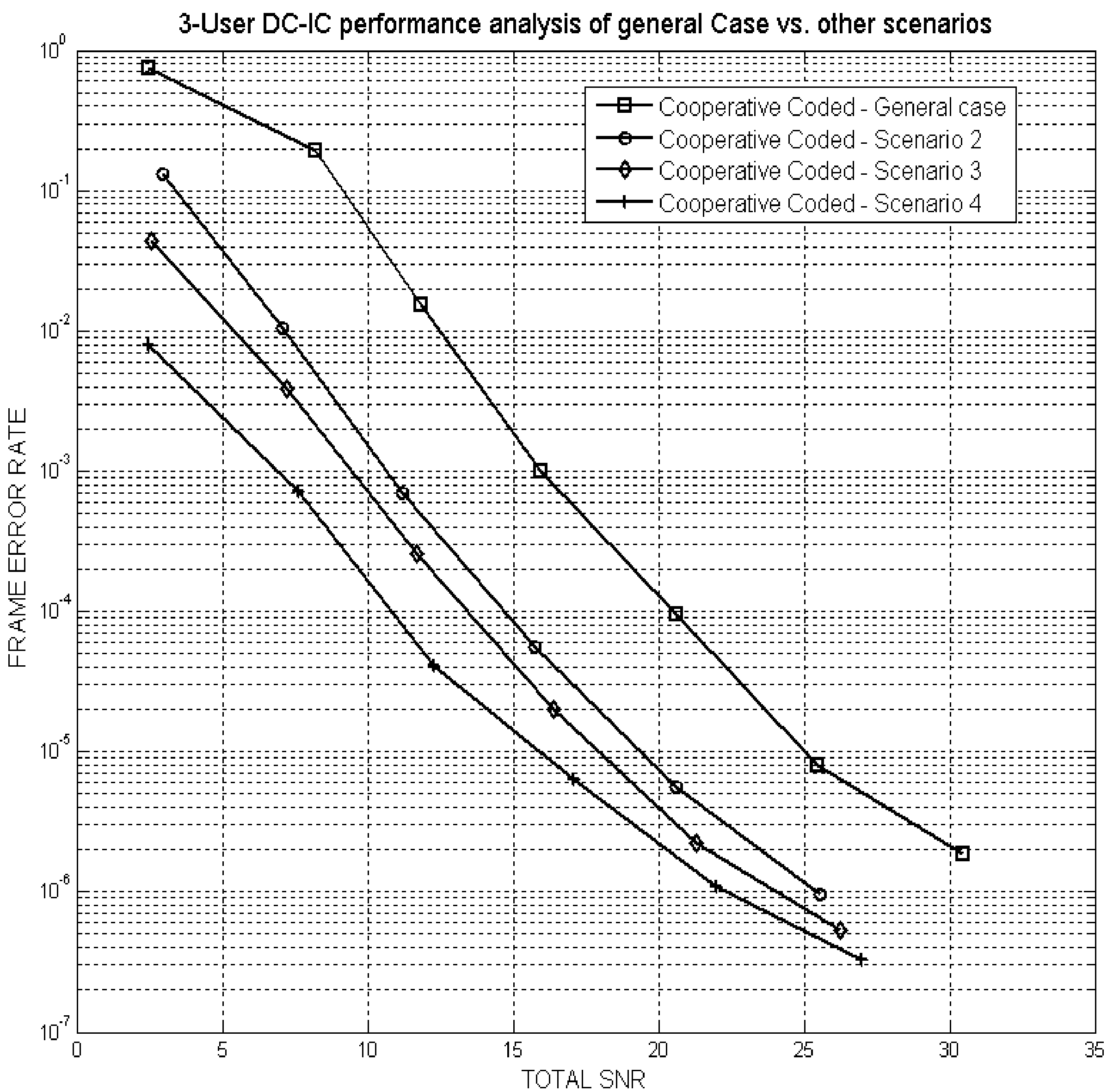


Figure 4.18 Comparison analysis between all scenarios

4.4.6 Comparison analysis between 2-user and 3-user DC-IC with the baseline scheme

In this subsection, we show the performance analysis of the 2-user scheme studied in previous chapter and the 3-user model considered for this chapter in comparison with the baseline schemes for coded and uncoded forms. Figure 4.19 illustrates the FER of various schemes. It shows about 7dB of gain at 10^{-5} of FER between 3-user and 2-user models, this advantage is due to the fact that the 3-user scheme has more diversity and network coding gain compared to the 2-user model.

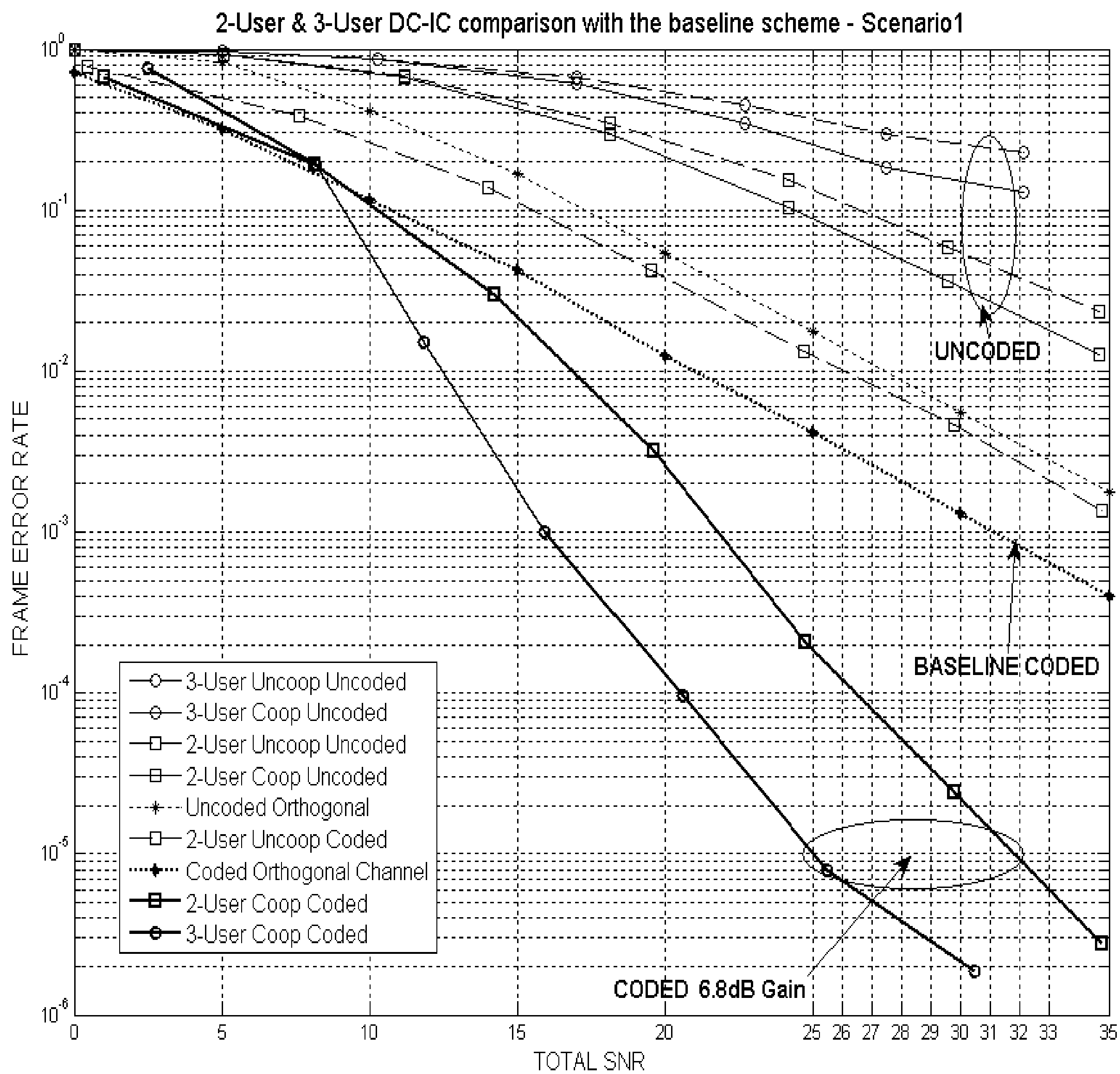


Figure 4.19 2-User and 3-User DC-IC comparison with the baseline scheme.

4.5 SUMMARY

In this chapter, we have considered the performance analysis of a 3-user Destination Cooperation scheme in an Interference Channel. In this model, one time slot is used for broadcasting the information from all source nodes and two time slots for cooperation. We have adopted the basic cooperation scheme where information that is missing at one destination node can be sourced from another destination node if it is available.

Furthermore, we proposed an enhanced scheme for cooperation that treats the $(2^3)^3 = 512$ presented cases at the destination nodes. This enhanced scheme, inspired by the fact that additional information offered at other destination nodes may help in successfully decoding the message that was previously decoded erroneously, has reduced the outage probability. For instance, in the basic scheme, when the information that, is missing at one destination node, is not available at any other destination node, this case was considered as an outage; whereas in the enhanced scheme, this outage is reduced to possibly few cases. In those cases, the same information is available at all nodes and it would be impossible to obtain the missing information even with further processing.

In the enhanced scheme, we have also introduced the network coding basic concept where available information at one node can be mixed (XOR'ed) prior to sending out the information. This operation is saving time slots in a cooperative environment; thus, on one hand it saves energy at the handheld devices by transmitting less and on the other hand, some cases that were previously considered as an outage are no longer in this category. We have shown that network coding provides about 6dB of gain at a FER of 10^{-4} compared to the scenario where there is no network coding.

We have shown, that this system outperforms the baseline orthogonal channel and the 2-user model presented in the previous chapter. This model provides about 7 dB of gain at 10^{-5} of FER compared to the 2-user model. The main advantage is in the cooperation phase that sends out another copy of the message that is experiencing different fading coefficients and therefore can assist in correctly decoding the messages at the final destinations. Another advantage in this system is that an additional user is available at the destination.

With 3 users, one can achieve a maximum diversity of order 3. It has been shown that this model achieves a diversity order of 2.85 when SNR is between 8 and 16 dB, 2.22 when SNR is between 16 and 25.5dB and 1.45 when SNR is above 26dB. This change in diversity order is due to the fact that the interference caused by the various users at high SNR compared to the thermal noise (low noise) is high. Another fact that might be the cause of such diversity degradation is the error floor produced by Turbo codes.

We have compared each various scenarios in which source nodes are located at different distances from each other. It has been shown that the performance of those scenarios is upper bounded by the special case where nodes are located at equal distance. In real applications, the performance is always below this bound and is somewhere in between those scenarios.

5 CONCLUSION

In this chapter, we summarize all the work we have driven and compiled in this thesis. We present all the simulation results. We also suggest future research as an extension to some of the work and a completely new scheme for other work.

5.1 CONTRIBUTION TO THE THESIS

In this thesis, we have evaluated and developed an enhanced collaborative protocol in interference channels.

In the 2-user model, we studied the performance analysis of 2-user destination cooperation in interference channels. We have developed an enhanced scheme that achieves full diversity and coding gain. The enhanced collaboration scheme consisted of two phases: the broadcast phase and the collaboration phase. In the broadcast phase, both source nodes transmit their information to their respective destination nodes at the same time in one transmission time slots; both destination nodes decode the received message using the successive interference cancellation technique. In the cooperation phase, the cooperation nodes try to cooperate with each other based on the quantity of information correctly received.

The destination node remained silent if it did not receive its own information, whereas it cooperated either if it has just received its information by sending it to the other user in the hope of this solid information would help the other user to reliably decode its own information or if it has received its information and the other user information by transmitting to the other destination node the other user's information. In the special scenario where all nodes are located at equal normalized distance $d_{ij} = 1;\ i, j, \epsilon\{1,2\}$ the basic cooperation scheme achieves a diversity order of 2 and a coding gain of about 13 dB at 10^{-4} of FER. The main advantage is in the cooperation phase that sends out another copy of the message that is experiencing different fading coefficients and therefore can assist in correctly decoding the messages at the final destinations. Moreover, another lead is the second cooperation scheme that exploits the available situations (case 2 & 3) at both destinations and not only case 4. In this scheme, the additional coding gain is about 2dB. The second scenario, achieved a higher gain because the distances$d_{ij} < 1$. Therefore, the system performance varies based on the location of each nodes pair and it is upper bounded by the special case.

In the 3-user model, the protocol consisted of one transmission time slots for broadcasting the information from all source nodes and two cooperation time slots for collaboration between destination nodes. The proposed enhanced scheme, inspired by the fact that additional information offered at other destination nodes may help in successfully decoding the message that was previously decoded erroneously, has possibly reduced the outage probability to few cases.

The outage probability has been defined as the state in which at least one of the destination nodes is unable to receive its own information. In the enhanced scheme, we have introduced the network coding where available information at one node can be mixed (XOR'ed) prior to sending out the information. This operation is saving time slots in a cooperative environment; thus, on one hand it saves energy at the handheld devices by transmitting less and on the other hand, some cases that were previously considered as outage are no longer in this category. We have shown that network coding provides about 6dB of gain at 10^{-4} of FER compared to the scenario where there is no network coding.We have shown, that this system outperforms the baseline orthogonal channel and the 2-user model presented in the previous chapter. This model provides about 7 dB of gain at $10^{-5}$of FER compared to the 2-user model. The main advantage is in the cooperation phase that sends out another copy of the message that is experiencing different fading coefficients and therefore can assist in correctly decoding the messages at the final destinations. Another advantage in this system is in the additional user that is available at the destination; with 3 users, one can achieve a diversity order of maximum 3.

It has been shown that the system achieves a diversity order of 2.85 when SNR is between 8 and 16 dB, 2.22 when SNR is between 16 and 25.5dB and 1.45 when SNR is above 26dB. This change in diversity order is due to the interference caused by the various users at high SNR compared to the thermal noise is high. Another fact that might be the cause of such diversity degradation is the error floor produced by Turbo codes.

Finally, we have compared various scenarios in which source nodes are located at different distances from the other nodes. It has been shown that the performance of those scenarios is upper bounded by the special case. In real applications, the performance is always below this bound and is somewhere in between those scenarios.

5.2 FUTURE RESEARCH DIRECTIONS

The work throughout this thesis has been a great experience. There are different ways to continue and extend the current results of this thesis. We consider the following recommendations for future research:

- A further work can be carried out on the enhanced scheme of the 3-user model. Specifically, this work consists of enhancing the diversity order especially as SNR increases.

- On the cooperation scheme in 3-user model as well. The enhanced cooperation scheme can be further improved by exploiting the unused transmission time slots after each complete transmission cycle. This work can be further developed for applications where delay is tolerable i.e. file sharing or perhaps voice application where a little percentage of delay is still tolerable.

- The work on the 3-user cooperation scheme can also be further extended to 4-user or generalized to N-user model. One important application that is very interesting as the number of users increases is the multicasting which is used to stream media and internet television. In multicasting, network coding can be more efficiently deployed.

- One interesting area of research would be to analytically evaluate the performance of both above described models.

- One can also consider using nested codes instead of network coding in the 3-user or N-user models.

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