PERFORMANCE EVALUATION OF CODED COOPERATION USING RCPC AND RCPT CODES

A DISSERTATION

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By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is presented in this dissertation report entitled, "**PERFORMANCE EVALUATION OF CODED COOPERATION USING RCPC AND RCPT CODES**" towards the partial fulfillment of the requirements for the award of the degree of **Master of Technology** with specialization in **Communication Systems**, submitted in the Department of Electronics and Computer Engineering, Indian Institute of Technology Roorkee, Roorkee (India) is an authentic record of my own work carried out during the period from July 2009 to June 2010, under the guidance of Sri **S.Chakravorty, Assistant Professor, Department of Electronics and Computer Engineering, Indian Institute of Technology Roorkee.**

I have not submitted the matter embodied in this dissertation for the award of any other Degree.

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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V SREEKANTH CHINTADA

ABSTRACT

Coded Cooperation is a burgeoning field of Cooperative Communications. This generates diversity in a new and interesting way. This method integrates cooperation into channel coding. Coded Cooperation allows single antenna systems to reap some of the benefits of multi input multi output (MIMO) systems without using multiple antennas. Cooperative Communication allows single-antenna mobiles to reap some of the benefits of MIMO systems. The basic idea is that single-antenna mobiles in a multi-user scenario “share” their antennas in a manner that creates a virtual MIMO system. The mobile wireless channel suffers from fading, i.e., the signal attenuation can vary significantly over the course of a given transmission. Coded Cooperation is the cost effective way to achieve spatial diversity.

Coded Cooperation framework can be implemented using block or convolutional codes. A simple and effective implementation of Coded Cooperation can be done using rate compatible punctured convolutional codes (RCPC). This provides better performance than Amplify and Forward (AF) and Detect and Forward (DF) schemes. This Coded Cooperation can be applied to the wireless networks where more than two users cooperate to transmit their data. By changing the cooperation percentages according to the channel conditions, users will achieve performance gains. The alternative to implement Coded Cooperation other than RCPC Codes comes in the form of RCPT Codes. RCPT Codes performs better than RCPC Codes in terms of error correction.

In this dissertation work, we proposed Coded Cooperation using RCPT codes in case of two users and multiple users to achieve better BER performance than RCPC Coded Cooperation. Coded Cooperation partitions the user’s code word into frames which are transmitted via independent fading paths. Formation of number of frames will depend on the number of users participating in cooperation. For an M-user cluster each user will divide his data frame into ‘M’ number of frames for cooperation. In this work, frames are formed using puncturing. In case of RCPC Coded Cooperation, Viterbi decoder is used at the users and also at the Base Station. For RCPT Coded Cooperation, Viterbi decoder is used at the users whereas Iterative Turbo decoder is used at the Base station. MATLAB environment is used for our simulations.

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AF	Amplify and Forward
AF	Amount of Fading
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BCJR	Bahl Cocke Jelinek Raviv
BEP	Bit Error Probability
BER	Bit Error Rate
BLER	Block Error Rate
BPSK	Binary Phase Shift Keying
CC	Coded Cooperation
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CSI	Channel State Information
DF	Decode and Forward
EDGE	Enhanced Data rates for GSM Evolution
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FSK	Frequency Shift Keying
GSM	Global System for Mobile Communications
IRWEF	Input-Redundancy Weight Enumerating Function
MAP	Maximum A-Posteriori
MGF	Moment Generating Function
MIMO	Multi Input Multi Output
MLD	Maximum Likelihood Decoding
MPSK	M-ary PSK
PCCC	Parallel Concatenated Convolutional Codes
PDF	Probability Density Function

PEP	Pairwise Error Probability
PSK	Phase Shift Keying
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RCPC	Rate Compatible Punctured Convolutional
RCPT	Rate Compatible Punctured Turbo
RSC	Recursive Systematic Convolutional
SEP	Symbol Error Probability
SISO	Soft Input Soft Output
SNR	Signal to Noise Ratio
SSI	Source Significance Information
TDMA	Time Division Multiple Access
UEP	Unequal Error Protection
UMTS	Universal Mobile Telecommunications System
VA	Viterbi Algorithm
VLSI	Very Large Scale Integration
W-CDMA	Wideband Code Division Multiple Access
WEF	Weight Enumerating Function

Chapter 1
INTRODUCTION

Wireless device usage is increasing manifold in our lives in the form of mobile phones, satellite television, computer mice, keyboards and headsets. Mobile phones, an example application of wireless technologies, are widely used today as they allow us to connect anywhere at any time. As we are taking so much liking to wireless technologies, the system capacity is increasing gradually. This is aggravated by bandwidth hungry applications ranging from web browsing to multimedia transmissions. Network designers are struggling to meet this ever increasing demand in capacity and are actively searching for different means to increase capacity.

Martin Cooper of Arraycomm observed that the wireless capacity has doubled every 30 months over the last 104 years [1]. This translated into an approximately million-fold capacity increase since 1960. This has been broken down to yield 25-times improvement from wider spectrum, a fivefold improvement by dividing the spectrum into smaller slices, a fivefold improvement by designing better modulation schemes, and 1600-fold gain through reduced cell sizes and transmits distance. Among the many possible approaches to capitalize on these attractive gains, cooperative techniques at the physical layer have great potential for reliable communication.

In traditional wireless communication systems, users individually communicate with the associated base station and vice versa. Cooperation is referred to as any architecture that deviates from this traditional approach, where a user's communication link is enhanced in a supportive way by relays or in a cooperative way by other users. Due to many available degrees of freedom in such systems, that is the many ways in which supportive relays and cooperative users can be deployed, an enormous variety of different architectures exist [1].

The roots of wireless communication can be traced back to 19th century. In 1893, Nikola Tesla demonstrated the first public radio communication. During November 1894 in a public demonstration at Town Hall of Kolkata, J.C.Bose ignited gunpowder and rang a bell at a distance using millimetre range wavelength microwaves. Bose wrote in a Bengali essay, Adrisya Alok (Invisible Light), "The invisible light can easily pass through brick walls, buildings etc. Therefore, messages can be transmitted by means of it without the mediation of wires." He invented "coherer" which is analogous to diode in series with a grounded capacitor to detect the RF signal picked up by the antenna. Later this model was used by Marconi for his wireless signalling experiments [2,3].

Since then, wireless communications has developed into a key element of modern society. From satellite transmission, radio and television broadcasting to mobile telephones, wireless communications has revolutionized the society functioning. Wireless channel mostly suffers from fading, outages, and circuit failures. To overcome these effects, transmit diversity can be used.

Transmit diversity requires signals that have been modulated with identical information originate from two or more independent sources. Their transmission characteristics vary at any given instant. When using diversity transmission and reception, the amount of received signal improvement depends on the independence of the fading characteristics of the signal as well as circuit outages and failures. Generally more than one antenna at the transmitter is needed for transmit diversity. However, many wireless devices are limited by size or hardware complexity to one antenna. Cooperative communication techniques enable single antenna mobiles in a multi-user environment to share their antennas and generate a virtual multiple-antenna transmitter that allows them to achieve transmit diversity. Cooperation in a wireless network of the cellular or ad hoc variety increases the effective quality of service (QoS), measured at physical layer for wireless users. In a cooperative communication system, each wireless user is assumed to transmit data as well as act as a cooperative agent for another user [4].

Cooperation leads to interesting trade-offs in code rates and transmit power. The baseline transmit power for each user will be reduced because of diversity. This trade-off provides a net reduction of transmit power, everything else being constant. In cooperative communication, each user transmits both his own as well as some code bits for his partner. By this, the spectral efficiency of each user improves because cooperation diversity permits an increase in channel code rates. Several studies demonstrated that cooperation is worth the incurred cost. The premise of cooperation is that certain allocation strategies for the power and bandwidth of mobiles lead to significant gains in system performance [4].

Coded Cooperation, ARQ/FEC techniques, JPEG image transmission and compression use unequal error protection methods. By rate variation within a data frame, unequal error protection is achieved. This rate variation is required when different levels of error protection are needed. Puncturing provides a trade-off between rate and performance. Deleting some parity bits from the codeword periodically is called puncturing. This deletion is performed using a predefined matrix structure, which is called puncturing matrix. Puncturing increases code rate without increasing complexity and decreases free distance of the code. The puncturing matrix must satisfy a rate compatibility criterion, i.e. lower rate (higher redundancy) codes transmit the same coded bits as all higher-rate codes plus additional bits. These are called rate compatible codes [5].

Viterbi algorithm (VA) is the most commonly used decoding strategy for convolutional codes. VA does not result in minimum bit error rate (BER), rather it finds the most likely sequence of transmitted bits. However, it performs close to the minimum possible BER, which can be achieved only with the aid of an extremely complex full-search algorithm evaluating the probability of all possible 2^n binary strings of a k-bit message. The minimum BER decoding algorithm was proposed in 1974 by Bahl *et al.* [6], which was termed the Maximum A-Posteriori (MAP) algorithm. Although the MAP algorithm slightly outperforms the VA in BER terms, because of its significantly higher complexity it was rarely used in practice, until Turbo codes were found by Berrou *et al.* in 1993[7].

From the past 15 years, Turbo coding and its associated iterative decoding method, the turbo principle, established itself as the error coding method of choice. Turbo codes outperform all previous FEC schemes by at least 3dB, thereby doubling the battery lifetime or saving 20% of the required spectrum. It is easy to implement and its performance in many cases reaches up to Shannon's theoretical limits. This suggests that Turbo coding is the right way to encode and decode digital data. The Turbo principle found applications even outside the narrow field of error control coding, in multiple access channel communications, in signalling over channels with intersymbol or interchannel interference, and in source coding. In all these applications, the principle has established itself as a very powerful processing method, leading to the design of receivers which are far superior to conventional methods [7].

Turbo codes can be decoded using MAP algorithm also called as BCJR algorithm. This gives the probability of individual trellis states or data symbols. Turbo decoding uses iterative processing in which each component decoder takes advantage of the work done by the other decoder, at the previous step [7].

1.1. Coded Cooperation

Coded Cooperation is a method that integrates cooperation into channel coding. This method works by sending different portions of each user's code word via two independent fading paths. The basic idea is that each user tries to transmit incremental redundancy to its partner. Whenever that is not possible, the users automatically revert to a non cooperative mode. The key to the efficiency of Coded Cooperation is that all this is managed automatically through code design, with no feedback between the users. In a multi-user environment, Coded Cooperation creates transmit diversity for small mobiles (e.g. handsets) that cannot support more than one antenna. Coded Cooperation allows these mobiles to share their antennas via a simple and effective coding method [8].

Coded Cooperation has two key characteristics. First, cooperation occurs through partitioning a user's code word such that part of the code word is transmitted by the user itself, while the remainder is transmitted by the partner through partial or complete decoding. Earlier, Detect and Forward (DF) and Amplify and Forward (AF) were proposed as cooperative strategies. However, these may not result in the best use of available bandwidth. Second, we employ error detection at the partner to avoid error propagation. Error propagation diminishes the performance, particularly when the channel between partners is poor [4].

The users divide their source data into blocks that are augmented with cyclic redundancy check (CRC) code, for a total of K bits per source block (including the CRC bits). Each block is then encoded with a forward error-correcting code, so that, for an overall rate R code, we have $N = K/R$ total code bits per block. In Coded Cooperation, each of the user's data is encoded into a codeword that is partitioned into two segments, containing N_1 bits and N_2 bits. The data transmission period for each user is divided into two time segments of N_1 and N_2 bit intervals, respectively. These time intervals are called frames.

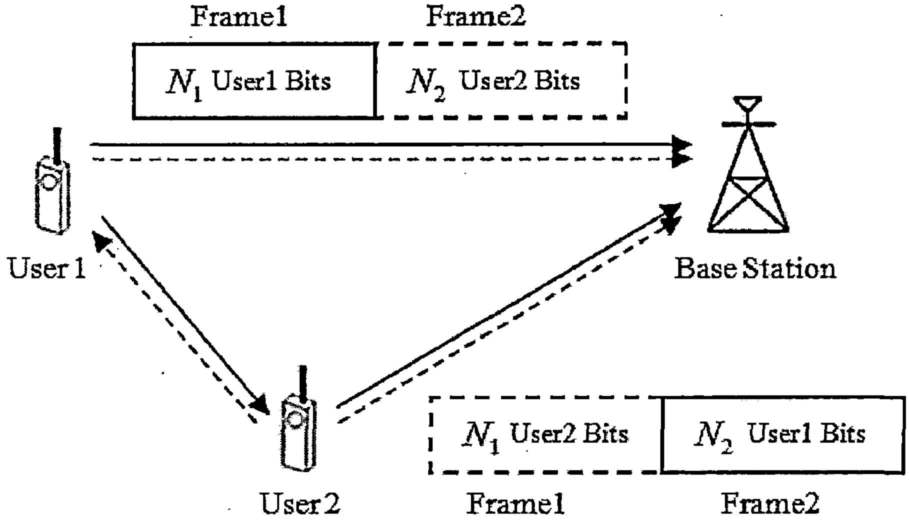

Figure 1.1 Implementation of Coded Cooperation [8]

Transmission of data frames at each user is shown in Figure 1.1 when both users decode successfully each other's data. User 1 will act as a cooperative partner for User 2 and vice versa. User 1's data is indicated with dark lines and User 2's data is indicated with dotted lines. Frame division in Coded Cooperation is a major task. The division of frames can be achieved by using block or convolutional codes. Coded Cooperation can be implemented using rate compatible punctured convolutional (RCPC) codes and rate compatible punctured Turbo (RCPT) codes.

1.2. Problem Statement

Coded Cooperation is a burgeoning field which provides remarkable performance gains over AF and DF protocols. To achieve Coded Cooperation in a wireless network, the cooperating user must decode successfully the partner's data. We use Pairwise error probability (PEP) and BER as performance measures, The main objectives of this dissertation are as follows:

1) To study Coded Cooperation using RCPC codes and to evaluate the performance of 2-user RCPC Coded Cooperation under Rayleigh and Rician fading.
2) To evaluate the performance of multi-user RCPC Coded Cooperation under Rayleigh fading.
3) To study Coded Cooperation using Turbo Codes and to evaluate the performance of proposed 2-user RCPT Coded Cooperation under Rayleigh fading.
4) To compare the RCPT Coded Cooperation results with RCPC Coded Cooperation and Turbo Coded Cooperation.

1.3. Organisation of the Report

The dissertation has been organised in 6 Chapters, including this introductory chapter. In Chapter 2, need for Cooperative Communication is established and various cooperative signalling methods discussed in detail.

Chapter 3 introduces Coded Cooperation using RCPC codes. The performance of 2-user RCPC Coded Cooperation is analyzed and measures like PEP and BER are evaluated. This chapter also includes the performance analysis of multi-user RCPC Coded Cooperation. In Chapter 4, RCPT Coded Cooperation is proposed and performance analysis for Turbo codes is included. In Chapter 5, simulation environment and results for RCPC and RCPT Coded Cooperation are presented. RCPC Coded Cooperation results for 2 users in Rayleigh, Rician fading and for multiple users in Rayleigh fading are shown. Performance of 2 User RCPT Coded Cooperation is obtained in Rayleigh fading. The dissertation concludes with Chapter 6 which also contains some suggestions for future work.

Chapter 2
COOPERATIVE COMMUNICATION

Any cooperative technology that depends on human decisions is doomed to fail. By contrast, if machines have access to some computerized decision making engines, cooperative schemes become viable communication techniques and occupy an important place in the technological landscape of the 21st century. For this reason, wireless cooperative communication systems received significant attention in the past decade. Also a large body of highly useful research papers have emerged [9].

This chapter presents a brief review of prior work in the area of cooperative communication. In particular, the need to move towards cooperative communications from conventional wireless systems is discussed. An information theoretical aspect of relay channel, different cooperative signalling methods and important performance measures used in cooperative communication are included.

2.1. NEED FOR COOPERATION

4G wireless communications will bear little resemblance to 1G and 2G. In order to meet the demands of multirate multimedia communications, next-generation cellular systems must employ advanced algorithms and techniques that not only increase the data rate, but also enable the system to guarantee the quality of service (QoS) desired by the various media classes. The techniques currently being investigated for meeting next-generation goals for the wireless environment include advanced signal processing, tailoring system components (such as coding, modulation, and detection) and using various forms of diversity. Among these techniques, diversity is of primary importance due to the nature of the wireless environment.

The mobile radio channel suffers from fading, implying that, within the duration of any given call, mobile users go through severe variations in signal attenuation. By effectively transmitting or processing independently fading copies of the signal, diversity techniques combat the effects of fading. Some well-known forms of diversity are spatial diversity, temporal diversity, and frequency diversity. In spatial diversity, signals transmitted from geographically separated transmitters, and/or to geographically separated receivers, experience independent fading [10].

Therefore, independently of whether other forms of diversity are being employed, having multiple transmit antennas is desirable due to the spatial diversity they provide. This is impractical in the uplink of a cellular system due to the size of the mobile unit. In order to overcome this limitation, yet still emulate transmit antenna diversity, a new form of spatial diversity can be achieved via the cooperation of in-cell users. That is, in each cell, each user has a "partner." Cooperation is a joint action for mutual benefit [4].

2.2. Pros and Cons of Cooperation

In cooperation each of the two partners is responsible for transmitting not only their own information, but also the information of their partner, which they receive and detect. This achieves spatial diversity through the use of the partner's antenna. Cooperative Communication has its own advantages and disadvantages.

2.2.1. Advantages of Cooperation

The key advantages of using cooperative relays in the system can be summarized as follows:

1) Performance Gains: Large system-wide performance gains can be achieved due to pathloss, diversity and multiplexing gains. These translate into decreased transmission powers, higher capacity or better cell coverage.
2) Balanced Quality of Service: In traditional systems users at the cell edge or in shadowed areas suffer from capacity and/or coverage problems. Relaying balances this discrepancy and gives almost equal QoS to all users.
3) Reduced Outage Probability: Relays used in cooperative networks provide the spatial diversity needed to reduce the outage probability. This leads to increased data rate provided to the end user, i.e. the link capacity increases [9].
4) Infrastructure-Less Deployment: The use of relays allows the roll-out of a system that has minimal or no infrastructure available prior to deployment. For instance, in disaster-struck areas, relaying can be used to facilitate communications even though the cellular system is non-functioning.
5) Reduced Costs: Compared to a purely cellular approach to provide a given level of QoS to all users in the cell, relaying is a more cost effective solution. The capital and operational expenditures are generally lower when relays are used so the savings are not dramatic [10].

2.2.2. Disadvantages of Cooperation

Cooperation is complicated by noisy interuser channel. It is also complicated by the fact that both partners have their own information to send. Hence this is not a simple relay problem. Some major disadvantages of using cooperative relays in wireless communication system are given below [9]:

1) Complex Schedulers: Maintaining a single cooperative relaying link is a fairly trivial task, at system level with many users and relays. Relaying requires more sophisticated schedulers since traffic and data flow of different users needs to be scheduled. Any gains due to cooperation at the physical layer should be handled properly to avoid losses at medium access and network layers.
2) Increased Overhead: A full system functioning requires handovers, synchronization, extra security. This clearly indicates an increased overhead with respect to a system that does not use relaying.
3) Partner Choice: To determine the optimum relaying and cooperative partners is an intricate task. Also, the complexity of maintaining such cooperative partnership is higher with respect to non cooperative relaying.
4) Increased Interference: If the offered power savings are not used to decrease the transmission power of the relay nodes but rather to boost capacity or coverage, then relaying will certainly generate intra- and inter-cell interference, which potentially causes the system performance to deteriorate. Therefore, an optimum trade-off is needed at system level.
5) Extra Relay Traffic: The relayed traffic is, from a system throughput point of view, redundant traffic and hence decreases the effective system throughput since in most cases resources in the form of extra frequency channels or time slots need to be provided.
6) Increased End-to-End Latency: Relaying involves the reception and decoding of the entire data packet before it can be re-transmitted. If delay-sensitive services are being supported, such as voice or the increasingly popular multimedia web services, then the latency induced by decoding may become detrimental. Latency increases with the number of relays and also with the use of interleavers, such as utilized in GSM voice traffic. To circumvent this latency, either simple transparent relaying or novel decoding methods need to be used.

7) Tight Synchronization: A tight synchronization is to be maintained to facilitate cooperation. This in turn requires expensive hardware and potentially large protocol overheads since nodes need to synchronize regularly by using some form of beaconing or other viable techniques.
8) More Channel Estimates: The use of relays effectively increases the number of wireless channels. This requires the estimation of more channel coefficients and hence more pilot symbols need to be provided if coherent modulation is used.

2.3. Background and Milestones

Early developments concerning supportive, cooperative and space–time relaying were related but have emerged independently. This section gives the exposure of early milestones that helped in shaping today's research landscape in cooperative systems:

1) Supportive Relaying: This is the simplest form of cooperation. Information theoretical developments stem back to contribution by Meulen in 1968 and by Cover and Gamal [11] in 1979. The communication and protocol developments received a revival in the early 1990s with the 3GPP Concept Group Epsilon. Harrold and Nix [12] proved by means of simulations that the short-term gains were sometimes unfavourable than every user gained in the long run by cooperating. They also showed that by using simple relaying, coverage holes could largely be closed in a cellular deployment.
2) Cooperative Relaying: In Cooperative relaying at least two users help each other to boost their performance. This has been pioneered by Sendonaris et al. [13] in 1998. Later, around 2000, Laneman and co-workers [14] formalized various types of supportive and cooperative relaying protocols and proved that significant performance and outage gains can be achieved. It is due to Laneman's work that the area of cooperative communication systems commenced to flourish. Later, Hunter, Stefanov and Erkip [15] were the first to propose a viable cooperative scheme based on channel coding and special code designs.
3) Space–Time Relaying: Space–time relaying had been pioneered by Dohler and co-workers [9] in 1999 and made public through mobile virtual centre of excellence (M-VCE), from 2000. Also some pioneering key contributions related to distributed space–time codes and their designs were emerged from Laneman and Wornell and Stefanov and Erkip [13].

2.4. Cooperative Signalling Method

2.4.1. The Relay Channel

The basic ideas behind cooperative communication can be traced back to the work of Cover and Gamal [11,16] on the information theoretic properties of the relay channel. Their work analysed the capacity of the three-node network consisting of a source (A), a destination(C), and a relay (B). It was assumed that all nodes operate in the same band, so the system can be decomposed into a broadcast channel from the viewpoint of the source and a multiple access channel from the viewpoint of the destination as shown in Figure 2.1.

The cooperative communication which we consider is different from the relay channel in two ways. First, recent developments motivated the concept of diversity in a fading channel, while Cover and Gamal mostly analysed capacity in an additive white Gaussian noise (AWGN) channel. Second, in the relay channel, the relay's sole purpose is to help the main channel, whereas in cooperation the total system resources are fixed, and users act both as information sources as well as relays.

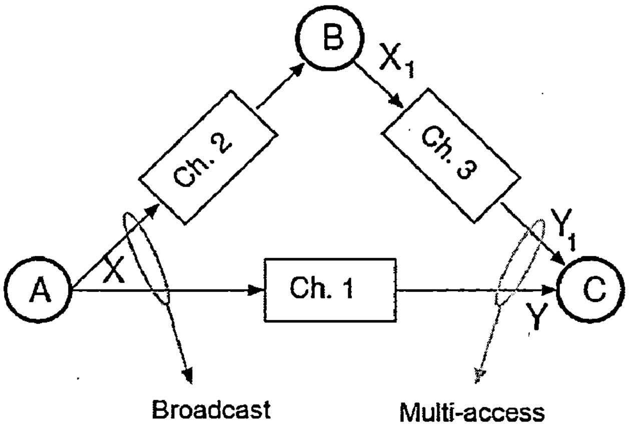

Figure 2.1 The Relay Channel [4]

2.4.2. Detect and Forward Method

This is closest to the idea of a traditional relay. In this a user attempts to detect the partner's bits and then retransmits the detected bits as shown in Figure 2.2. The partners may be assigned mutually by the base station, or via some other technique. Here two users partnering with each other for providing a second data path for diversity [4,17].

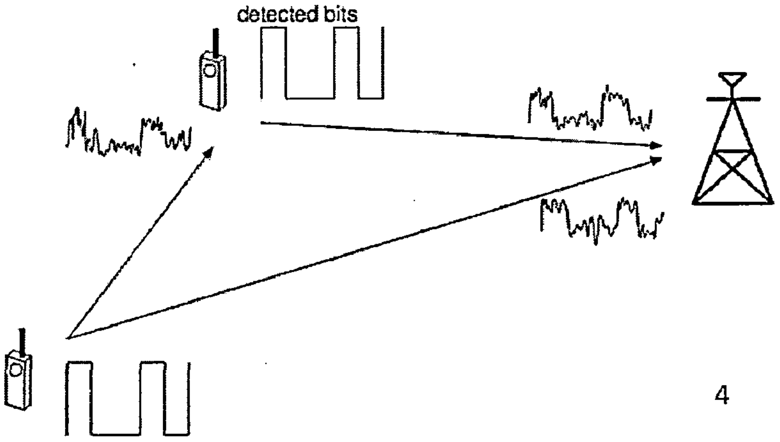

Figure2.2 Detect and Forward [4]

An example of decode and forward signalling is found in the work of Sendonaris, Erkip, and Aazhang [13]. In this scheme, two users are paired to cooperate with each other. Each user has its own spreading code, denoted by $c_i(t)$, as in the case of CDMA. The two user's data bits are denoted $b_i^{(n)}$ where i= 1, 2 are the user indices and n denotes the time index of information bits. Factors a_{ij} denote signal amplitudes, and hence represent power allocation to various parts of the signalling. The term $\hat{b}_i^{(n)}$ denotes the partner's hard-detected estimate of User i's bit. Each signalling period consists of three bit intervals. The signal of User 1 is denoted as $X_1(t)$ and the signal of User 2 as $X_2(t)$.

$$X_1(t) = a_{11}b_1^{(1)}c_1(t), \quad a_{12}b_1^{(2)}c_1(t)\ , \ a_{13}b_1^{(2)}c_1(t) + a_{14}\hat{b}_2^{(2)}c_2(t) \tag{2.1}$$

$$X_2(t) = a_{21}b_2^{(1)}c_2(t), \ a_{22}b_2^{(2)}c_2(t), \ a_{23}\hat{b}_1^{(2)}c_1(t) + a_{24}b_2^{(2)}c_2(t) \tag{2.2}$$

In the first and second intervals, each user transmits its own bits. Each user then detects the other user's second bit, and in the third interval, both users transmit a linear combination of their own second bit and their estimate of the partner's second bit, each multiplied by the appropriate spreading code. The transmit powers for the first, second, and third intervals are variable, and by optimizing the relative transmit powers according to the conditions of the uplink channel and the inter-user channel, this method provides adaptability to channel conditions.

2.4.3. Amplify and Forward Method

Amplify-and-forward is conceptually the most simplest of the cooperative signalling methods. Each user in this method receives a noisy version of the signal transmitted by its partner. As the name implies, the user then amplifies and retransmits this noisy signal as shown in Figure 2.3[4].

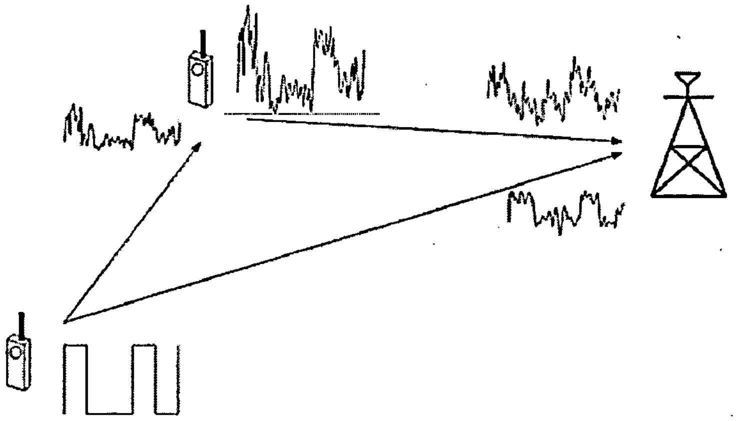

Figure 2.3 Amplify and Forward [4]

The destination will combine the information sent by the user and partner and will make a final decision on the transmitted symbol. Although the noise of the partner is amplified in this scheme, the destination still receives two independently-faded versions of the signal and is thus able to make better decisions for the transmitted symbols. In this method it is assumed that the base station knows the interuser channel coefficients to do optimal decoding, so some mechanism of exchanging or estimating this information must be incorporated into implementation. Another challenge is that sampling, amplifying, and retransmitting analog values is technologically nontrivial.

2.4.4. Coded Cooperation

Previously studied cooperative methods have users detecting and repeating estimates of the partner's transmitted symbols (Detect and Forward), or amplifying and forwarding the partner's analog signal (Amplify and Forward). Coded Cooperation is a new framework of Cooperative communications which uses the available bandwidth most efficiently. This integrates cooperative signalling with channel coding. Coded Cooperation implementation has already been presented in Section 1.1. Also we present Coded Cooperation in detail using RCPC and RCPT codes in Chapter 3 and Chapter 4 respectively.

2.5. Information Theoretical Aspects of Relay channel

In a relay channel, between the sender X and the receiver Y at least one relay exists. Generally, the relay can both transmit its own information and help forwarding other sources information. This summary considers the relay as a helper to the receiver. The relay and the transmitter cooperate to resolve the receiver's uncertainty. Due to the presence of relay, the relay channel capacity is difficult to determine. Here the simplest relay channel with only one relay is considered. An outer bound for the capacity of the general relay channel is described. Also capacity definitions for degraded relay channel, reversely degraded relay channel are shown [11].

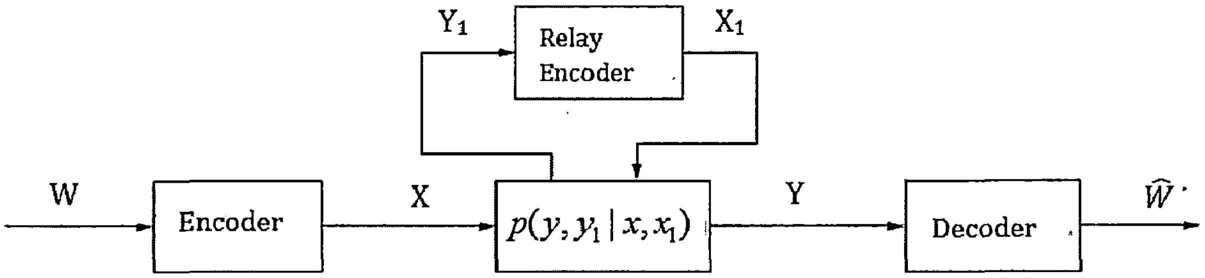

Figure 2.4 The Relay Channel

Fig. 2.4 illustrates the simplest general relay channel which has only one relay. The channel consists of four finite sets $\mathcal{X},\mathcal{X}_1,\mathcal{Y},$ and $\mathcal{Y}_1$, and a collection of probability mass functions $p(y,y_1 \mid x,x_1)$. x is input to the channel and y is the output of the channel. y_1 is the relay's observation and x_1 is the input chosen by the relay and depends only on the past observation $(y_{11},y_{12},...y_{1i-1})$. The capacity problem is finding the channel capacity between X and Y. An (M,n) code for the relay channel consists of a set of integers $\mathcal{M}=\{1,2,....,M\}$ an encoding function X$:\mathcal{M}\to\mathcal{X}^n$, a set of relay functions $\{f_i\}_{i=1}^{n}$ such that

$$x_{1i}=f_i(Y_{11},Y_{12},....,Y_{1i-1})$$

and a decoding function $g:\mathcal{Y}^n \to \mathcal{M}$

The channel is memoryless in the sense that (Y_i,Y_{1i}) depends on the past only through the current transmitted symbols (X_i,X_{1i}). Thus for any choice $p(w)$, $w\in\mathcal{M}$, code choice

$x:\mathcal{M}\rightarrow \mathcal{X}^n$ and relay functions $\{f_i\}_{i=1}^{n}$,the joint probability mass function on $\mathcal{M}\times \mathcal{X}^n \times \mathcal{X}_1^n \times \mathcal{Y}\times \mathcal{Y}_1^n$ is given by .

$$p(w,x,x_1,y,y_1)=p(w)\prod_{i=1}^{n}p(x_{1i}\mid y_{11},y_{12},\dots,y_{1i-1}).p(y_i,y_{1i}\mid x_i,x_{1i}) \tag{2.3}$$

The average probability of error is defined as follows:

$$p_e^{(n)}=\frac{1}{2^{nR}}\sum_{w\in\mathcal{M}}\Pr\{g(Y)\neq w\mid w\text{ sent}\}=\frac{1}{2^{nR}}\sum_{w\in\mathcal{M}}\lambda(w) \tag{2.4}$$

The relay channel combines a broadcast channel (X to Y and Y_1) and a multiple access channel (X_1 and X to Y). Applying the max-flow-min-cut theorem for general multi terminal networks to the relay channel, an upper bound of the capacity is obtained.

Theorem 1: For any relay channel, the capacity is bounded above by

$$C\leq \sup_{p(x,x_1)}\ \min\{I(X,X_1;Y),I(X;Y,Y_1\mid X_1)\} \tag{2.5}$$

The first term in the above equation upper bounds the maximum rate of information transfer from senders X and X_1 to receiver Y (Multiple Access Channel); the second term bounds the rate from X to Y and Y_1 (Broadcast Channel, but the ultimate receiver Y should first decode the relay signal X_1 before decoding X, which contributes to the conditioning term X_1 in $I(X;Y,Y_1\mid X_1)$.

2.5.1. Degraded Relay Channel

The degraded relay channel, similar to the degraded broadcast channel, implies that one receiver is a degraded version of the other receiver. Based on the degradedness's there are two types of relay channels exists. One is degraded relay channel, in which the relay receiver y_1 is better than the ultimate receiver y and thus the relay can cooperate to send x. The other case is reversely degraded relay channel in which the relay y_1 is worse than y, is of less .interest, because the relay can contribute no new information to the receiver [16].

Definition 1 :

The relay channel $(\mathcal{X}\times\mathcal{X}_1, p(y,y_1\mid x,x_1), \mathcal{Y}\times\mathcal{Y}_1)$ is said to be degraded if

$$p(y,y_1\mid x,x_1)=p(y_1\mid x,x_1)p(y\mid y_1,x_1) \tag{2.6}$$

Equivalently, a relay channel is degraded if $p(y, y_1 | x, x_1) = p(y | y_1, x_1)$, i.e., $X \to (X_1, Y_1) \to Y$ forms a Markov chain. A degraded relay channel can be treated as a family of physically degraded broadcast channels indexed by x_1.

Theorem 2: The capacity C of the degraded relay channel is given by

$$C = \sup_{p(x,x_1)} \min\{I(X, X_1; Y), I(X; Y_1 | X_1)\} \tag{2.7}$$

where the supremum is over all joint distributions $p(x, x_1)$ on $\mathcal{X} \times \mathcal{X}_1$.

Here, $I(X; Y, Y_1 | X_1) = I(X; Y_1 | X_1)$, which is due to degradedness.

2.5.2. Reversely Degraded Relay Channel

When the relay y_1 is worse than y, the channel is called reversely degraded relay channel.

Definition 2: The relay channel is reversely degraded if $p(y, y_1 | x, x_1)$ can be written in the form

$$p(y, y_1 | x, x_1) = p(y | x, x_1) p(y_1 | y, x_1) \tag{2.8}$$

In this case, the relay cannot cooperate to send x, and thus just facilitates the transmission of x by sending the best x_1 [11].

Theorem 3: The capacity C_0 of the reversely degraded relay channel is given by

$$C_0 = \max_{x_1 \in \mathcal{X}_1} \max_{p(x)} I(X; Y_1 | x_1) \tag{2.9}$$

In other words, the relay y_1 sees a corrupted version of what y sees, and then x_1 can contribute no new information to y. Thus x_1 is set constantly at the symbol that “opens” the channel for the transmission of x directly to y at rate $I(X; Y_1 | X_1)$.

2.6. Performance Measures

To compute the performance of different digital communication systems characterized by a variety of modulation/detection types and fading channel models we need some set of tools. Tools should allow us to perform accurate performance evaluation and to provide insight into the manner in which this performance depends on the key system parameters. These set of tools are useful for the wireless applications, satellite, terrestrial, and maritime communications. These will provide several measures of performance related to practical communication system design and analytical methods to evaluate them [18].

2.6.1. Average Signal-to-Noise Ratio

The most common performance measure of a digital communication system is signal-to-noise ratio (SNR). Most often this is measured at the output of the receiver and is thus directly related to the data detection process itself. Of the several possible performance measures that exist, this is easiest to evaluate and most often serves as an excellent indicator of the overall fidelity of the system. Traditionally the term "noise" in signal to noise ratio refers to the ever-present thermal noise at the input to the receiver, in the context of a communication system subject to fading impairment, the more appropriate performance measure is average SNR, where the term "average" refers to statistical averaging over the probability distribution of the fading. If γ denotes the instantaneous SNR (a random variable) at the receiver output that includes the effect of fading [18], then

$$\bar{\gamma} = \int_0^\infty \gamma\, p_\gamma(\gamma)\, d\gamma \tag{2.10}$$

$\bar{\gamma}$ is the average SNR, where $p_\gamma(\gamma)$ denotes the probability density function (PDF) of γ. Rewriting (2.10) in terms of the moment generating function (MGF) associated with γ will become

$$M_\gamma(s) = \int_0^\infty p_\gamma(\gamma) e^{s\gamma} d\gamma \tag{2.11}$$

Taking the first derivative of (2.11) with respect to s and evaluating the result at $s = 0$, we see from (2.10) that

$$\bar{\gamma} = \frac{dM_\gamma(s)}{ds}\Big|_{s=0} \tag{2.12}$$

i.e., the MGF of the instantaneous SNR allows the evaluation of the average SNR via a simple differentiation operation.

2.6.2. Outage Probability

Another standard performance criterion for diversity systems operating over fading channels is outage probability-denoted by P_{out}. It is defined as the probability that the instantaneous error probability exceeds a specified value or equivalently the probability that the output SNR, γ, falls below a certain specified threshold, γ_{th} [18]. Mathematically, we have

$$P_{out} = \int_{0}^{\gamma_{th}} p_{\gamma}(\gamma) d\gamma \tag{2.13}$$

which is the cumulative distribution function (CDF) of γ, namely, $P_{\gamma}(\gamma)$,evaluated at $\gamma = \gamma_{th}$. Since the PDF and the CDF are related by

$$p_{\gamma}(\gamma) = dP_{\gamma}(\gamma)/d\gamma \tag{2.14}$$

and since $p_{\gamma}(0) = 0$, the Laplace transforms of these two functions are related by

$$\hat{P}_{\gamma}(s) = \frac{\hat{p}_{\gamma}(s)}{s} \tag{2.15}$$

As MGF is just the Laplace transform of the PDF with argument reversed in sign i.e., $\hat{p}_{\gamma}(s) = M_{\gamma}(-s)$ then the outage probability can be found from the inverse Laplace transform of the ratio $M_{\gamma}(-s)/s$ evaluated at $\gamma = \gamma_{th}$

$$P_{out} = \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{M_{\gamma}(-s)}{s} e^{s\gamma_{th}} ds \tag{2.16}$$

where σ is chosen in the region of convergence of the integral in the complex s-plane. Methods for evaluating inverse Laplace transforms have received widespread attention in the literature.

2.6.3. Average Bit Error Probability

The third performance criterion is average bit error probability (BEP). This reveals about the nature of the system behaviour and is often illustrated in system performance evaluations. The evaluation of average BEP involves the evaluation of conditional BEP on fading, which is in general, a nonlinear function of the instantaneous SNR, as the nature of the nonlinearity is a function of the modulation/detection scheme employed by the system. In the multichannel case, the average of the conditional BEP over the fading statistics is not a simple average of the per channel performance measure. MGF-based approach is useful in simplifying the analysis and in a variety of cases allows unification [18]. Suppose the conditional BEP is of the form

$$P_b(E\,|\,\gamma) = C_1 \exp(-a_1\gamma) \tag{2.17}$$

This would be the case for differentially coherent detection of phase shift keying (PSK) or non-coherent detection of orthogonal frequency shift keying (FSK). Then, the average BEP is written as

$$P_b(E) = \int_0^\infty P_b(E\,|\,\gamma)p_\gamma(\gamma)d\gamma = \int_0^\infty C_1 \exp(-a_1\gamma)p_\gamma(\gamma)d\gamma = C_1 M_\gamma(-a_1) \tag{2.18}$$

where $M_\gamma(s)$ is the MGF of the instantaneous fading SNR and depends only on the fading channel model assumed. Suppose if the nonlinear functional relationship between $P_b(E\,|\,\gamma)$ and γ is expressed as an integral whose integrand has an exponential dependence on γ is in the form of

$$P_b(E\,|\,\gamma) = \int_{\xi_1}^{\xi_2} C_2 h(\xi)\exp(-a_2 g(\xi)\gamma)d\xi \tag{2.19}$$

where $h(\xi)$ and $g(\xi)$ are arbitrary functions of the integration variable and both ξ_1 and ξ_2 are finite. A relationship of the form in above equation can result from the Gaussian *Q*-function and Marcum *Q*-function, which are characteristic of the relationship between $P_b(E\,|\,\gamma)$ and γ corresponding to coherent detection of PSK and non-coherent detection of quadrature phase shift keying (QPSK), respectively. Another possibility is that the nonlinear functional relationship between $P_b(E\,|\,\gamma)$ and γ is inherently in the form of (2.19). Regardless of the particular case, averaging (2.19) over the fading gives (after interchanging the order of integration)

$$\begin{aligned} P_b(E) = \int_0^\infty P_b(E\,|\,\gamma)p_\gamma(\gamma)d\gamma &= \int_0^\infty \int_{\xi_1}^{\xi_2} C_2 h(\xi)\exp(-a_2 g(\xi)\gamma)d\xi\, p_\gamma(\gamma)d\gamma \\ &= C_2 \int_{\xi_1}^{\xi_2} h(\xi) \int_0^\infty \exp(-a_2 g(\xi)\gamma)p_\gamma(\gamma)d\gamma d\xi \\ &= C_2 \int_{\xi_1}^{\xi_2} h(\xi) M_\gamma(-a_2 g(\xi))d\xi \end{aligned} \tag{2.20}$$

The integrals of the form in (2.20) can be obtained in closed form for many special cases. In worst case, the resulting expression will be a single integral with finite limits and an integrand composed of elementary functions [18]. Since (2.18) and (2.20) cover a wide variety of different modulation/detection types and fading channel models. This is the unified MGF-based approach for evaluating average error probability and the associated forms of the conditional error probability as desired forms.

2.6.4. Amount of Fading

Above three performance measures discussed are the ones most commonly employed to describe the behaviour of digital communication systems in the presence of fading. Average SNR is simple to compute as it requires the knowledge of only first statistical moment of the instantaneous SNR. In the context of diversity combining, this performance criterion does not capture all the diversity benefits. If the diversity advantage were limited to an average SNR gain, then this is achieved by simply increasing the transmitter power. The aptitude of diversity systems is to reduce the fading-induced fluctuations or equivalently to reduce the relative variance of the signal envelope. In order to capture this effect, performance measures that take into account higher moments of the combiner output SNR are required [18].

Computation of amount of fading (AF) requires knowledge of first and second moments of the instantaneous SNR. This was introduced by Simon and Alouini [18] to describe the behaviour of dual-diversity combining systems over correlated log-normal fading channels. This is associated with the output of the combiner. AF measure is often appropriate in the context of describing the behaviour of systems with arbitrary combining techniques and channel statistics. Letting γ_t denote the total instantaneous SNR at the combiner output, AF is defined as

$$\mathrm{AF} = \frac{\operatorname{var}\gamma_t}{(E[\gamma_t])^2} = \frac{E(\gamma_t^{\,2}) - (E[\gamma_t])^2}{(E[\gamma_t])^2} \tag{2.21}$$

which can be expressed in terms of the MGF of γ_t by

$$\mathrm{AF} = \frac{\dfrac{d^2 M_{\gamma_t}(s)}{ds^2}\Big|_{s=0} - \left(\dfrac{dM_{\gamma_t}(s)}{ds}\Big|_{s=0}\right)^2}{\left(\dfrac{dM_{\gamma_t}(s)}{ds}\Big|_{s=0}\right)^2} \tag{2.22}$$

The AF defined in (2.21) is computed at the output of the combiner, its evaluation will reflect the behaviour of the particular diversity combining technique and statistics of the fading channel. So this is a kind of performance measure of entire system.

2.6.5. Pairwise error probability (PEP)

The PEP is the basic building block for the derivation of union bounds to the error probability of a coding scheme. This is can be used for analysing performance of Coded Cooperation scheme. PEP is defined as selecting code word $e=[e(1),e(2),...e(n)]$, when code word $C=[c(1),c(2),...c(n)]$ is transmitted. For a binary code with BPSK modulation, coherent detection, and maximum likelihood decoding, the PEP is conditioned on the set of instantaneous received SNR values $\gamma=[\gamma(1),\gamma(2),...,\gamma(N)]$ can be written as (2.23) [17].

$$P(C\rightarrow e\,|\,\gamma)=Q\left(\sqrt{2\sum_{n\in\eta}\gamma(n)}\right) \tag{2.23}$$

where $Q(x)$ denotes the Gaussian Q-function, and $\gamma(n)$ is the instantaneous received SNR for code bit n as defined in Equation (2.24).

$$\gamma_{i,j}(n)=\frac{\alpha_{i,j}^{2}(n)E_{b,i}}{N_{j}} \tag{2.24}$$

$\alpha_{i,j}^{2}(n)$ is the fading coefficient magnitude between Users i and j. $E_{b,i}$ is the transmitted energy per bit for User i. The set η is the set of all n for which $C(n)\neq e(n)$, and the cardinality of η is equal to the Hamming distance d between code words C and e. The selection of e over C is known as an error event, and thus d is typically referred to as the corresponding error event Hamming weight.

Chapter 3

CODED COOPERATION USING RCPC CODES

Coded Cooperation is achieved through channel coding methods instead of a direct relay or repetition. Each user's codeword is partitioned into two subsets. The first frame is transmitted using his own antenna and the second frame is transmitted using cooperating partner's antenna. Coded Cooperation achieves impressive gains compared to a non-cooperative system while maintaining the same information rate, transmit power, and bandwidth [8]. Coded Cooperation can be implemented using RCPC or RCPT codes for two users and also for multi user scenarios.

It is possible to implement Coded Cooperation in a natural and simple manner by a method that uses common error control codes. The incorporation of cooperation with channel coding allows a great degree of flexibility, since by varying the associated code rate, the coupling between the cooperating users can be controlled and adapted to channel conditions. In general, various channel coding methods can be used within the Coded Cooperation framework. For example, the overall code may be a block or convolutional code, or a combination of both. The code bits for the two frames can be selected through puncturing, product codes and parallel or serial concatenation codes. In Coded Cooperation using rate compatible punctured convolutional (RCPC) codes, the code word for the first frame of N_1 code bits is obtained by puncturing a code word of length N bits. The additional code bits transmitted in the second frame are those punctured to form the first frame code word [17].

In this chapter we discussed Coded Cooperation and its implementation in detail. Brief introduction to RCPC Codes is included. Mainly this chapter is divided into three sections. In Section 3.1 definition and necessity of RCPC Codes is presented. In Section 3.2 RCPC codes are used with 2 User Coded Cooperation and its performance analysis is shown under slow and fast Rayleigh fading. In Section 3.3 we studied Coded Cooperation in multi user scenario.

3.1. Rate Compatible Punctured Convolutional Codes

Punctured convolutional codes were first introduced by Cain, Clark, and Geist [19] mainly for the purpose of obtaining simpler Viterbi decoding for rate K/N codes with two branches arriving at each node instead of 2^K branches. They obtained codes of rate 2/3 and 3/4 by puncturing rate 1/2 codes. These punctured codes were almost as good as the best known codes. Some of the good codes used the same basic rate 1/2 generators. Later, Yasuda *et al.* [19], found a family of $(N-1)/N$ codes by puncturing 1/2 codes for N up to 14, and built selectable rate encoders and Viterbi decoders using soft decisions.

The design of an error correction coding system usually consists of selecting a fixed code with a certain rate and correction capability matched to the protection requirement of all the data to be transmitted and adapted to the average or worst channel conditions to be expected. In many cases it is required that the data to be transmitted have different error protection needs and the channel is time varying or has insufficiently known parameters. Consequently, flexible channel encoding and an adaptive decoder are required. As shown in Figure 3.1, the information to be transmitted might carry source significance information (SSI) indicating different protection requirements. Also the channel characteristics or the channel state might vary considerably as encountered in mobile or multipath radio transmission, in a jamming environment, during rain fading, or in HF transmission [5].

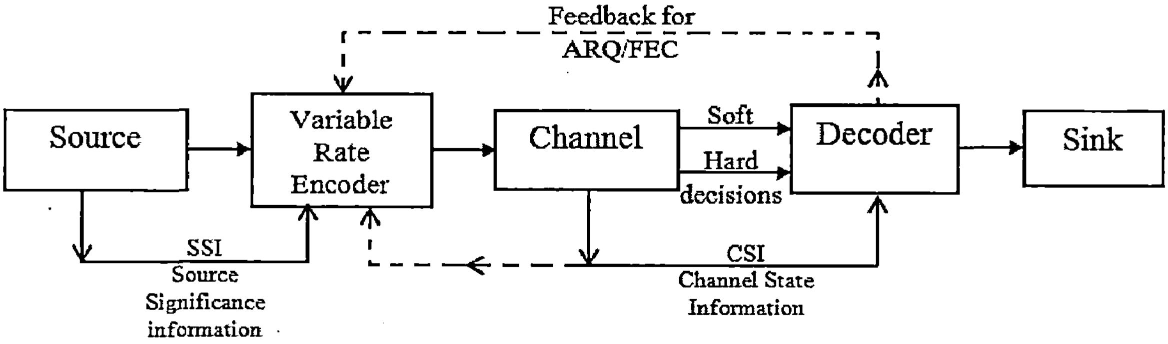

Figure 3.1 Coded transmission scheme with source significance information (SSI) and channel state information (CSI) [5].

The CSI in Figure 3.1 indicates the channel state information. In rare cases the instantaneous CSI is available at the encoder where code adaptation takes place. Mostly the receiver uses a fading depth, noise level variation, short term signal loss, or jammer activity as CSI measures. The CSI can significantly improve decoder performance together with soft decisions at the receiver. Whenever a return channel is available, the CSI can be indirectly relayed to the transmitter by asking for a retransmission as employed in automatic repeat request (ARQ) systems. Such ARQ systems can also be combined with forward error correction (FEC) to yield type I or type II ARQ/FEC hybrid schemes. The latter schemes match the average channel rate or the throughput with the channel conditions and some of them use different FEC codes for repeated transmission attempts.

The scenarios shown in Figure 3.1 require variable codes adapted to the source and channel needs. The code rate can be a variable, i.e., the number of check bits, and hence the correction power of the code during transmission of an information frame according to source and channel needs. For practical purposes, it is not possible to have just switching between a set of encoders and decoders, but one encoder and one decoder which can be modified without changing their basic structure. This can be achieved by not transmitting certain code bits, namely, by puncturing the code. Puncturing is the trade-off between rate and performance. Puncturing increases code rate without increasing complexity and decreases free distance of code. The redundant bits in coding decrease the bandwidth efficiency. The bandwidth efficiency decreases with increase in redundant bits in coding [5].

The concept of punctured convolutional codes is modified for the generation of a family of codes by adding a rate-compatibility restriction to the puncturing rule. The restriction implies that all the code bits of a high rate punctured code are used by the lower rate codes, or in other words, the high rate codes are embedded into the family of lower rate codes. If the higher rate codes are not sufficiently powerful to decode channel errors, only supplemental bits which were previously punctured have to be transmitted in order to upgrade the code. Since codes are compatible, rate variation within a data frame is possible to achieve unequal error protection. These are defined as rate compatible punctured convolutional (RCPC) codes.

A family of RCPC codes is described by the mother code of rate $R = 1/N$ and memory M having the generator tap matrix [5]

$$\mathbf{g} = \begin{pmatrix} g_{11} & \cdots & g_{1(M+1)} \\ \vdots & g_{ik} & \vdots \\ g_{N1} & \cdots & g_{N(M+1)} \end{pmatrix}_{N\times(M+1)}$$

with the tap connections $g_{ik} \in (0,1)$ where a 1 represents a connection from the k^{th} shift register stage to the i^{th} output. Together with N, the puncturing period P determines the range of code rates

$$R = \frac{P}{P+l} \qquad l = 1, \ldots (N-1)P$$

These rates range between $P/(P+1)$ and $1/N$. The RCPC codes are punctured codes of the mother code with puncturing matrices

$$\mathbf{a}(l) = \begin{pmatrix} a_{11}(l) & \cdots & a_{1P}(l) \\ \vdots & a_{ij}(l) & \vdots \\ a_{N1}(l) & \cdots & a_{NP}(l) \end{pmatrix} \qquad a_{ij}(l) \in (0,1)$$

where 0 implies puncturing. The rate-compatibility restriction implies the following rule:

$$\text{if} \quad a_{ij}(l_0) = 1 \quad \text{then} \quad a_{ij}(l) = 1 \quad \text{for all} \quad l \geq l_0 \geq 1$$

or equivalently

$$\text{if} \quad a_{ij}(l_0) = 0 \quad \text{then} \quad a_{ij}(l) = 0 \quad \text{for all} \quad l \leq l_0 \leq (N-1)P-1.$$

3.2. Two-user RCPC Coded Cooperation

3.2.1. System Model

Using rate-compatible punctured convolutional (RCPC) codes, implementation of the code word for the first frame is obtained by puncturing this codeword down to N_1 bits. Which itself is a valid (weaker) codeword. The remaining N_2 bits transmitted in the second frame are those punctured to form the first frame code word. For the first frame, each user transmits a rate R_1 code word, $R_1 > R$, consisting of the N_1-bit code partition.

Each user also attempts to decode the transmission of its partner. If this attempt is successful, (which is determined by checking the CRC code), in the second frame the user calculates and transmits the second code partition of its partner, containing N_2 code bits. Otherwise, the user transmits its own second partition, again containing N_2 bits. Thus, each user always transmits a total of $N = N_1 + N_2$ bits per source block over the two frames. The level of cooperation is defined as N_2 / N, which is the percentage of the total bits transmitted by the user for its partner. A smaller percentage implies a more powerful code for the first frame and increased probability that a user successfully decodes the partner. However, this also means a smaller N_2, thus reducing gain from diversity. Figure 3.2 illustrate the Coded Cooperation framework [8].

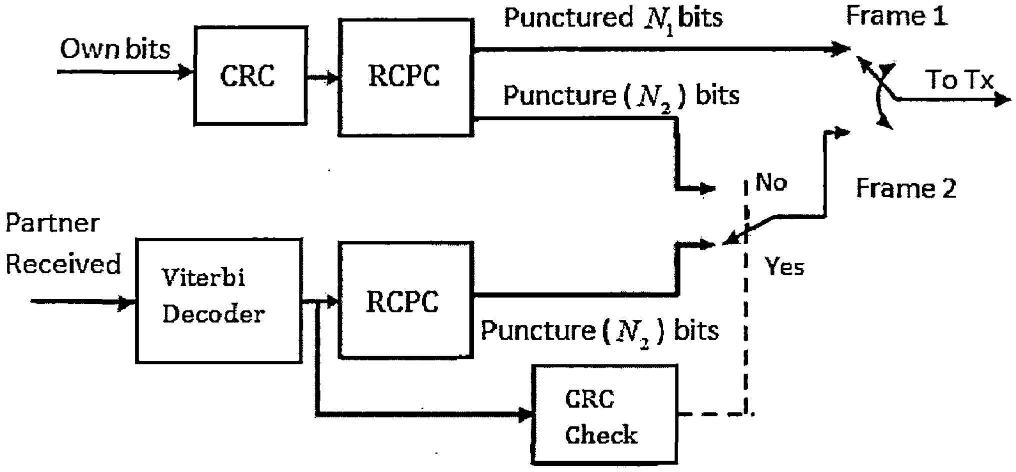

Figure 3.2 A user's implementation of Coded Cooperation with RCPC codes [8]

The Coded Cooperation framework and an implementation for a TDMA system is shown in Figure 3.3.

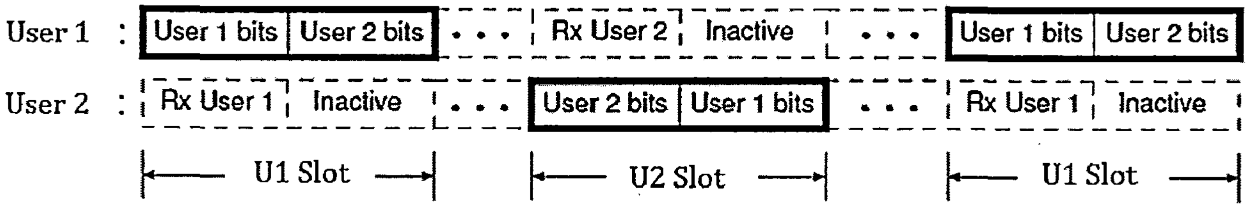

Figure 3.3 Coded Cooperation implementation for a system using TDMA [8]

The users act independently in the second frame, with no knowledge of whether their own first frame was correctly decoded or not. As a result, there are four possible cooperative cases for the transmission of the second frame as illustrated in Figure 3.4.

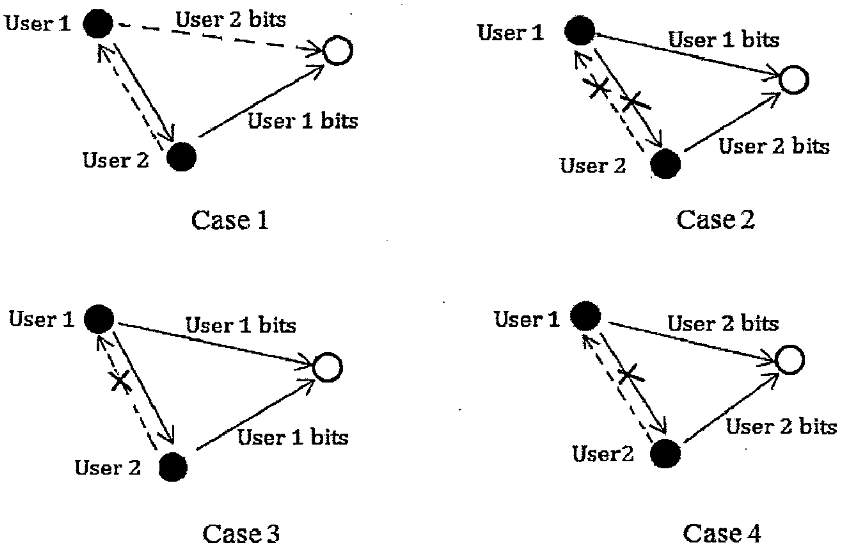

Figure 3.4 Four cooperative cases for second frame transmission based on the first frame decoding results [8]

In Case 1, both users successfully decode each other, so that each can transmit its partner's second frame, resulting in the fully cooperative scenario. In Case 2, neither user successfully decodes its partner's first frame, and the system reverts to the non-cooperative case for that pair of source blocks. In Case 3, User 2 successfully decodes User 1, but User 1 does not successfully decode User 2. Consequently, neither user transmits the second set of code bits for User 2 in the second frame, instead both transmit the second set for User 1. These two independent copies of User 1's bits are optimally combined at the destination prior to decoding. Case 4 is identical to Case 3 with the roles of User 1 and User 2 reversed. Clearly the destination must know which of these four cases has occurred in order to correctly decode the received bits. This model considers [20]:

1) Two users, both are transmitting to a single destination
2) The channels between users (inter-user channels) and from each user to the destination (uplink channels) are mutually independent and subjected to Rayleigh fading.

The users transmit on orthogonal channels (e.g., TDMA, CDMA, or FDMA), which allows the destination, and other users in the cooperative case, to separately detect each user. In this model the receivers maintain channel state information and coherent detection is employed, so the magnitudes of the fading coefficients are considered for analysis. To simplify the model BPSK modulation is used [17]. The baseband-equivalent discrete-time signal transmitted by User $i \in \{1,2\}$ and received by User $j \in \{0,1,2\}$ ($j \neq i$, and $j=0$ denotes the destination) is given by

$$r_{i,j}(n) = \alpha_{i,j}(n)\sqrt{E_{b,i}}.b_i(n) + z_j(n) \tag{3.1}$$

where $E_{b,i}$ is the transmitted energy per bit for User i, $b_i(n) \in \{-1,+1\}$ is the BPSK modulated code bit at time n, $\alpha_{i,j}(n)$ is the fading coefficient magnitude between Users i and j, and $z_j(n)$ accounts for noise and other additive interference at the receiver. $\alpha_{i,j}(n)$ is modelled as independent samples of a Rayleigh-distributed random variable characterized by mean-square value

$$\Omega_{i,j} = E_{\alpha_{i,j}}\left[\alpha_{i,j}^2(n)\right] \tag{3.2}$$

where $E_x[.]$ denotes the expectation operator with respect to random variable x.

The value of $\Omega_{i,j}$ accounts for large-scale path loss and shadowing effects. For slow fading, the fading coefficients remain constant ($\alpha_{i,j}(n) = \alpha_{i,j}$) over the transmission of each source block, while for fast fading, they are i.i.d. for each transmitted symbol. The noise term $z_j(n)$ is modelled as independent, zero-mean additive white Gaussian noise with variance N_j i.e., samples of a band pass white noise process with two-sided power spectral density $N_j/2$. The instantaneous received SNR for the channel between users i and j as

$$\gamma_{i,j} = \frac{\alpha_{i,j}^2(n)E_{b,i}}{N_j} \tag{3.3}$$

For $\alpha_{i,j}(n)$ Rayleigh distributed, $\gamma_{i,j}(n)$ has an exponential distribution with mean

$$\Gamma_{i,j} = E_{\alpha_{i,j}}[\gamma_{i,j}(n)] = E_{\alpha_{i,j}}\left[\frac{\alpha_{i,j}^2(n)E_{b,i}}{N_j}\right] = \Omega_{i,j}\frac{E_{b,i}}{N_j} \tag{3.4}$$

3.2.2. Performance analysis under slow fading

For slow fading, the fading coefficients for each uplink channel are constant over the code word, e.g., $\alpha_{i,0}(n)=\alpha_{i,0}$ and $\gamma_{i,0}(n)=\gamma_{i,0}$ constant for $n=1,.....N$ for User i's uplink channel. When both users successfully decode each other's first frame, each user's coded bits are divided between the two user channels.

For Case 1 in Figure 3.4, when both users successfully decode each other's first frame, each user's coded bits are divided between the two user channels [8,21]. Considering User 1's code word, Equation (2.23) will becomes as

$$P(d\,|\,\gamma_{1,0},\gamma_{2,0})=Q\left(\sqrt{2d_1\gamma_{1,0}+2d_2\gamma_{2,0}}\right) \tag{3.5}$$

where d_1 and d_2 are the portions of the error event bits transmitted through User 1's and User 2's channel respectively, such that $d_1+d_2=d$. Note that d_1 and d_2 are independent of $\gamma_{1,0}$ and $\gamma_{2,0}$. Now averaging Equation (3.5) over the fading distributions, unconditional PEP is obtained as shown below,

$$P(d)=\int_0^\infty\int_0^\infty P\left(d\,|\,\gamma_{1,0},\gamma_{2,0}\right)p(\gamma_{1,0})p(\gamma_{2,0})d_{\gamma_{1,0}}d_{\gamma_{2,0}} \tag{3.6}$$

where $p(x)$ is the probability density function of random variable x. Alternative representation for Equations (3.5) and (3.6) using Gaussian Q-function is as follows [17]:

$$Q(x)=\frac{1}{\pi}\int_0^{\pi/2}\exp\left(-\frac{x^2}{2\sin^2\theta}\right),\ x\geq 0 \tag{3.7}$$

Using (3.7) in (3.5) and (3.6) gives

$$P(d)=\frac{1}{\pi}\int_0^{\pi/2}\left[\int_0^\infty\exp\left(-\frac{d_1\gamma_{1,0}}{\sin^2\theta}\right)p(\gamma_{1,0})d_{\gamma_{1,0}}\right]\times\left[\int_0^\infty\exp\left(-\frac{d_2\gamma_{2,0}}{\sin^2\theta}\right)\right]d\theta \tag{3.8}$$

The two inner integrals in Equation (3.8) have the form of moment-generating functions for the two densities $p(\gamma_{1,0})$ and $p(\gamma_{2,0})$ as

$$M_x(s)=\int_0^\infty e^{sx}p(x)dx \tag{3.9}$$

where $M_x(s)$ the moment-generating function of random variable x. Thus Equation (3.8) becomes

$$P(d) = \frac{1}{\pi}\int_0^{\pi/2} M_{\gamma_{1,0}}\left(-\frac{d_1}{\sin^2\theta}\right) M_{\gamma_{2,0}}\left(-\frac{d_2}{\sin^2\theta}\right) d\theta \tag{3.10}$$

Moment-generating function is also equivalent to the Laplace transform with a change of sign in the exponent [18]. So it is possible to employ all well-known techniques for moment-generating functions and Laplace transforms to solve integrals of this form. In case of Rayleigh fading, the moment-generating function for the instantaneous SNR γ is given by

$$M_\gamma(-s) = \frac{1}{1+s\Gamma},\ s>0 \tag{3.11}$$

where Γ is average SNR per symbol. Using (3.12) in (3.11) we get

$$P(d) = \frac{1}{\pi}\int_0^{\pi/2} \left(1+\frac{d_1\Gamma_{2,0}}{\sin^2\theta}\right)^{-1} \left(1+\frac{d_2\Gamma_{2,0}}{\sin^2\theta}\right)^{-1} d\theta \tag{3.12}$$

Equation (3.12) is an exact expression for unconditional PEP. $\Gamma_{i,j}$ is the average uplink SNR between User i and User j, here j=0 indicates a base station. This is evaluated using numerical integration techniques, by maximizing the integrand taking $\sin^2\theta = 1$,

$$P(d) \le \frac{1}{2}\left(\frac{1}{1+d_1\Gamma_{1,0}}\right)\left(\frac{1}{1+d_2\Gamma_{2,0}}\right) \tag{3.13}$$

For large SNR, the PEP is inversely proportional to the product of the average SNR of the uplink channels. Thus, if d_1 and d_2 are both non-zero, full diversity order of two is achieved when both partners successfully receive each other and cooperate. This is a significant improvement over no cooperation, which is fundamentally limited to diversity order one as shown below.

For non-cooperative transmission in slow fading, all the code bits for a user are transmitted through the same channel (e.g., $d_1 = d$ and $d_2 = 0$) also $\Gamma_{1,0} = \Gamma_{2,0} = \Gamma$. Thus for slow fading the conditional and unconditional PEP becomes [17]

$$P(d \mid \gamma) = Q\left(\sqrt{2d\gamma}\right)$$

$$\begin{aligned} P(d) &= \frac{1}{\pi}\int_{0}^{\pi/2}\left(1+\frac{d\Gamma}{\sin^2\theta}\right)^{-1} d\theta \\ &\le \frac{1}{2}\left(\frac{1}{1+d\Gamma}\right) \end{aligned} \tag{3.14}$$

For Case 3, where User 1 does not successfully decode User 2, but User 2 successfully decodes User 1, both users send the same additional parity bits for User 1 in the second frame. These bits are optimally combined at the destination, so that the conditional PEP Equation (3.5) for User 1 becomes

$$\begin{aligned} P(d \mid \gamma_{1,0}, \gamma_{2,0}) &= Q\left(\sqrt{2d_1\gamma_{1,0} + 2d_2\left(\gamma_{1,0}+\gamma_{2,0}\right)}\right) \\ &= Q\left(\sqrt{2d\gamma_{1,0} + 2d_2\gamma_{2,0}}\right) \end{aligned} \tag{3.15}$$

and the unconditional PEP becomes

$$\begin{aligned} P(d) &= \frac{1}{\pi}\int_{0}^{\pi/2}\left(1+\frac{d\Gamma_{1,0}}{\sin^2\theta}\right)^{-1}\left(1+\frac{d_2\Gamma_{2,0}}{\sin^2\theta}\right)^{-1} d\theta \\ &\le \frac{1}{2}\left(\frac{1}{1+d\Gamma_{1,0}}\right)\left(\frac{1}{1+d_2\Gamma_{2,0}}\right) \end{aligned} \tag{3.16}$$

So from Equation (3.16) we can say User 1 achieves full diversity order two for Case 3. From [8] it is observed that Coded Cooperation with a perfect inter-user channel performs virtually identically to a comparable two-antenna transmit diversity system. As the interuser channel worsens the amount of improvement decreases i.e., the BER Probability increases.

3.2.3. Performance analysis under fast fading

For fast fading, the fading coefficients are no longer constant over the code word, but are i.i.d. across the coded bits. Thus, for Case 1, generalizing Equation (3.5) as

$$P(d \mid \gamma_{1,0}, \gamma_{2,0}) = Q\left(\sqrt{2\sum_{n\in\eta_1}\gamma_{1,0}(n) + 2\sum_{n\in\eta_2}\gamma_{2,0}(n)}\right) \tag{3.17}$$

where the set η_i is the portion of the d error event bits transmitted through User i's channel. The cardinalities of η_1 and η_2 are d_1 and d_2 respectively, where again $d_1+d_2=d$, d_1 and d_2 are independent of $\gamma_{1,0}(n)$ and $\gamma_{2,0}(n)$ for all n [20].

Averaging over the fading to obtain the unconditional PEP involving a d-fold integration with Q-function of Equation (3.7) gives

$$P(d)=\frac{1}{\pi}\int_0^{\pi/2}\prod_{n\in\eta_1}\left[\int_0^{\infty}\exp\left(-\frac{\gamma_{1,0}(n)}{\sin^2\theta}\right)p(\gamma_{1,0}(n))d\gamma_{1,0}(n)\right]\times\prod_{n\in\eta_2}\left[\int_0^{\infty}\exp\left(-\frac{\gamma_{2,0}(n)}{\sin^2\theta}\right)p(\gamma_{2,0}(n))d\gamma_{2,0}(n)\right]d\theta \tag{3.18}$$

Each inner integral in Equation (3.18) has the same form as in Equation (3.8), so for Rayleigh fading we obtain

$$P(d)=\frac{1}{\pi}\int_0^{\pi/2}\left[\prod_{n\in\eta_1}\left(1+\frac{\Gamma_{1,0}}{\sin^2\theta}\right)^{-1}\right]\left[\prod_{n\in\eta_2}\left(1+\frac{\Gamma_{2,0}}{\sin^2\theta}\right)^{-1}\right]d\theta \tag{3.19}$$

Applying the assumption that $\Gamma_{1,0}$ and $\Gamma_{2,0}$ are constant over n results in

$$\begin{aligned}P(d)&=\frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{\Gamma_{1,0}}{\sin^2\theta}\right)^{-d_1}\left(1+\frac{\Gamma_{2,0}}{\sin^2\theta}\right)^{-d_2}d\theta\\&\le\frac{1}{2}\left(\frac{1}{1+\Gamma_{1,0}}\right)^{d_1}\left(\frac{1}{1+\Gamma_{2,0}}\right)^{d_2}\end{aligned} \tag{3.20}$$

Equation (3.20) shows that the diversity order for fast fading is equal to the total Hamming weight $d=d_1+d_2$. For statistically dissimilar uplink channels ($\Gamma_{1,0}\neq\Gamma_{2,0}$), Equation (3.20) indicates definite improvement for the user with the lower uplink average SNR [17].

For fast fading, the unconditional PEP with $\Gamma_{1,0}=\Gamma_{2,0}=\Gamma$ is given by

$$\begin{aligned}P(d)&=\frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{\Gamma}{\sin^2\theta}\right)^{-d}d\theta\\&\le\frac{1}{2}\left(\frac{1}{1+\Gamma}\right)^{d}.\end{aligned} \tag{3.21}$$

From Equation (3.21) it is found that Coded Cooperation does not provide additional diversity in fast fading when the average uplink SNR are equal. For Case 3, the conditional PEP (3.17) for User 1 becomes

$$P(d+\gamma_{1,0},\gamma_{2,0})=Q\left(\sqrt{2\sum_{n\in\eta_1}\gamma_{1,0}(n)+2\sum_{n\in\eta_2}\gamma_{1,0}(n)+2\sum_{n\in\eta_2}\gamma_{2,0}(n)}\right)$$

$$=Q\left(\sqrt{2\sum_{n\in\eta}\gamma_{1,0}(n)+2\sum_{n\in\eta_2}\gamma_{2,0}(n)}\right) \tag{3.22}$$

and unconditional PEP becomes

$$P(d)=\frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{\Gamma_{1,0}}{\sin^2\theta}\right)^{-d}\left(1+\frac{\Gamma_{2,0}}{\sin^2\theta}\right)^{-d_2}d\theta$$

$$\leq\frac{1}{2}\left(\frac{1}{1+\Gamma_{1,0}}\right)^{d}\left(\frac{1}{1+\Gamma_{2,0}}\right)^{d_2}. \tag{3.23}$$

This shows that User 1 does achieve improved diversity of order $d+d_2$ compared with no cooperation of order d for Case 3.

3.2.4. Bit and Block Error Rate Analysis

To determine the end-to-end bit and block error probabilities for Coded Cooperation, PEPs are used. The first step is to calculate the probabilities of the cooperative cases. The cooperative case probabilities are determined by the BLER of the first frame transmission [8]. The BLER for a terminated convolutional code is bounded by

$$P_{block}(\gamma)=1-(1-P_E(\gamma))^B\leq B.P_E(\gamma) \tag{3.24}$$

where B is the number of trellis branches in the code word, and $P_E(\gamma)$ is the error event probability conditioned on, the vector state of the channel. P_E is bounded as

$$P_E(\gamma)\leq\sum_{d=d_f}^{\infty}a(d)P(d\mid\gamma) \tag{3.25}$$

where d_f is the code free distance $a(d)$ is the number of error events of Hamming weight d.

Parameterizing the four cases by $\Theta \in \{1,2,3,4\}$ and the conditional probability for Case 1 ($\Theta = 1$) as follows:

$$\begin{aligned} P(\Theta=1 \mid \boldsymbol{\gamma}_{1,2}, \boldsymbol{\gamma}_{2,1}) &= (1-P_{block}(\boldsymbol{\gamma}_{1,2}))(1-P_{block,2}(\boldsymbol{\gamma}_{2,1})) \\ &\geq (1-P_{E,1}(\boldsymbol{\gamma}_{1,2}))^{B}(1-P_{E,2}(\boldsymbol{\gamma}_{2,1}))^{B} \\ &\geq (1-BP_{E,1}(\boldsymbol{\gamma}_{1,2}))(1-BP_{E,1}(\boldsymbol{\gamma}_{2,1})) \end{aligned} \tag{3.26}$$

The unconditional probability of Case $\Theta, P(\Theta)$ is as follows

$$P(\Theta) = \int_{\gamma_{1,2}} \int_{\gamma_{1,2}} P(\Theta \mid \boldsymbol{\gamma}_{1,2}, \boldsymbol{\gamma}_{2,1}) p(\boldsymbol{\gamma}_{2,1}) p(\boldsymbol{\gamma}_{2,1}) d\boldsymbol{\gamma}_{2,1} d\boldsymbol{\gamma}_{2,1} \tag{3.27}$$

For slow fading, vectors $\boldsymbol{\gamma}_{1,2}$ and $\boldsymbol{\gamma}_{2,1}$ reduce to scalars $\gamma_{1,2}$ and $\gamma_{2,1}$. In addition, for reciprocal inter-user channels, $\gamma_{1,2} = \gamma_{2,1}$, and $P(\Theta \mid \gamma_{1,2})$ is conditioned on a single is conditioned on a single variable, reducing $P(\Theta)$ to a single integral

$$P(\Theta) = \int_{0}^{\infty} P(\Theta \mid \gamma_{1,2}) p(\gamma_{1,2}) d\gamma_{1,2} \tag{3.28}$$

3.3. Multi-user RCPC Coded Cooperation

The performance analysis of a two-user Coded Cooperation in Section 3.2 is based on the assumption that errors occurring in a codeword are equally distributed among the subframes sent by the cooperating users. This assumption is not necessarily true. Furthermore, this approach becomes inaccurate and complicated when the number of cooperating users exceeds two. In this section we study analytical framework for deriving and evaluating the error performance of Coded Cooperation with multiple cooperating users. Also the end-to-end probability of error averaged over different cooperation scenarios is derived. The bit error probability for specific cooperation scenarios and PEP for uncorrelated uplink channels are shown [22].

3.3.1. System Model

The Coded Cooperation scenario with multiple users is illustrated in Figure 3.5. Coded cooperation starts by forming clusters of users, where users in a cluster cooperate to transmit their information to a common BS. The users within a cluster are called partners. Let J be the number of cooperating users in a cluster. For each user, a frame is formed by encoding K bits into $L = K / R$ bits, where R is the code rate.

Partners cooperate by dividing their L bit frames into J subframes containing $L_1, L_2, ... L_J$ bits, where $L = L_1 + L_2 + ... + L_J$. In the first $N_1 T$ seconds of each frame, each user transmits his first subframe composed of $N_1 = K / R_1$ coded bits. Here R_1 is the code rate of the codeword in the first subframe, obtained by puncturing N-bit codeword. Upon the end of first subframe, each user decodes the rate-R_1 codewords of his partners. The partitioning of the coded bits in the J subframes may be achieved using RCPC codes. In the remaining $J-1$ subframes, each user in the cluster transmits one subframe for each of his $J-1$ partners. Each of these subframes contains parity bits of one of his partners which were not sent yet to the BS [22].

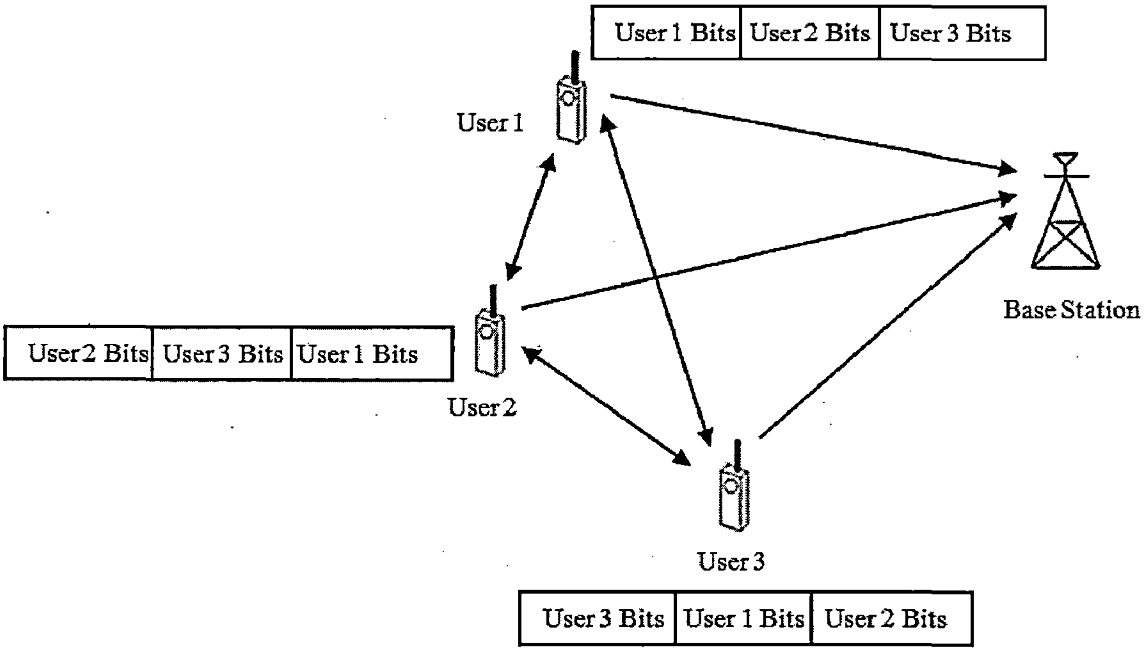

Figure 3.5: Schematic diagram of a 3-user cluster employing Coded Cooperation

Figure 3.5 shows the contents of the J subframes of each user in a 3-user cluster, i.e., $J = 3$. If a user was not able to decode the first subframe of his partner, whom he should send his parity in a given subframe, then he sends his next parity subframe, i.e., the parity subframe that was not yet sent by any of his partners. Thus each user transmits a total of N bits per source block over the J subframes. The cooperation level is defined as the percentage of the total bits per each source block that each user transmits for his partners, i.e. $(N - N_1)/N$.

After the information block is encoded, the coded bits are modulated using BPSK. The matched filter output at User k due to User l in the time interval 't' in the first subframe is modelled by

$$y_{l,k}(t) = \sqrt{E_i}\, a_{l,k} s_l(t) + z_k(t), \qquad (3.29)$$

where $s_l(t)$ is the signal transmitted from User l in time instance t in the first subframe and $z_k(t)$ is an AWGN sample at User k with a Normal distribution given by $\mathcal{N}\left(0, \frac{N_0}{2}\right)$. Here, E_i is the average received energy through the interuser channel and the average interuser SNR is $\gamma_i = E_i / N_0$. The coefficient $a_{l,k}$ is the gain of the interuser channel between User l and User k.

The interuser channels are assumed to be independent and identically distributed (i.i.d) with a Rayleigh distribution. When $k = 0$, the signal model in (3.29) represents the uplink channel from User l to the BS, where the received average energy is denoted by E_s and the average uplink SNR is $\gamma_s = E_s / N_0$. The uplink channels from different users are assumed to be i.i.d with a Rayleigh distribution. Moreover, the interuser channels and the uplink channels are assumed to be mutually independent and slow enough such that the fading process stays fixed within a subframe. This is a reasonable assumption for slowly moving mobile units that are separated enough in the space [22]. In addition, the interuser channels are assumed as reciprocal [13]. At the receivers of users and the BS, coherent detection is employed using perfect channel side information.

3.3.2. Performance Analysis

In this section we present the end-to-end bit error probability for users in a Coded Cooperation network. The subscripts *c*, *u* and *b* are used to denote conditional, unconditional and bit error probabilities, respectively. In a cluster, each user acts independently from his partners, not knowing whether his partners have decoded successfully his first subframe. Hence, there are different scenarios for the transmission in the subsequent $J-1$ subframes for each user in the cluster. The end-to-end error probability is obtained by averaging the error probability (of a specific cooperation scenario) over the different cooperation scenarios.

In a cluster of size J, there are J^2 possible cooperation scenarios. The end-to-end error probability of a user is obtained by averaging the probability of error over two random variables. The first random variable U indicates the number of partners who were able to decode the first subframe of the user. The second variable V indicates the number of partners whose first subframes were decoded successfully by the user. In order to simplify analysis, it is assumed that the effect of duplicate reception of subframes, from the user and one of his partners is negligible, i.e., subframes are transmitted once through the cluster [22].

The end-to-end bit error probability averaged over all cooperation scenarios is given by

$$P_b = \sum_{v=0}^{J-1} \sum_{u=0}^{J-1} \binom{J-1}{v} \binom{J-1}{u} p_{v,u} P_b(v,u), \tag{3.30}$$

where $P_b(v,u)$ is the conditional bit error probability of a user given that u partners decoded his first subframe successfully, and he decoded v of his partners, and $p_{v,u}$ is the probability of such event and given by

$$p_{v,u} = E_{h_i}\left\{[1-P_B(h_i)]^{v+u} P_B(h_i)^{2J-2-v-u}\right\}, \tag{3.31}$$

where h_i is the gain of the interuser channel and $P_B(h_i)$ is the packet error probability of the first subframe, which is upper bounded as

$$P_B(h_i) \leq 1-[1-P_E(h_i)]^B, \tag{3.32}$$

where B is the number of trellis branches in the rate-R_1 codeword of the first subframe.

In general, for a rate-$1/N$ convolutional code (or obtained by puncturing a rate-$1/N$ code), B is equal to the source block length K. In (3.32), $P_E(h_i)$ is the error event probability that is evaluated using the limiting-before-averaging approach as,

$$P_B(h_i) \le \min\left\{1, \sum_{d=d_{\min}}^{N_1} a_d P_c(d \mid h_i)\right\}, \tag{3.33}$$

where a_d is the number of error events with a Hamming distance d from the all-zero codeword and $P_c(d \mid h_i) = Q\left(\sqrt{2d \mid h_i \mid^2}\right)$ is the conditional Pairwise error probability of a weight-d codeword over the interuser channel with a channel gain of h_i. Here $P_c(d \mid h_i)$ is the probability of decoding a received sequence as a weight-d codeword in a rate-R_1 code given that the all-zero codeword was transmitted. For a fixed interuser channel quality, the probability of no cooperation increases as the cluster size increases, which causes the performance of large-size clusters to be worse than that of small size clusters. As the uplink quality improves for a fixed interuser quality, small-size clusters are expected to outperform large-size clusters. This is because small size clusters has a smaller probability of no cooperation which has a clear effect on the performance especially at high uplink SNR [22].

The bit error probability corresponding to a specific cooperation scenario is shown as below. Given $U = u$ and $V = v$ for a user in a cluster, the bit error probability of the corresponding convolutional code is upper bounded [22] as

$$P_b(v,u) \le \sum_{d=d_{\min}}^{N(v,u)} c_d P_u(v,u;d), \tag{3.33}$$

where $d_{\min}$ is the minimum distance of the code and c_d is the number of information bit errors corresponding to codewords with output weight d. In (3.33), $P_u(v,u;d)$ is the unconditional pairwise error probability for a weight-d codeword given that u partners decoded correctly the first subframe of this user and he decoded the first subframe of v of his partners. Furthermore, $N(v,u)$ is the codeword length corresponding to $V = v$ and $U = u$.

Conditioning on $U = u$ and $V = v$ has two consequences on the error performance of a user. First, the received codeword at the BS has a rate R_ξ, where $\xi = \max(J - v, u+1)$ .This is due to the negligible effect of duplicate transmission of subframes because of the dominant performance of the no and full cooperation scenarios as discussed above. In this case, $\{c_d\}$ used in (3.33) are for the rate-R_ξ code. Second, given that $U = u$, each codeword is transmitted over $u + 1$ subframes, whose lengths are $\{N_j\}|_{j=1}^{u+1}$ bits. Recall that each subframe is transmitted over an independent fading channel via one of the partners in a cluster.

The pairwise error probability $P_u(v,u;d)$ is a function of the distribution of the d error bits over the $u + 1$ subframes transmitted by the u+1 partners. Since the coded bits of each subframes may not be consecutive bits due to the puncturing used, this distribution is quantified assuming uniform distribution of the coded bits over the subframes [22].

Denoting the weight of j^{th} subframe in the codeword by w_j such that $\sum_{j=1}^{u+1} w_j = d$, then the pairwise error probability averaged over the weight patterns $W = \{w_j\}_{j=1}^{u+1}$ is given by

$$P_u(v,u;d) = \sum_{w_1, w_2, \ldots, w_{u+1}} \frac{\binom{N_1}{w_1}\binom{N_2}{w_2}\cdots\binom{N_{u+1}}{w_{u+1}}}{\binom{N}{d}} P_u(v,u;d \mid w) \tag{3.34}$$

The pairwise error probability $P_u(v,u;d \mid w)$ is found by averaging $P_c(v,u;d \mid w)$ over the fading gains. The conditional pairwise error probability for BPSK with coherent detection is given by

$$P_c(v,u;d \mid w) = Q\left(\sqrt{2\gamma_s \sum_{j=1}^{u+1} w_j a_j^2}\right) \tag{3.35}$$

where $a_j = | h_j |$ An exact expression of the pairwise error probability can be found by using the integral expression of the Q-function, $Q(x) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} e^{(-x^2/2\sin^2\theta)} d\theta$ as

$$P_u(v,u;d\,|\,w)=\frac{1}{\pi}E_{\mathbf{a}}\left[\int_0^{\frac{\pi}{2}}\exp\left(-\beta_\theta\sum_{j=1}^{u+1}w_j a_j^2\right)d\theta\right]$$

$$=\frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{j=1}^{u+1}\frac{1}{1+w_j\beta_\theta}d\theta \qquad (3.36)$$

where $\mathbf{a}=\left\{a_j\right\}_{j=1}^{u+1}$, $\beta_\theta=\gamma_s/\sin^2\theta$ and the product results from the independence of the fading processes affecting different subframes. Due to the summation in (3.34), the union bound in (3.33) becomes complicated when d is large. So an approximation to the bit error probability can be obtained by truncating (3.33) to a distance $d_{\max}$.

Chapter 4

CODED COOPERATION USING RCPT CODES

Coded Cooperation achieves diversity by each user transmitting his own as well as his partner's data. Rate compatible punctured turbo (RCPT) codes can be used when rate compatibility, low bit error rates and more powerful codes are required. Some important applications of RCPT Codes are given below [23,24]:

1) Speech or image compression requires some bits to have a higher level of protection than others. By using different encoders/decoders for different groups of bits would increase the complexity of the communication system. The rate-compatible codes offer different levels of protection to different blocks of bits using the same encoder and decoder blocks.
2) In image transmission JPEG image is partitioned into two groups, i.e., DC components and AC components according to their respective sensitivity to channel noise. The highly sensitive DC components are better protected with a lower coding rate, while the less sensitive AC components use a higher coding rate.
3) 3G Mobile radio systems like UMTS, CDMA2000 and EDGE etc. provides packet oriented data services with data rates in the order of Mbit/s. To achieve these, RCPT codes are used.

As Coded Cooperation involves two code components, Turbo codes are a natural fit. We investigated Turbo Coded Cooperation and proposed RCPT Coded Cooperation. Turbo Coded Cooperation performs slightly better than RCPT Coded Cooperation. Our proposed method has the following benefits over Turbo Coded Cooperation:

1) Hardware complexity of mobile devices is low as they perform conventional Viterbi decoding instead of Turbo decoding.
2) Decoding delays are low at mobiles.
3) BCJR algorithm has thrice the computational complexity of a Viterbi decoder. Hence using the latter at the mobiles reduces the computational complexity drastically.

In this chapter Coded Cooperation using Turbo Codes is examined to get better BER performance than RCPC Coded Cooperation. Turbo decoder is implemented using BCJR algorithm. In Section 4.1 RCPT codes are explained in brief. Bit and block error rate analysis of Turbo codes is presented in Section 4.2. System models for two user and multi- user RCPT Coded Cooperation are presented in sub sequent sections.

4.1. Rate Compatible Punctured Turbo Codes

In a wireless network, control signals such as channel state, power control, and scheduling information are often more important than the payload data, and should be protected more carefully. This can be achieved via unequal error protection (UEP). Turbo codes provide UEP in the similar way as RCPC codes. For the bits which need higher protection, the interleaver size could be increased. Increasing the interleaver size decreases the BER. But the hardware implementation is cumbersome. Another option is to vary the number of coded bits associated with each information bit by using puncturing. Even though the performance of punctured turbo code is worse than without puncturing turbo code, puncturing improves bandwidth efficiency [25].

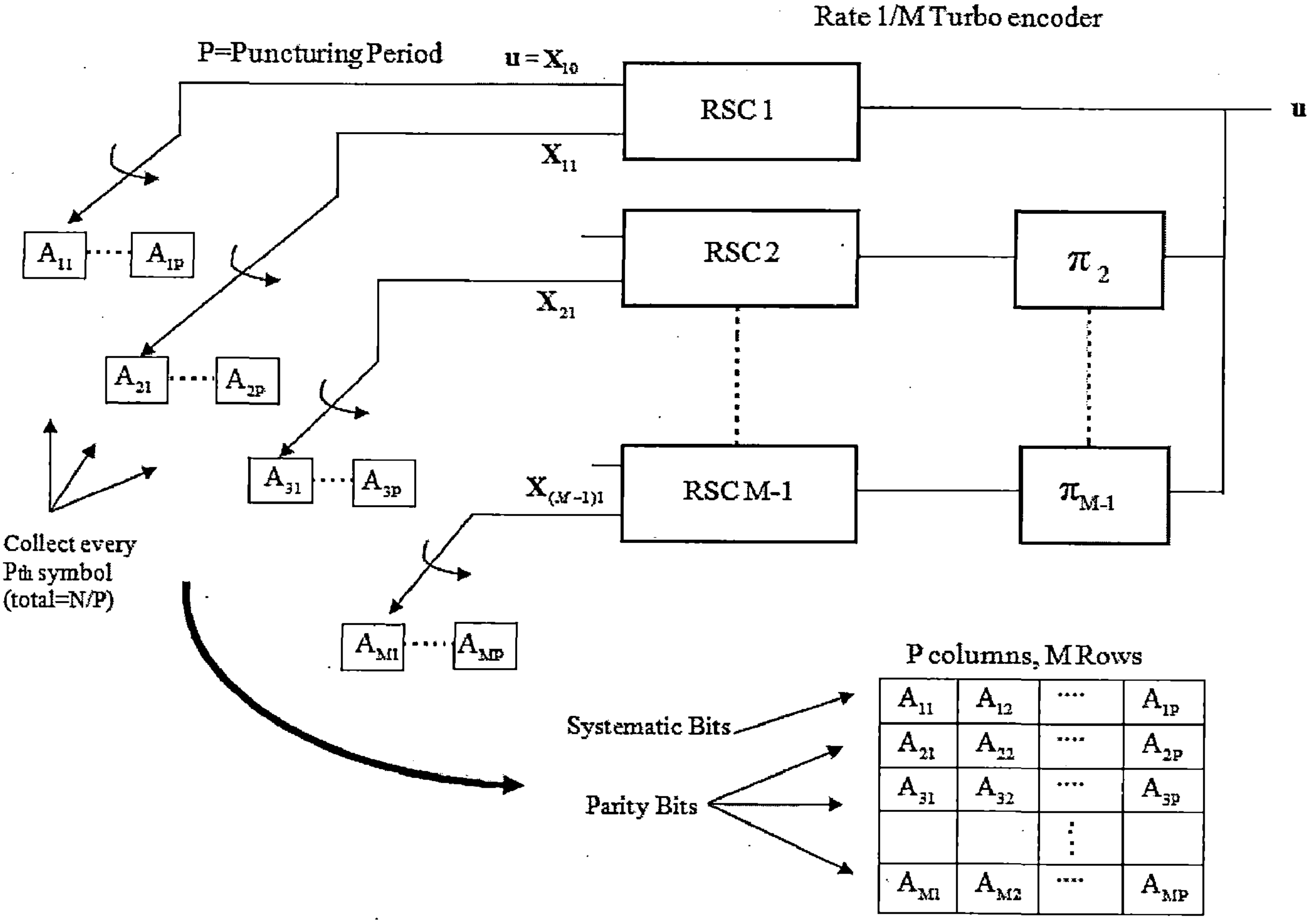

Figure 4.1 Block diagram of RCPT Encoder [25]

To construct RCPT Codes the binary data source is encoded into blocks in accordance with a low redundancy (N, K) block error detection code. This encoded data source is input to the RCPT encoder which performs the following operations [25]:

1) Turbo encoding on the data sequence and
2) Partitioning the resulting code symbols for each systematic/parity stream into subblocks of size N / P, where P is called puncturing period.

In Figure 4.1, RCPT encoder is formed from rate $1/M$ turbo encoder, consisting of $M-1$, rate $1/2$ constituent RSC encoders. The composite encoder can be formed by using a fewer number of lower rate RSC encoders. Moreover, the constituent RSC code rates need not be equal. In Figure 4.1, the systematic bits of all except the first encoder are discarded and the resulting single systematic plus $(M-1)$ parity streams are each represented as a collection of P subblocks. For example the subblock A_{11} contains a fraction $1/P$ of the systematic bits. Since the turbo code is of rate $1/M$, there are MP total subblocks produced for potential transmission. All such subblocks are collected and stored in $M \times P$ matrix form, where each row corresponds to a different systematic/parity stream, and each column refers to a different decimated subsequence of that data stream.

The RCPT puncturing rule amounts to sending collections of one or more subblocks of the turbo encoded data, such that at least P subblocks are sent in the initial transmission and no subblock is sent twice. The code construction allows for a family of codes of rates

$$R_l = \frac{P}{P+l}, \qquad l = 0,1,,...(M-1)P$$

For each value of l, we define a binary $M \times P$ puncturing matrix ***a(l)***. If $a_{ij}(l) = 1$, then the j^{th} subblock of the i^{th} systematic/parity stream belongs to the subcode of rate R_l. Therefore, based on the above restrictions, based on the above restrictions, ***a(0)*** must contain P ones, ***a(l+1)*** must have ones in the same positions as in ***a(l)*** plus an additional one, and, finally, ***a((M - 1)P)*** is a matrix of all ones [25].

4.2. Bit and Block Error Rate Analysis for Turbo Codes

Given an *(n, k)* systematic block code *C*, its weight enumeration function (WEF) is given by

$$B^C(H) = \sum_{i=0}^{n} B_i H^i \tag{4.1}$$

where B_i is the integer number of codewords with Hamming weight (number of ones) i and H is a dummy variable. The WEF of a code can be used to compute the exact expression of probability of undetected errors and an upper bound on word error probability. The input-redundancy weight enumerating function (IRWEF) of the code is given by

$$A^C(W,Z) = \sum_{w,j} A_{w,j} W^w Z^j \tag{4.2}$$

where $A_{w,j}$ denotes the (integer) number of codewords generated by an input information word of Hamming weight w whose parity check bits have Hamming weight j, so that the overall Hamming weight is $(w+j)$ [26].

The IRWEF makes explicit the separate contributions of the information and of the parity check bits to the total Hamming weight of the codewords in each term of the WEF. It thus provides additional information on the Hamming weight profile of the code. The IRWEF characterizes the whole encoder, as it depends on both input information words and codewords, whereas the WEF only depends upon the code. As a consequence, the WEF is related to the word error probability of the code, whereas the IRWEF provides information on the bit error probability. Based on the definitions, the following relationship holds true:

$$B^C(H) = A^C(W = H, Z = H)$$

with

$$A^C(H,H) = \sum_{w,j} A_{w,j} H^{w+j} = \sum_{k} B_k H^k \tag{4.3}$$

where $B_k = \sum_{w+j=k} A_{w,j}$

For turbo codes with uniform interleaver, the WEF of the overall concatenated code is given based on the WEF of the constituent codes. Consider a turbo code with C_1 and C_2 as the constituent systematic recursive convolutional codes and an interleaver of size K. The conditional WEF of a block code $A_w^C(Z)$ gives all possible code words generated by the set of input sequences with weight w (Z is a dummy variable). Let $A_w^{C_1}(Z)$ and $A_w^{C_2}(Z)$ be the conditional WEFs of C_1 and C_2 respectively. Then for the probabilistic uniform interleaver, the conditional WEF of the turbo code given by,

$$A_w^C(Z,Y) = \frac{A_w^{C_1}(Z) \times A_w^{C_2}(Z)}{\binom{K}{w}} \tag{4.4}$$

Keeping the WEF of C_1 and C_2 separate with two dummy variables Z and Y makes it possible to deal with the four different scenarios in the cooperation schemes. The BER and BLER of the turbo code are obtained using below union bound arguments

$$P_b(\gamma) \le \sum_{z=0}^{K} \sum_{y=0}^{K} \sum_{w=1}^{K} \frac{w}{K} a_{w,z,y} P(d \mid \gamma) \tag{4.5}$$

$$P_{block}(\gamma) \le \sum_{z=0}^{K} \sum_{y=0}^{K} \sum_{w=1}^{K} \frac{w}{K} a_{w,z,y} P(d \mid \gamma), \tag{4.6}$$

where $a_{w,z,y}$ denotes the multiplicity of code words corresponding to input weight w and parity weights z and y, obtained from the corresponding code WEF. The expressions above assume $R_1 = R_2 = 1/2$. Note that d_1 is equal to the summation of the exponents of W and Z, and d_2 is equal to the exponent of Y [21].

The overall end-to-end unconditional BER is equal to the average of the unconditional BER over the four possible transmission cases discussed in Section 3.2.1.

$$P_b = \sum_{i=1}^{4} P_b(Case\ i) P(Case\ i) \tag{4.7}$$

where $P_b(Case\ i)$ denotes the BER corresponding to Case *i*, and $P(Case\ i)$ is the probability of occurrence of Case *i*. The end-to-end BLER has an identical expression. Bounds on the probabilities $P(Case\ i)$ for each of the four cases are obtained from the BLER corresponding to the code used for the first frame transmissions. Based on (4.7), the overall end-to-end diversity achieved via cooperation is similar to a weighted average of the diversity corresponding to each of the four cases, where the relative weights are determined by the inter-user channel conditions [27].

4.3. Turbo Coded Cooperation

Turbo coding can be used with either Coded Cooperation or Space-Time Cooperation. The difference between the two cases is in the second frame. In Turbo Coded Cooperation, each user transmits its partner's parity bits in the second frame using all available power. In Space-Time Turbo Coded Cooperation, each user transmits its own as well as its partner's second set of parity bits, by splitting the available power. In either case, if the first frame of the partner is not successfully decoded, the user will interleave, encode and transmit the second set of parity bits for its own source block using all of its power [27].

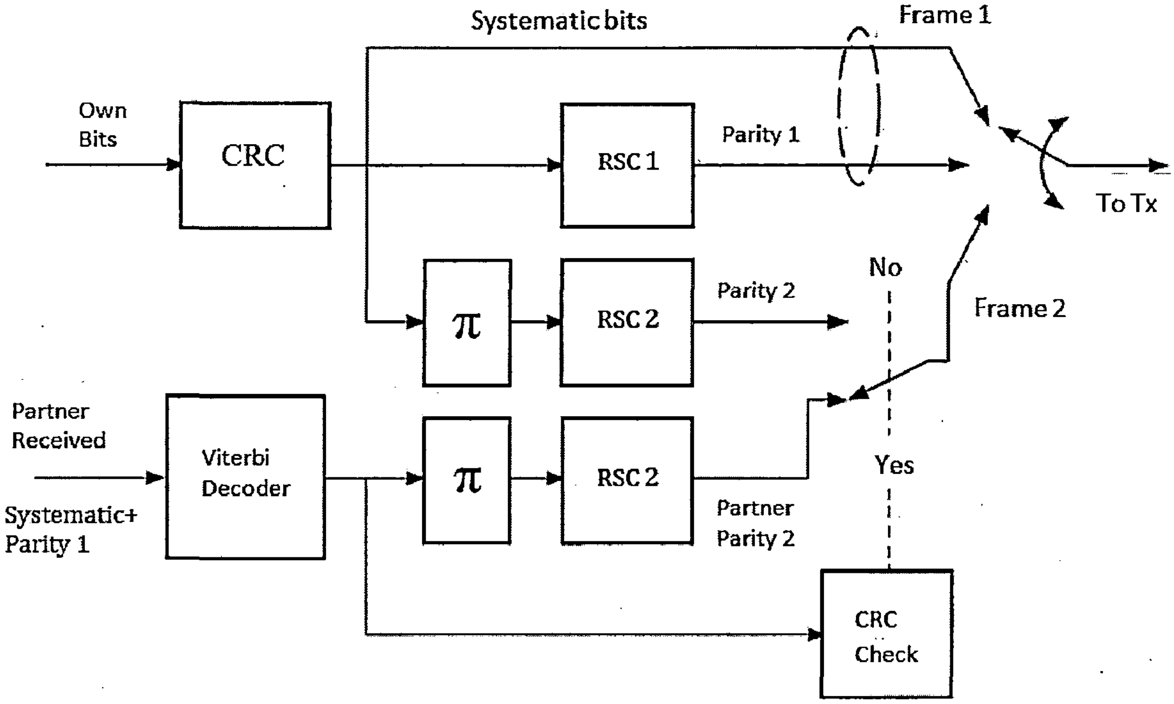

Figure 4.2 A user's implementation of Turbo Coded Cooperation [27]

The implementation of Coded Cooperation using turbo codes is shown in Figure 4.2. Turbo codes employ two constituent recursive systematic convolutional (RSC) codes with interleaving [26,28]. The users and the destination have the same random interleaver, shown as π in Figure 4.2. The code word for the first frame is obtained using the first RSC code. Upon successful ~~de-puncturing and~~ decoding of the partner data, the user interleaves the source bits over the K-bit block and transmits the parity bits corresponding to the second RSC code. CRC is appended to the information bits for error detection at the partner. But CRC can be appended directly to encoded Frame1 to save bandwidth as Viterbi decoding is performed only on Frame1.

4.4. Two-user RCPT Coded Cooperation

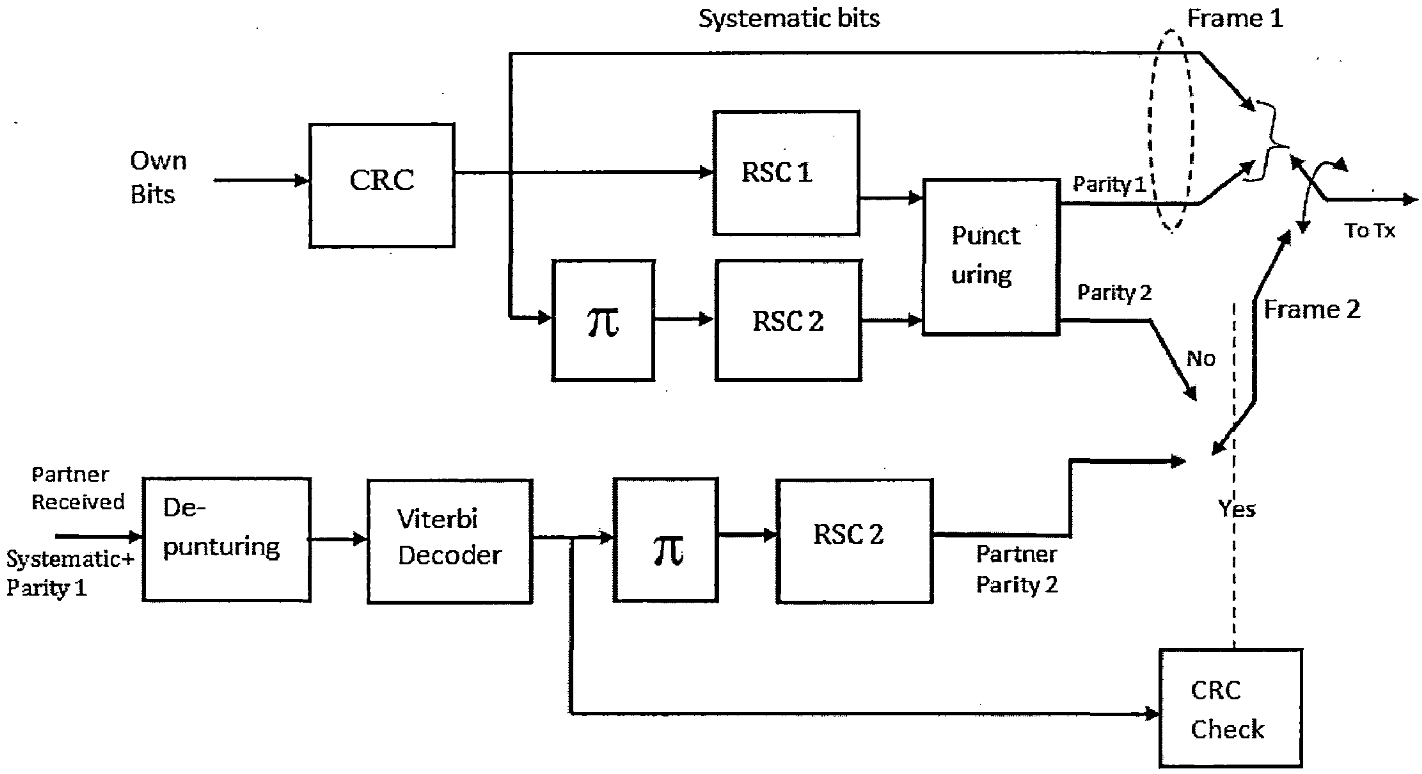

Figure 4.3 A user's implementation of Coded Cooperation with RCPT codes

Cooperation percentage increases by puncturing the parity data using a suitable parity matrix. Turbo codes provide flexible cooperation percentage, as well as better performance by puncturing, which results in rate compatible punctured turbo codes (RCPT) [25]. However, the mobiles need not perform Turbo decoding on the partner's bits. As shown in Figure 4.3 each user's Frame 1 contains systematic bits and punctured Parity 1 bits. Partner's Parity 2 bits are found by performing de-puncturing, conventional Viterbi decoding on the received partner's data. Frame 2 of a user contains either partner's Parity 2 bits or Parity 2 bits of his own based on the CRC check. At the base station, the combination of the first and second frames offers the possibility of turbo decoding. We used iterative decoder based on BCJR Algorithm for decoding Turbo codes at the base station. The algorithm description can be found in [6, 29]. This proposed RCPT Coded Cooperation has a little degraded performance (< 1dB) than Turbo Coded Cooperation as shown in Figure 5.6. This model embedded puncturing in its design. So based on the channel state we can adapt transmission rates. This can further be extended for multiple users by using different puncturing rates.

4.5. Multi-user RCPT Coded Cooperation

In multi-user RCPT Coded Cooperation more than two-users participate in cooperation. Multiple users cooperate among themselves similar way as show in Figure 3.5. In multi-user scenario partners data can be transmitted in two ways.

1) Each user decodes all its partners data and transmits their second frames after successful encoding. This is a kind of repetition of the second frame, which doesn't provide better BER performance.
2) Each user decodes all its partners data and transmits their corresponding second frames with different puncturing rates. This allows the users to transmit the bits which were not transmitted by their partners. This adds more diversity to the system. So this method is preferred for simulations in multi user case.

If J number of cooperating users exist in a cluster then for each user, a frame is formed by encoding K bits into $L = K/R$ bits, where R is the code rate. Partners cooperate by dividing their L bit frames into J subframes containing $L_1, L_2, ..., L_J$ bits, where $L = L_1 + L_2 + ... + L_J$. In the first N_1T seconds of each frame, each user transmits his first subframe composed of $N_1 = K/R_1$ coded bits, where R_1 is the code rate of the codeword in the first subframe, obtained by puncturing N-bit codeword. Also $R_1 > R_J = R$. Upon the end of the first subframe, each user decodes the rate-R_1 codewords of his partners.

The partitioning of the coded bits in the J subframes is achieved by puncturing. In the remaining $J-1$ subframes, each user in the cluster transmits one subframe for each of his $J-1$ partners. Each of these subframes contains parity bits of one of his partners which were not sent yet to the BS. The cooperation level is defined as $(N-N_1)/N$ i.e. the percentage of the total bits per each source block that each user transmits for his partners. The code rates corresponding to different cooperation levels $R_1 > R_2 > R_3 > ..... > R_J = R$. BPSK modulation and coherent detection can be employed in the system. Each user is equipped with Viterbi decoder and at the Base Station Turbo decoding is performed. The BS receiver combines all the received subframes for a user to produce a codeword of a more powerful code i.e., a lower rate code [22]. In this way we implement the multi-user RCPT Coded Cooperation.

Chapter 5

RESULTS AND DISCUSSION

In this chapter, we describe simulation results for Coded Cooperation using RCPC and RCPT codes. The performance results for RCPC Coded Cooperation were obtained under Rayleigh and Rician fading for two users. Also, performance in Rayleigh fading with multiple users is examined. We also simulated Coded Cooperation using Turbo Codes. RCPT codes are implemented by puncturing Turbo codes. As expected, using RCPT codes with Coded Cooperation resulted in better BER performance than using RCPC codes. This proposed RCPT Coded Cooperation provided more than 3dB gain over RCPC Coded Cooperation at BER of 10^{-3}. We have used Iterative Turbo decoder based on BCJR algorithm. All the simulation results in this thesis were performed in MATLAB environment.

5.1. Simulation Results for RCPC Coded Cooperation

Coded Cooperation diversity is proposed first with Convolutional codes by puncturing, which are called as RCPC codes. Users in the network share their resources (antennas) and generate a virtual multiple-antenna transmitter system to achieve transmit diversity. In our work, both at the Users and at Base Stations, we used Viterbi Decoder to decode convolutional codes.

Performance results for RCPC Coded Cooperation are obtained using the simulation parameters shown in the Table 5.1.

Table 5.1 Simulation parameters for RCPC Coded Cooperation

Convolutional Encoder	(4,1,4)
Puncturing Period	P=8
Mother code Rate	R= ¼
Source data block size	K=128 bits
16-Bit CRC	Coefficients 15935 (Hexadecimal notation)
Rates used for 3-user Cooperation	4/11, 4/13, 4/14
Rates used for 4-user Cooperation	4/10, 4/13, 4/14, 4/15
Convolutional Decoder	16-State Viterbi decoder
Performance measure	BER

To achieve different cooperation percentages, family of RCPC codes given by Hagenauer [5] are used. CRC code is used for error detection at the Users. For performance analysis, perfect error detection is assumed. To obtain 25% Cooperation rate 4/6 puncturing matrix is used.

Figure 5.1 shows BER performance of RCPC Coded Cooperation with different interuser SNR values at Base station. 25% cooperation is used by the users or mobile units. From the results it is observed that cooperation is advantageous over no cooperation. As the interuser SNR increases we get better performance. From the above figure, we can conclude that cooperation gives better performance than no cooperation even when interuser SNR is worse. These results are verified from the previous work done by Hunter [21, Figure 3] on Coded Cooperation using RCPC Codes for two user cooperation.

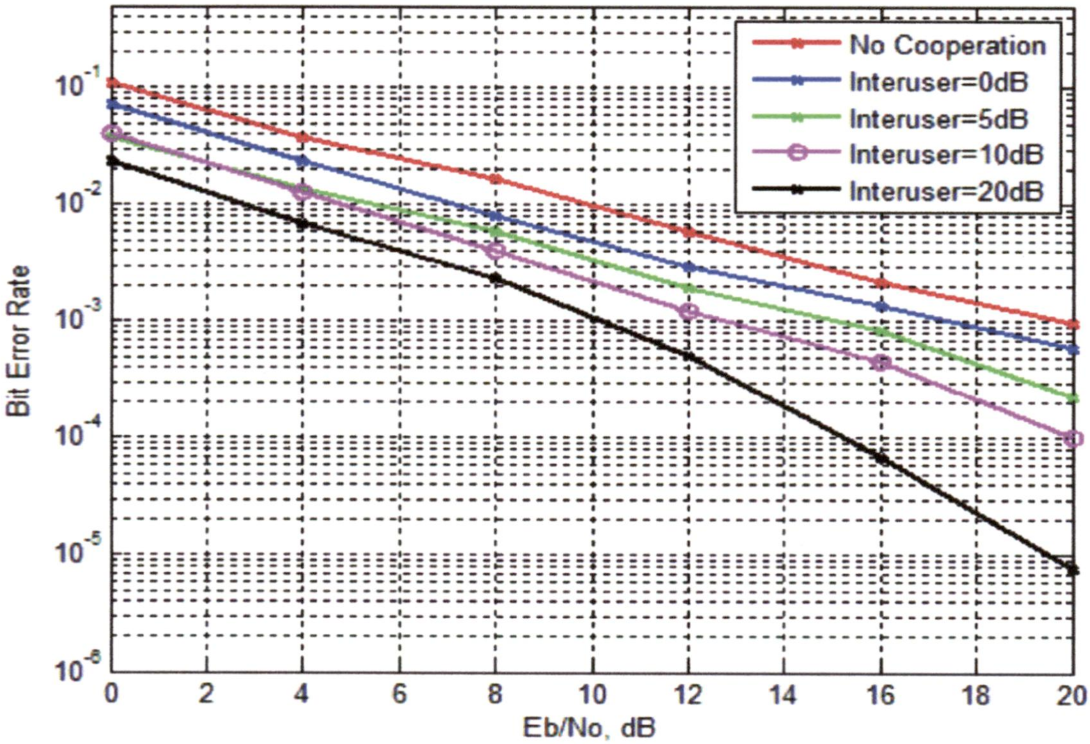

Figure 5.1 BER performance of RCPC Coded Cooperation under Slow Rayleigh fading.

Figure 5.2 shows the performance of Coded Cooperation in Fast Rayleigh fading and Slow Rayleigh fading. We assume a 10dB interuser SNR and 25% cooperation. It is observed that fast fading performance is better than slow fading under good interuser conditions. This is because of the higher diversity order is achieved in the case of fast fading compared to slow fading [20].

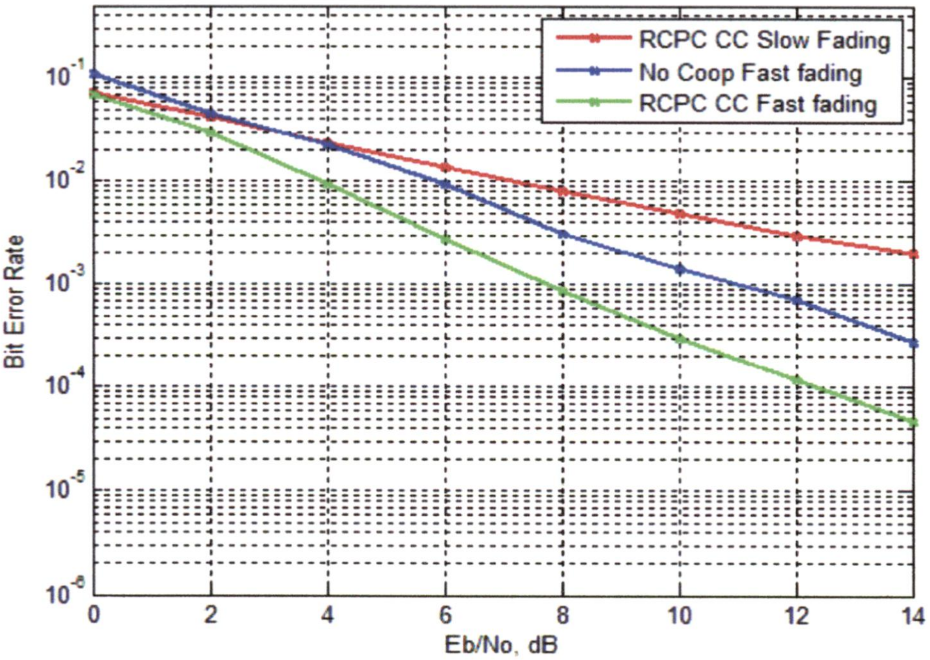

Figure 5.2 BER performance of RCPC Coded Cooperation at the Base Station under Fast Rayleigh fading.

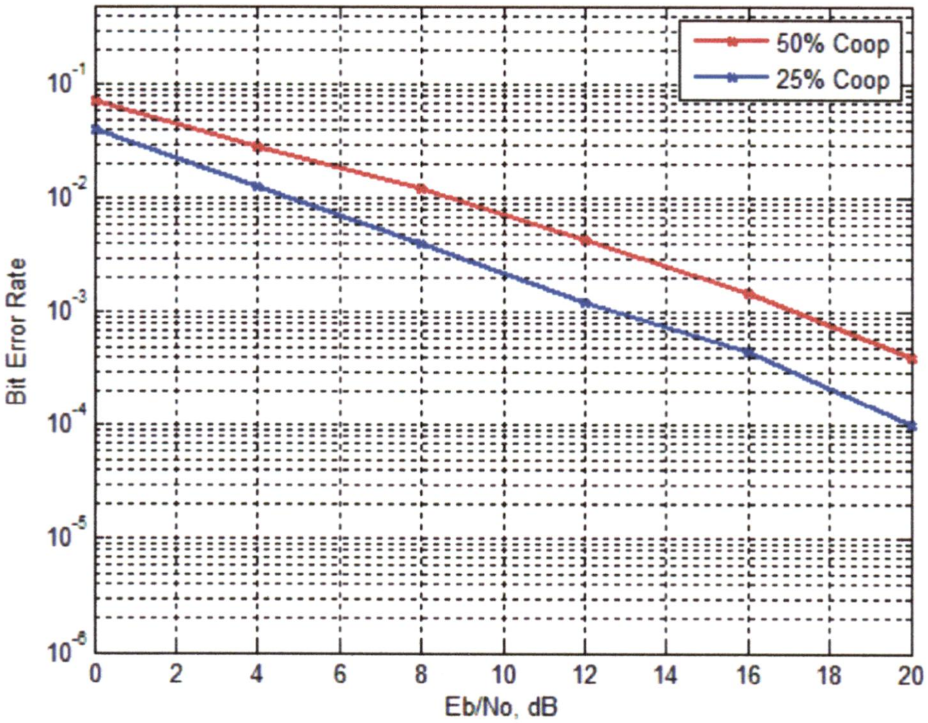

Figure 5.3 BER performance of RCPC Coded Cooperation at Base Station with different cooperation levels in Slow Rayleigh fading.

By changing the level of cooperation between the two users i.e. varying the numbers of bits sent by a user for its partner, we obtain Figure 5.3. 10dB interuser SNR is used for simulation. As the cooperation percentage increases, the users must send higher number of bits for his partner. This leads to performance degradation for the cooperating user. This result compares well with the results reported in [17, Figure 3.11].

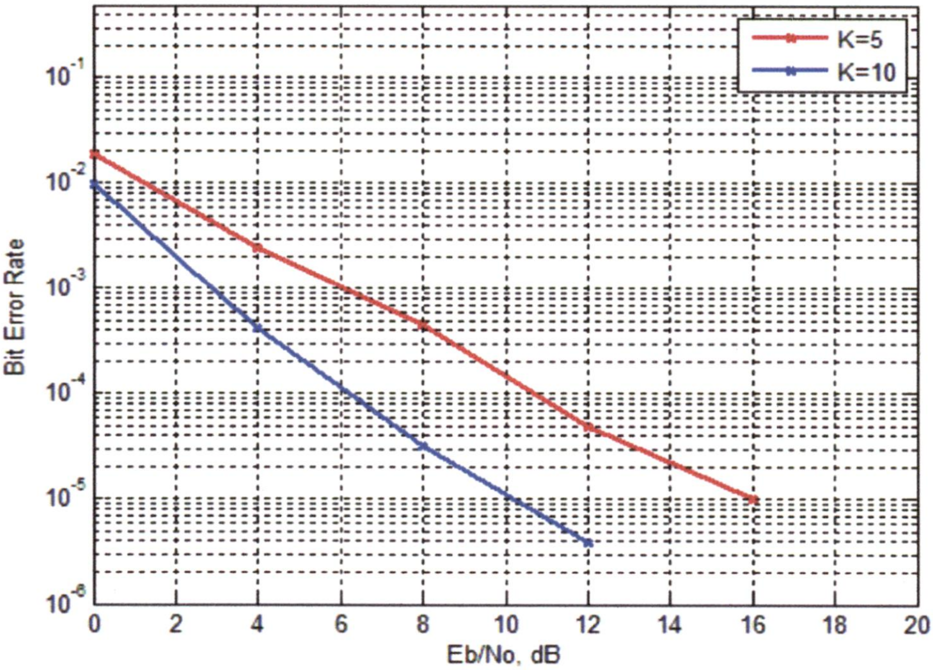

Figure 5.4 BER performance of RCPC Coded Cooperation under Slow Rician fading.

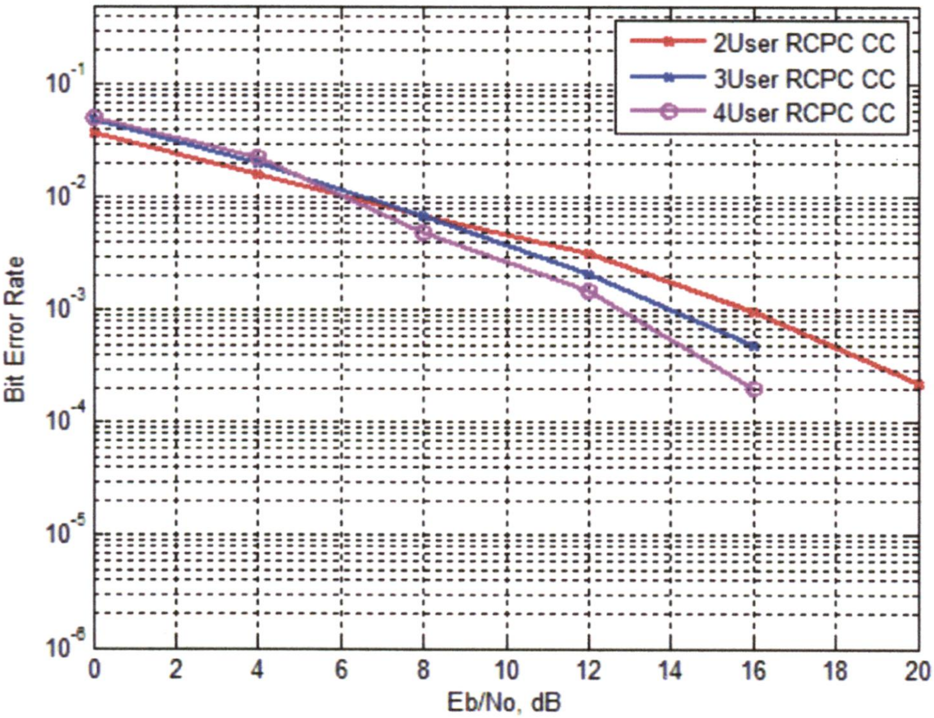

Figure 5.5 BER performance of RCPC Coded Cooperation for multiple users in Slow Rayleigh fading.

Figure 5.4 shows the BER performance under Slow Rician fading with 25% cooperation. Two different values of Rician K-factor (the ratio of signal power in dominant component over the scattered power in dBs) are used with 10dB interuser SNR. It is observed that better performance is obtaied by increasing the K-factor from 5dB to 10dB. Figure 5.5 shows the multi-user RCPC Coded Cooperation with 25% cooperation under 5dB interuser SNR. The BER performance results shows that as the number of users increases, the cooperation yields better results beyond a certain SNR. It can be observed that 2 User RCPC Coded Cooperation is better than 3 User and 4 User RCPC Coded Cooperation when the SNR is less than 6dB. But beyond 6dB, Coded Cooperation with more number of users results in better performance because at higher values of SNR the probability of correct decoding of partner's data by a user increases. This result compares well with the result in [22, Figure 2,3].

5.2. Simulation Results for RCPT Coded Cooperation

In our proposed scheme using RCPT Coded Cooperation we puncture the parity bits in accordance with a puncturing matrix. Viterbi decoder is used at the users and Iterative decoding based on BCJR Algorithm is implemented at the Base station. The simulation parameters are shown in Table 5.2.

Table 5.2 Simulation parameters for RCPT Coded Cooperation

Turbo Encoder	(12,3) PCCC
Convolutional Encoder	(2,1,1) SRCC
Puncturing Period	P=2
Mother code Rate	R= ¼
Source data block size	K=128 bits
16-Bit CRC	Coefficients 15935 (Hexadecimal notation)
Rates used for 3-user Cooperation	4/11, 4/13, 4/14
Convolutional Decoder	2-State Viterbi decoder
Turbo Decoder	BCJR Iterative decoder
Performance measure	BER

Parallel concatenated convolutional codes (PCCC) are implemented using systematic recursive convolutional codes (SRCC). CRC is used for error detection at the Users. In Turbo Coded Cooperation, 33% of cooperation is assumed. Rate 4/6 puncturing matrix is used in simulations to obtain 66% cooperation in case of RCPT Coded Cooperation.

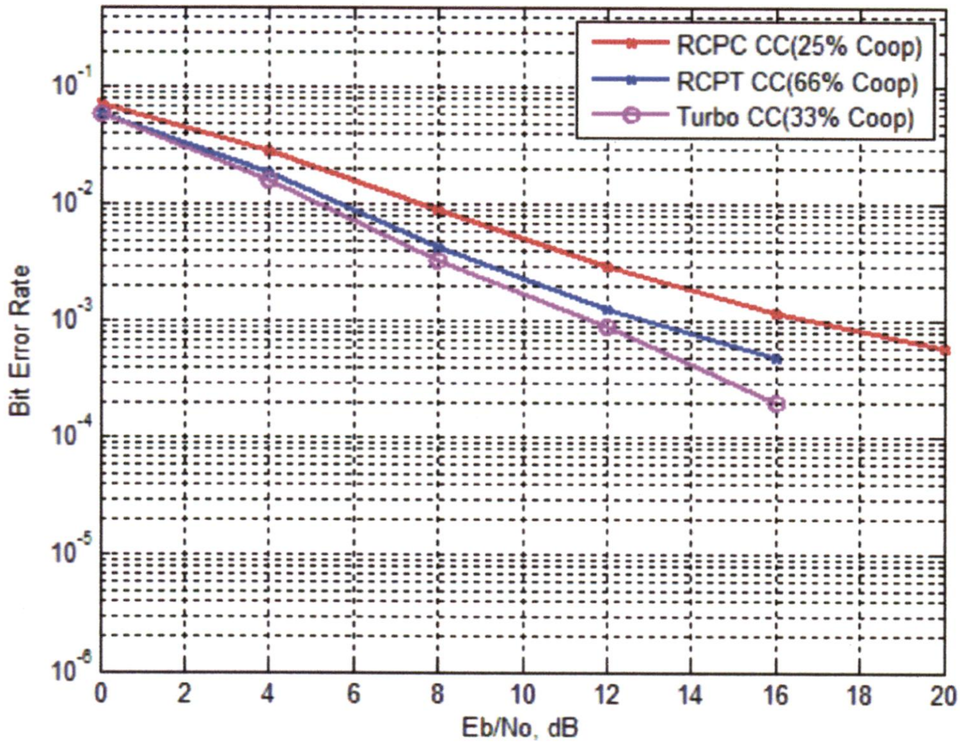

Figure 5.6 BER performance of RCPT Coded Cooperation compared to RCPC Coded Cooperation in Slow Rayleigh fading.

BER performance comparisons between RCPC Coded Cooperation with 25% cooperation are shown in Figure 5.6. We implemented 33% Turbo Coded cooperation and 66% RCPT Coded Cooperation at interuser SNR of 0dB. We observe more than 3dB gain for RCPT Coded Cooperation over RCPC Coded Cooperation at BER of 10^{-3}. However, cooperation using Turbo codes without puncturing provides very little benefits. Turbo Coded Cooperation provides a performance gain of about 1dB over RCPT Coded Cooperation at BER of 10^{-3}. This can be compared with the results reported in [27, Figure 8]. We used Iterative BCJR Algorithm for decoding at the base station.

Figure 5.7 shows the BER performance of RCPT Coded Cooperation over RCPC Coded Cooperation in AWGN channel. Interuser SNR is 0dB is used. Increasing the number of iterations provides diminishing returns.

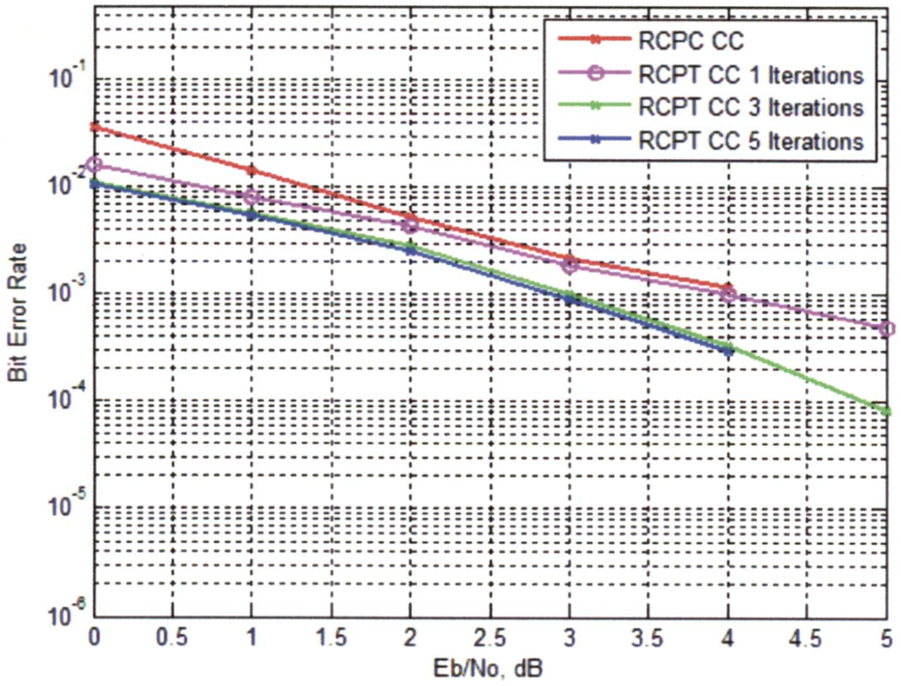

Figure 5.7 BER performance of RCPT Coded Cooperation with different number of iterations at Base Station in AWGN channel.

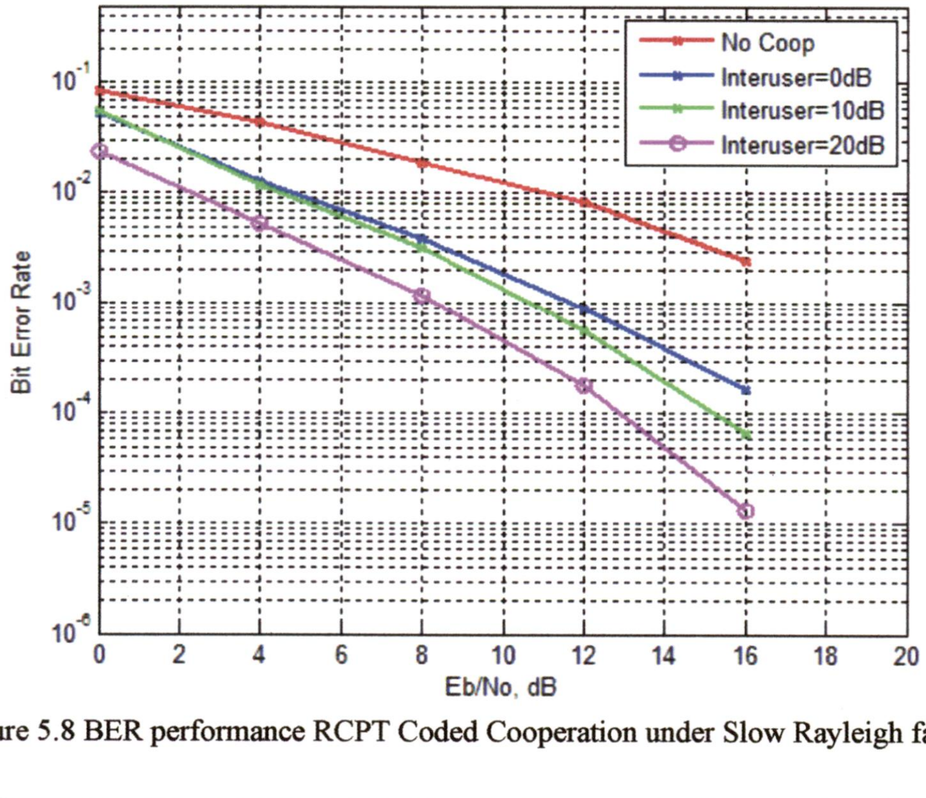

Figure 5.8 BER performance RCPT Coded Cooperation under Slow Rayleigh fading.

In figure 5.8, we observe the BER performance of RCPT Coded Cooperation with changing interuser SNR values. We assume 66% cooperation among the users. It is also observed that RCPT Coded Cooperation has significant performance improvement over no cooperation. For example, at a BER of 10^{-2}, the minimum gain available in a cooperation scenario is 6dB.

Performance comparison between RCPC Coded Cooperation and RCPT Coded Cooperation at 0dB interuser SNR is shown in Figure 5.9. Slow Rayleigh fading is used with 66% Cooperation and Interuser is SNR 0dB. RCPT Coded Cooperation has a gain of 2dB gain over RCPC Coded Cooperation at BER of 10^{-3}. It is also observed with increasing the number iterations from 1 to 3 in RCPT Coded Cooperation under Rayleigh fading has a gain <1dB at all BER values.

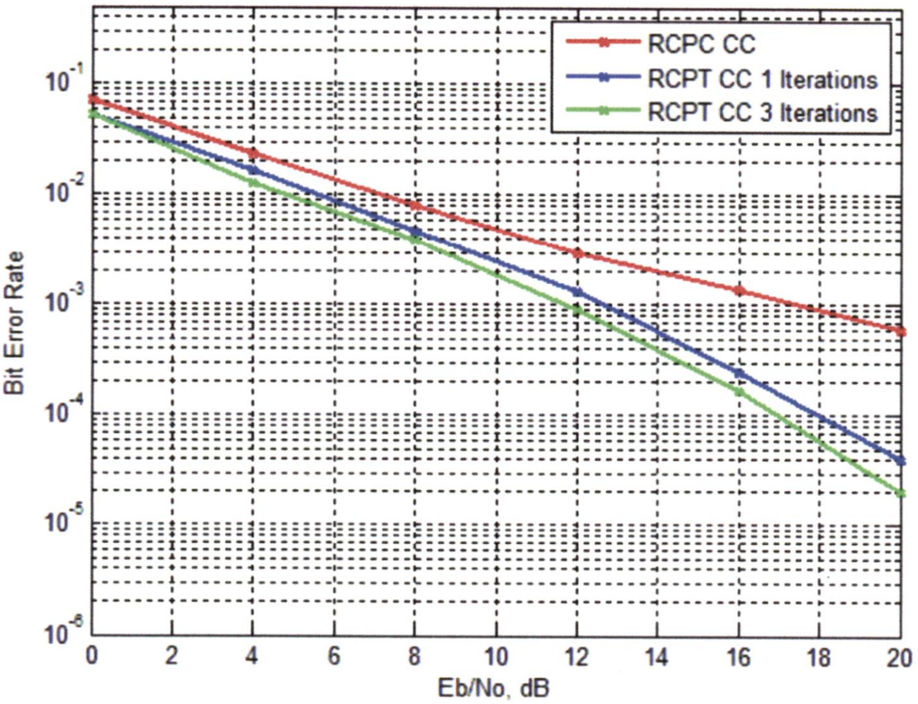

Figure 5.9 BER performance of RCPT Coded Cooperation with different number of iteration at the BS decoder.

Chapter 6
CONCLUSIONS

Cooperation is essential in the view point to reduce the hardware and cost among mobile devices. Due to the broadcast nature of wireless signals, neighbouring nodes retransmit the overhead information to achieve diversity. Diversity techniques can be used to overcome the effects of multipath fading. Coded cooperation achieves diversity by sending different portions of each user's code word via two independent fading paths. In this report, we studied Coded Cooperation using RCPC codes and to achieve better performance with reduced hardware complexity and cost of mobile devices, we proposed RCPT Coded Cooperation. Using Turbo code components in Coded Cooperation does not add to the mobile complexity as mobiles decode using Viterbi algorithm. The conclusions drawn based on the simulation results are as follows:

Coded Cooperation using RCPC codes provides better performance by increasing the interuser SNR between the users. To achieve a BER of 10^{-3} in slow Rayleigh fading, with an interuser SNR of 20dB, we observed a 10dB improvement over no cooperation. In fast Rayleigh fading RCPC Coded Cooperation achieves a BER of 10^{-3} at 8dB SNR. Whereas no cooperation achieves the same BER at 10.5dB. This concludes that either in slow or fast fading Coded Cooperation yields better results over no cooperation. It is also observed that by increasing cooperation percentages degrades the BER performance. Because increase in cooperation causes an increased data overhead on the cooperating user. As the number of cooperating users increases we achieve better BER results. We observed the RCPC Coded Cooperation performance with 3 users and 4 users through a proper frame division.

Turbo-Coded Cooperation improves the performance over non cooperative turbo-coded systems that have comparable computational complexity. Using RCPT codes provides a flexibility of changing rates according to the channel conditions. Coded Cooperation using RCPT codes provides a gain of 2dB over RCPC Coded Cooperation at BER of 10^{-3}. However RCPT Coded Cooperation results in degraded performance by 0.5dB when compared to Turbo Coded Cooperation at the same BER. Increasing the number of decoding iterations in RCPT Coded Cooperation from 1 to 3 results in performance gain of 0.5dB. Further increasing the iterations achieves no remarkable gains.

Future work

This dissertation work can be extended for future work in many ways. In RCPC Coded Cooperation we have used hard decision Viterbi decoding in simulations. Soft decisions can be done by using different quantization levels for decoding. This provides better BER performance over hard decision decoding. We have applied RCPT codes for 2-user Coded Cooperation. This can be extended in case of multi user networks by using different rates. With BER performances achieving Shannon's limit, LDPC Codes are giving a big competition to Turbo codes. So these can be best alternate codes where transmission delays are tolerable.

Unlike the original Coded Cooperation framework, where users transmit their partner's data in the second frame, a method called space-time cooperation can be used, in which the users send both their own as well as their partner's parity bits in the second frame. This strategy is effective in the fast fading channels. This can be considered with RCPT Coded Cooperation for the future work.

Achieving high data rate in wireless services is one of main design considerations. Nodes in a wireless network are allowed to adapt their data rates to match the channel conditions to maximize the throughput. So adaptive modulation can be applied to RCPT Coded Cooperative systems to achieve better throughput. Multi-hop using relays with adaptive modulation mitigates pathloss. This is another dimension for extending the Coded Cooperation in an effective manner.

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