DESIGN AND ANALYSIS OF MULTILEVEL CODING SCHEME WITH COOPERATIVE DIVERSITY FOR IMPROVED SYSTEM PERFORMANCE

A Thesis

submitted in fulfilment of the requirement

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DOCTOR OF PHILOSOPHY

by

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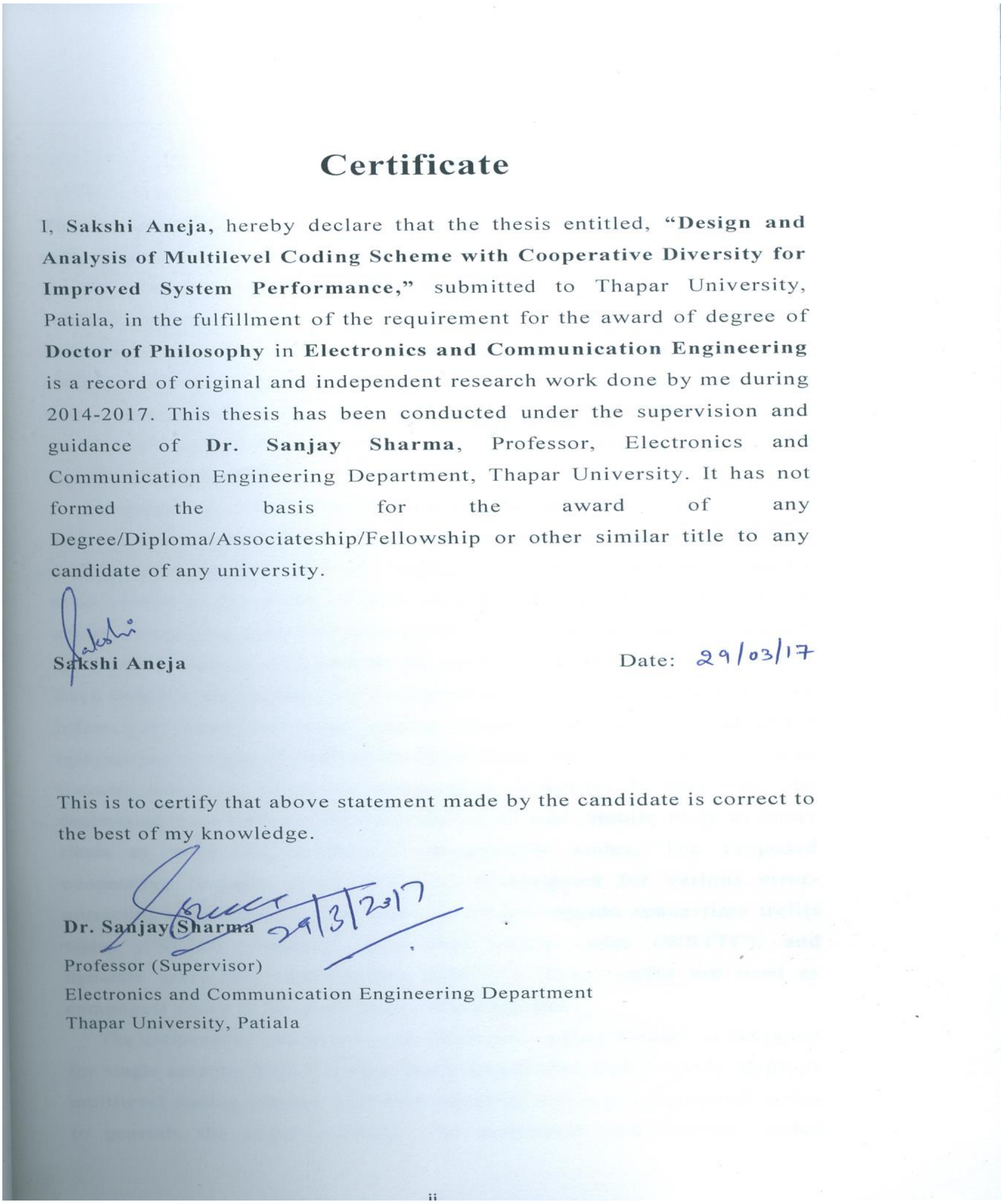

Certificate

I, **Sakshi Aneja,** hereby declare that the thesis entitled, **"Design and Analysis of Multilevel Coding Scheme with Cooperative Diversity for Improved System Performance,"** submitted to Thapar University, Patiala, in the fulfillment of the requirement for the award of degree of **Doctor of Philosophy** in **Electronics and Communication Engineering** is a record of original and independent research work done by me during 2014-2017. This thesis has been conducted under the supervision and guidance of **Dr. Sanjay Sharma**, Professor, Electronics and Communication Engineering Department, Thapar University. It has not formed the basis for the award of any Degree/Diploma/Associateship/Fellowship or other similar title to any candidate of any university.

Sakshi

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

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Abstract

The next generation communication systems aim at providing higher data rate, enhanced spectral efficiency, improved coverage and lower latency for the connection of billions of wireless devices. The rising demand of reliable wireless communication requires an innovation in the wireless technology. In this research work, multilevel coding scheme in conjunction with cooperative diversity is investigated in an endeavor to meet these requirements. The cooperative multilevel coding system provides a significant improvement in performance over non-cooperative multilevel coding system.

The proposed system considers various mobile nodes communicating with a common destination node. Due to broadcast nature of wireless medium, each mobile node can overhear the information transmitted by other mobile nodes to the common destination node. The mobile nodes act as cooperative nodes by sharing their antennas in order to transmit their own information as well as the information of neighboring nodes. Each mobile node encodes the overheard information along with its own information using multilevel coding scheme and transmits the coded information to common destination node. This creates a different form of transmit diversity, known as cooperative diversity. In this way, the destination node receives the information of each mobile node as many times as there are number of cooperative nodes. The proposed cooperative communication system is investigated for various error-correcting codes such as convolutional codes, pseudo space-time trellis codes (PSTTC), weighted space-time trellis codes (WSTTC), and dynamic space-time trellis codes (DSTTC). These codes are used as component codes in the multilevel coding scheme.

The cooperative multilevel convolutional coding system is designed for single antenna mobile nodes. Each cooperative mobile node employs multilevel coding scheme with convolutional codes as component codes to generate the coded symbols. The multilevel convolutional coded

symbols are mapped and transmitted to destination node. The simulation results indicate that cooperative multilevel convolutional coding system outperforms non-cooperative multilevel convolutional coding system by ~0.5 dB at frame error rate (FER) of 10^{-1} using one transmit and one receive antenna.

The cooperative multilevel pseudo space-time trellis coding (CMLPSTTC) system is also designed for single antenna mobile nodes. Each cooperative node employs novel multilevel pseudo space-time trellis coding (MLPSTTC) scheme to generate the coded symbols. MLPSTTC use the recently invented pseudo space-time trellis codes as component codes. The MLPSTTC symbols generated at each cooperative node are transmitted to destination node. The simulation results show that the performance of proposed CMLPSTTC technique is superior to existing non-cooperative MLPSTTC technique by ~0.7 dB at FER of 3×10^{-1} using one transmit and one receive antenna.

The cooperative multilevel weighted space-time trellis coding (CMLWSTTC) system is designed in the following manner. The cooperative nodes employ multilevel coding scheme with space-time trellis codes as component codes to encode the information of neighboring nodes along with its own information. The coded symbols are mapped and weighted by appropriate beamforming coefficients to achieve receive signal-to-noise ratio gain. The weighted symbols are transmitted to destination node. The simulation results show that the performance of CMLWSTTC system is superior to non-cooperative multilevel weighted space-time trellis coding system by ~2 dB at FER of 3×10^{-1} using two transmit and one receive antenna.

The cooperative multilevel dynamic space-time trellis coding (CMLDSTTC) system is designed by employing multilevel coding scheme with dynamic space-time trellis codes as component codes at each cooperative node. DSTTC adapt to the current channel conditions by selecting the optimum code-set of generator sequences. The multilevel

dynamic space-time trellis coded (MLDSTTC) symbols generated at each cooperative node are transmitted to the destination node. The CMLDSTTC system outperforms non-cooperative MLDSTTC system by ~3.1 dB at FER of 3×10^{-1} using 1 bit feedback information in the case of two transmit and one receive antenna.

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Acronyms and Abbreviations

1G : First generation

2G : Second generation

3G : Third generation

4G : Fourth generation

5G : Fifth generation

AF : Amplify and forward

AGMLSTTC : Adaptively grouped multilevel space-time trellis coding

AWGN : Additive white Gaussian noise

BCH : Bose, Chaudhuri, and Hocquenghem

BER : Bit error rate

CMLDSTTC : Cooperative multilevel dynamic space-time trellis coding

CMLPSTTC : Cooperative multilevel pseudo space-time trellis coding

CMLWSTTC : Cooperative multilevel weighted space-time trellis coding

CSI : Channel state information

DF : Decode and forward

DSTTC : Dynamic space-time trellis codes

FER : Frame error rate

GMLDSTTC : Grouped multilevel dynamic space-time trellis coding

GMLSTTC : Grouped multilevel space-time trellis coding

IP : Internet protocol

LDPC : Low-density parity-check

MAP : Maximum a posteriori

MATLAB : Matrix laboratory

MIMO : Multiple-input multiple-output

MISO : Multiple-input single-output

ML : Maximum likelihood

MLDSTTC : Multilevel dynamic space-time trellis coding

MLPSTTC : Multilevel pseudo space-time trellis coding

MLSTTC : Multilevel space-time trellis coding

MLWSTTC : Multilevel weighted space-time trellis coding

MRM : Multi-resolution modulation

M-QAM : *M-ary* quadrature amplitude modulation

OSTBC : Orthogonal space-time block codes

PAM : Pulse amplitude modulation

PANC : Physical layer algebraic network coding

PDF : Probability density function

PSTTC : Pseudo space-time trellis codes

SCL : Self-information cancelling linear

SEP	:	Symbol error probability
SER	:	Symbol error rate
SNR	:	Signal-to-noise ratio
SPC	:	Superposition coding scheme
S/P	:	Serial to parallel
STBC	:	Space-time block codes
STTC	:	Space-time trellis code
SS	:	Symbol superposition
TD	:	Time-division
TCM	:	Trellis coded modulation
WSTTC	:	Weighted space-time trellis codes
WAGMLDSTTC	:	Weighted adaptively grouped multilevel dynamic space-time trellis coding
WAGMLSTTC	:	Weighted adaptively grouped multilevel space-time trellis coding

Chapter 1

Introduction based on Literature Review

Contents

1.1 Introduction

Wireless Communication has transformed the world into a smaller place by providing numerous advantages over wireline communication such as low cost installation and maintenance, flexible connectivity to varied number of users, mobility of wireless devices and user convenience. In the past decade, wireless networks have become a ubiquitous part of our daily lives. The number of wireless users are increasing day by day, which generates the demand for high data rate, coverage, spectral efficiency and low outage.

The era of wireless communication started in 1980s with first generation (1G) technology, based on frequency reuse in a cellular system. But, 1G technology use analog modulation for voice transmission resulting in poor call quality and data insecurity. This led to the advent of second generation (2G) technology in 1991. 2G technology introduced data services such as short messaging service, picture messages and multimedia messages. The radio signals used for voice and data transmission were digital which enabled the use of encryption techniques for data security. 2G technology enhanced the quality of service and spectral efficiency in comparison to 1G technology. But, 2G technology is designed for slow data transmission. So, in 1998, third generation (3G) technology was introduced to provide better data transmission rate. Moreover, 3G technology provides some of the applications which were not earlier available to mobile users such as mobile TV, global positioning system, video conferencing, location based services and video on demand. Later than, in 2008, fourth generation (4G) technology based on an all-internet protocol (IP) network infrastructure was introduced. 4G technology has the capability of providing peak data transmission rates, peak spectral efficiency and applications such as IP telephony, 3D television, high definition mobile TV, gaming services and video conferencing.

Currently, the next generation viz. fifth generation (5G) communication systems aim at providing enhanced spectral efficiency, higher data rate, improved coverage and lower latency for the connection of billions of wireless devices. The rising demand of reliable wireless communication requires an innovation in the wireless technology. In this research work, multilevel coding scheme in conjunction with cooperative diversity is investigated in an endeavour to meet these requirements. The multilevel coding scheme deploys several error-correcting codes for data coding. It has the potential of providing flexible data transmission rate, coding gain and improved spectral efficiency. The cooperative diversity technique creates virtual transmit diversity in single antenna mobile users through mutual cooperation and combats the effects of multipath fading. It is capable of providing diversity gain, better error performance, improved coverage, lower latency, greater reliability of data reception and reduction in outage probability.

The multilevel coding scheme is based on performing independent coding at various levels. The main advantage of this scheme is that a high spectral efficiency can be obtained. However, the multilevel signals are prone to channel noise, therefore, these must be accompanied with suitable error-correcting codes to generate efficient communication systems. The multilevel coding scheme can use error-correcting codes as component codes to provide coding gain and flexible data transmission rate. The multistage decoding is usually used for the detection of multilevel coded information. This involves decoding the received signal at various stages to detect information at the corresponding level. The multistage decoder results in a very low decoding complexity.

Spatial diversity is one of the promising solutions to combat multipath fading and improve the quality of information transmission. Spatial diversity at the transmitting end is usually created by installing multiple antennas for data transmission. However, the mobile station can have size, cost or hardware limitations and it is not always possible to increase the number of antennas. In such cases, virtual transmit diversity can be created by mutual cooperation between mobile stations. This is known as cooperative diversity and it is based on exploiting the broadcast nature of wireless medium. The mobile users share each other’s antennas for multiple data transmission. The cooperative diversity shows a remarkable performance in wireless communication systems through a reduction in error rates and outage probability.

The combination of multilevel coding scheme and cooperative diversity can prove beneficial in wireless communication systems in order to achieve high spectral efficiency, high data rates, low error rates, low outage probability, low latency and improved coverage. Such a transmission scheme has the potential of forming the basis for next generation communication systems.

1.2 Motivation for Research

Cooperative diversity outshines the various solutions explored by researchers to combat the adverse effects of multipath fading and improve the quality of information transmission. It enables the mobile users to share their antennas in order to create virtual transmit diversity. The mobile users can act as cooperative users by sending their own information as well as the overheard information of nearby mobile users to the common base station. Cooperative diversity shows a remarkable performance in wireless communication systems in terms of diversity gain, enhanced transmission reliability, quality of service and network capacity.

Numerous cooperative transmission protocols have been explored in literature, but most of them fall under the category of time-division (TD) cooperation protocol and symbol superposition (SS) cooperation protocol. The TD cooperation protocol has a drawback that transmission efficiency decreases with number of cooperative users and, SS cooperation protocol has a drawback that receiver complexity increases exponentially with number of cooperative users.

Recently, a new cooperation protocol has been introduced to overcome the drawbacks of TD and SS cooperation protocol. It uses multilevel coding scheme at each mobile node to transmit the information of nodes to a common destination node in a cooperative manner. Multilevel coding scheme is capable of providing flexible data transmission rate, coding gain and improved spectral efficiency without exponential increase in receiver complexity. This multilevel coded cooperation system enhances the cooperation probability, spectral efficiency and provides a flexible code design without exponential increase in receiver complexity. So far, the research has been done for a system that uses multilevel coding scheme with convolutional codes as component codes at each cooperative node. To the best of our knowledge, such a multilevel coded cooperation system has not been investigated yet for other error-correcting codes apart from convolutional codes. In this thesis, we propose a novel cooperative communication system based on multilevel coding scheme. Further, we investigate the proposed cooperative multilevel coding system for various error-correcting codes.

1.3 Multilevel Coding Scheme

Multilevel coding scheme combines error-correcting codes and modulation. The information stream is partitioned into sub information streams which are encoded at independent levels to generate error-correcting component codes. These component codes are mapped to M-ary constellation based on a partitioning strategy that maximises the minimum Euclidean distance. The mapped symbols are modulated and transmitted over wireless channel. The multilevel codes are usually decoded by a multistage decoder due to its low decoding complexity. The design of good multilevel codes depends on various factors such as signal constellation size, partitioning strategy, Euclidean distance between signal points, type of error-correcting codes used as component codes and code rates of component codes. A good design of multilevel code provides high data transmission rate, coding gain and spectral efficiency with a low decoding complexity. The encoding and decoding procedure of multilevel codes is explained in the following sub-sections.

1.3.1 Multilevel Encoder

The transmission process of a system using multilevel coding scheme is shown in figure 1.1. The information data stream, I is split into L sub-streams of information, $I(1)$, $I(2)$,…,$I(L)$, each of length ‘k’. The information sub-streams are passed through independent encoders with rate k/n to create L different error-correcting component codes, $C(1)$, $C(2)$,…,$C(L)$, each of length ‘n’. The generated component codes are passed through a symbol translator to create L-bit coded symbols. These coded symbols are mapped to M-ary signal constellation by following a partitioning strategy that maximizes the minimum Euclidean distance. The mapped symbols are modulated and transmitted over wireless channel.

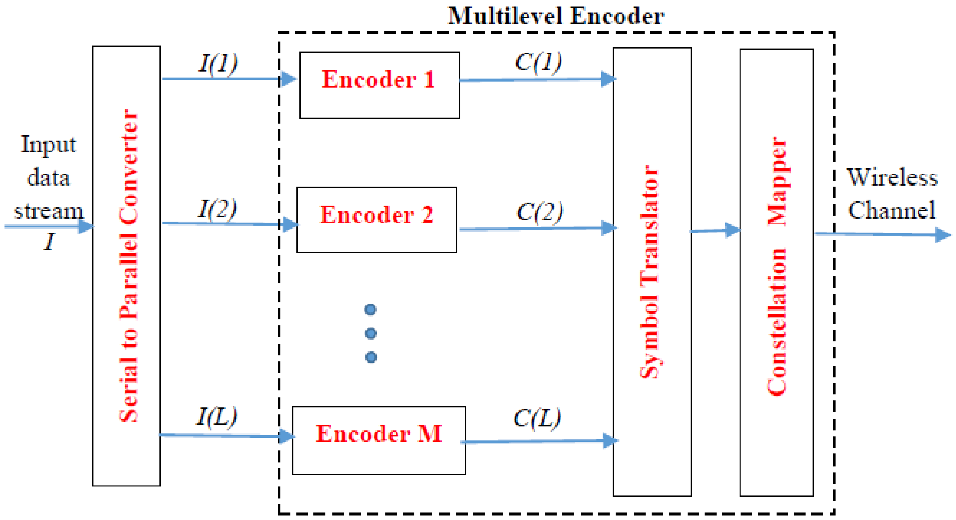

Figure 1.1: Multilevel coding of information stream

In this research work, *M*-QAM signal constellation with MRM partitioning is considered for mapping the coded symbols. Figure 1.2 depicts MRM partitioning technique by considering 64-QAM signal constellation. At first level of partitioning, 64 points in constellation set of 64-QAM are split into 4 clusters with each cluster having 16 points. Considering 4-cluster as the elementary unit of resolution, these clusters are split into 4 sub-clusters at the second level of partitioning with each sub-cluster having 4 points. Finally, at the third level of partitioning, these sub-clusters are split into 4 single constellation points. The labelling of constellation points based on MRM partitioning is shown in figure 1.2, where we have 3 clusters, each having 4 sub-clusters. The circles shown in figure 1.2 depict one sub-cluster of each cluster. In general, the clusterization procedure is followed for L levels of partition with $M=4^L$. MRM partitioning of constellation considers each cluster as a 4-QAM constellation. As a result, component codes designed for 4-QAM can be directly used in the mapping process. The output of encoder at first level is mapped to clusters spaced by certain distance Δ_1. The output of encoder at second level is mapped to sub-clusters spaced by certain distance Δ_2.

Finally, the output of encoder at level L is mapped to the actual constellation points. As shown in figure 1.2, the output of encoder at third level is mapped to constellation points spaced by certain distance Δ_3, the output of encoders at second and first levels are mapped to virtual centroids of clusters. The coded output symbols from encoder at each level are drawn from a 4-QAM constellation.

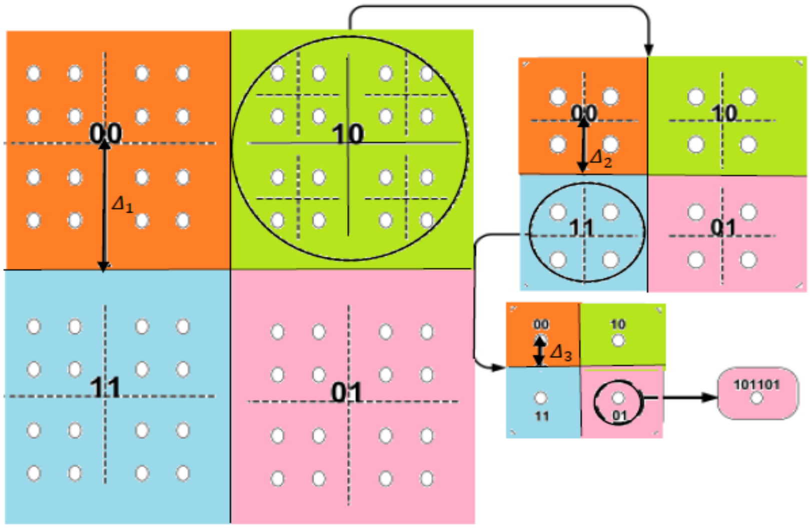

Figure 1.2: Multi-resolution modulation (MRM) partitioning and labelling technique for 64-QAM constellation

Furthermore, a quasi-static frequency non-selective Rayleigh fading channel is considered where fading coefficients vary very slowly during the transmission of a frame such that they can be assumed to be constant for a frame. However, fading coefficients change independently from one frame to the other frame.

1.3.2 Multistage Decoder

The signal received at destination node is demodulated to extract the coded signal, which is then fed to multistage decoder to extract information stream. The multistage decoder performs in various stages, starting from stage 1 and terminating after the decoding operation at stage L as shown in figure 1.3. A Viterbi decoder is used at each stage that computes branch metrics for a data frame by executing a search based on maximising likelihood function in order to detect information. The Viterbi decoder at stage 1 estimates first component code. The estimate $\hat{I}(1)$ is passed to decoding stages 2,…,L. The Viterbi decoder at stage 2 decodes the second component code by using the estimate $\hat{I}(1)$. The estimate $\hat{I}(2)$ at second stage is passed to decoding stages 3,…,L. The similar decoding procedure is followed for decoding stages 3,…,L. Finally, the Viterbi decoder at stage L uses the estimates $\hat{I}(1),\dots,\hat{I}(L-1)$ to decode the component code at stage L and gives estimated value $\hat{I}(L)$. The estimated values of component codes, $\hat{I}(1),\dots,\hat{I}(L)$, are passed through a parallel to serial converter to produce the estimated information stream.

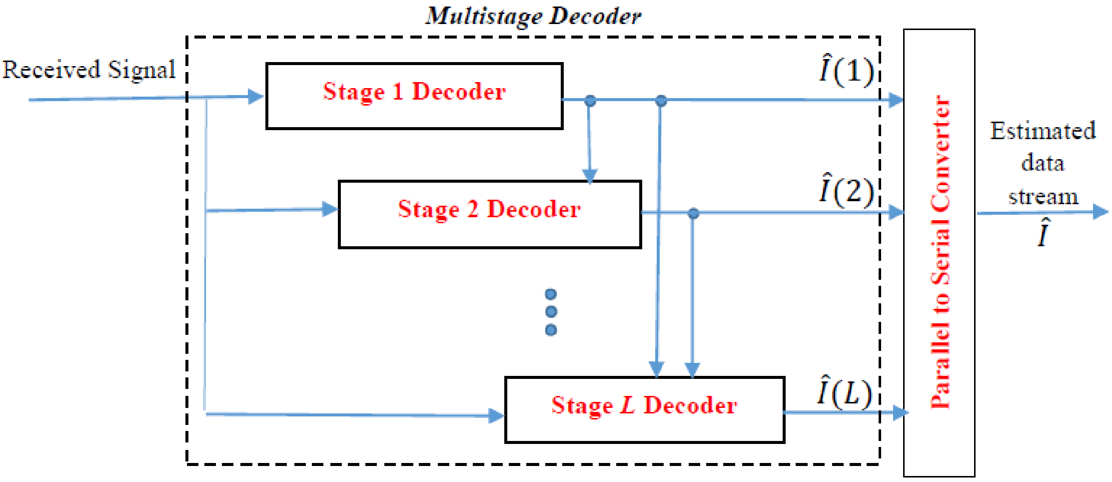

Figure 1.3: Multistage decoding of multilevel codes

Normally, multistage decoder is preferred over maximum-likelihood decoder because its complexity is proportional to the summation of decoding complexities of component codes in lieu of the product in case of maximum-likelihood decoder.

1.4 Cooperative Diversity

In a wireless communication system, the signals experience multipath fading due to reflections, diffractions and scattering from a number of objects [1]. The multipath fading tends to limit quality of service and data rate of mobile users within the duration of a call. Spatial diversity is one of the well-known techniques used to combat the adverse effects of multipath fading. Spatial diversity at transmitter (also known as transmit diversity) can be created by sending signal copies from multiple transmit antennas such that independently faded copies of signal reach the receiver [2]. However, transmit diversity may not be practical in the uplink of wireless communication system when mobile node has certain constraints such as size, complexity, cost, etc.

In order to overcome this limitation, a new form of transmit diversity technique was proposed, where single antenna mobile nodes in a cell cooperate with each other by sharing their antennas to send the signal copies. Due to broadcast nature of wireless medium, the mobile nodes can listen to each other's transmissions. Each mobile node receives the information transmitted by other nodes, detects it and transmits it along with its own information to destination node. The signals are transmitted from different locations, such that independently faded versions of signal reach the destination node. Thus, a virtual form of transmit diversity, known as 'cooperative diversity' is created. Figure 1.4 shows the system model of cooperative diversity. The mobile nodes trade off the cost in computational complexity to avail the greater benefit achieved by cooperative diversity [3]. Cooperative diversity shows a remarkable performance in wireless systems in terms of diversity gain, enhanced transmission reliability, quality of service and network capacity.

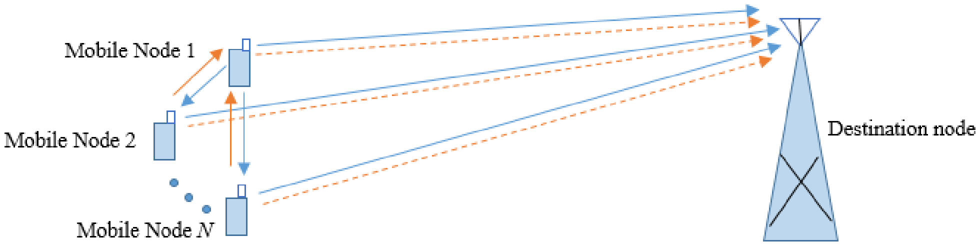

Figure 1.4: Cooperative diversity

There are different forms of cooperative diversity which can be created at the transmitting end viz. amplify and forward, decode and forward, and coded cooperation. Figure 1.5 shows the mechanism of different cooperative diversity techniques. AF cooperative diversity is created when cooperative node simply amplifies the overheard signal of other mobile nodes for transmission to destination node. DF cooperative diversity is created when cooperative node decodes the overheard signal of other mobile nodes and re-encodes it for transmission to destination node.

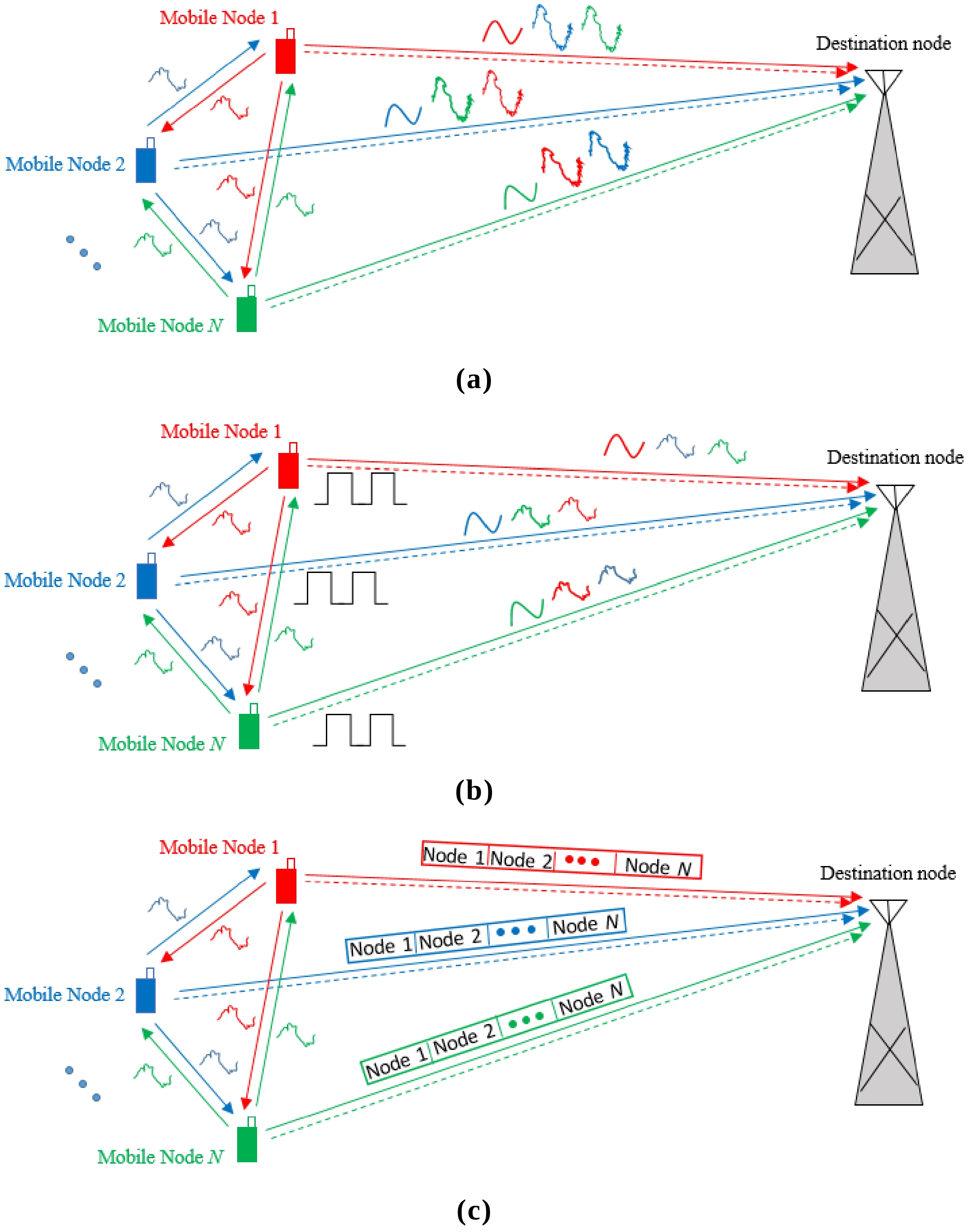

Figure 1.5: a) Amplify and forward cooperative diversity b) Decode and forward cooperative diversity c) Coded cooperation

Coded cooperation outperforms AF and DF cooperative diversity techniques by achieving significant gains even when the quality of channel between mobile nodes is worse than the uplink channel. Coded cooperation integrates channel coding and cooperative diversity. The cooperative node decodes the information of neighbouring mobile nodes. In case of successful decoding, the cooperative node generates codewords comprising a portion of their own information and a portion of the information of nearby mobile nodes. Each cooperative node follows this procedure to transmit its own information as well as the information of neighbouring mobile nodes to destination node. A full diversity order can be achieved if each cooperative node successfully decodes the information of neighbouring mobile nodes.

1.5 Literature Review

The following sub-sections show a detailed literature survey on multilevel coding scheme, cooperative diversity and coded cooperation techniques, which was carried out in order to design an efficient cooperative communication system.

1.5.1 Multilevel Coding

Massey [4] proposed an efficient digital communication system based on the concept that coding techniques are more effective when combined with suitably designed modulation scheme. The design of coded modulation system is such that the modulator can generate any of the q-ary codewords for transmission. This system provides improved error performance and coding gain.

Ungerboeck and Csajka [5] extended Massey's work by designing a trellis coded modulation (TCM) system that intends to provide coding gain and spectral efficiency without compromising data rate. It is based on optimising the Euclidean distance while mapping codewords to signal constellation. Ungerboeck [6]–[8] described a new procedure for mapping trellis codes, known as ‘set partitioning’. This involves designing the trellis codes for multilevel/phase signals such that minimum Euclidean distance is maximised. By transmitting same amount of information within same bandwidth, it was observed that TCM can provide significant coding gain in comparison to uncoded multilevel modulation. Calderbank and Mazo [9] proposed an analytical description of trellis codes which describes many practical codes simply. It combines the two steps used for designing trellis codes viz. specification of convolutional code and mapping of codewords to signal constellation. Calderbank and Sloane [10] proposed a new technique to construct trellis codes that maps the codes to a set of points in n-dimensional lattice. This technique enabled the coding theorists to use larger signal constellation and complicated lattices. Later than, researchers contributed in improving the performance of TCM by combining error-correcting codes with multidimensional signal constellations [11], [12].

Imai and Hirakawa [13] introduced another coded modulation technique known as multilevel coding that improves coding gain and spectral efficiency. It involves partitioning the information sequence into M component information sequences. Each of these component information sequences is passed through an independent error-correction encoder to generate M component codes. The symbols of component codes are combined to produce 2^M-ary symbols. These symbols are mapped to M-ary signal constellation such that minimum Euclidean distance is maximised. Finally, mapped symbols are transmitted over wireless channel. The multilevel coded symbols are decoded by a multistage decoder. The multistage decoder detects corresponding component codes by processing the received signal in multiple stages where the output of one stage is passed to subsequent stages. Imai and Hirakawa used block codes as component codes in multilevel coding scheme.

The main advantage of multilevel coding scheme over TCM is that it provides flexibility in code design as well as data transmission rate. Any error-correcting code can be used for multilevel coding of information, and coded symbols can be mapped to M-ary signal constellation using any partitioning strategy. Moreover, constellation dimensionality can be decoupled from code rate.

Ginzburg [14] extended the work of Imai and Hirakawa by using multidimensional signal constellation for mapping coded symbols in order to improve the performance of multilevel coding. Biglieri and Elia [15] introduced a class of multidimensional signals based on generalized group alphabets and examined their performance by combining with convolutional codes using Ungerboeck's scheme and block codes using Ginzburg's scheme. It was observed that transmission systems based on this technique show a good performance at the cost of modest complexity. Calderbank [16] extended multilevel coding technique to coset codes in order to design a coding scheme that is immune to Gaussian noise and resistant to impulse noise. These codes are accompanied with a multistage decoder due to its low decoding complexity. Pottie and Taylor [17] showed that any code which is designed in accordance with the partitioning of signal constellation can be combined into a multilevel code in order to reduce decoding complexity. Fazel and Ruf [18] combined multilevel coding and multiresolution modulation (MRM) [19] for digital broadcast applications and analysed its performance by optimising different parameters. This technique shows a significant coding gain and can be used to reduce emitter power or to enlarge the broadcasting area. Calderbank and Seshadri [20] proposed two different combinations of multilevel coding and modulation for unequal error protection in a bandlimited environment.

Huber and Wachsmann [21] reported that multistage decoding of multilevel codes results in predominance of errors at lowest level in the case of Ungerboeck set partitioning. In an endeavour to reduce the errors at lowest level, it was proposed that rates can be selected in accordance with the capacities of equivalent channels for different coding levels. Fischer et al. [22] emphasized the importance of information theory in designing optimal multilevel coded modulation. The code rates for different component codes are assigned by calculating capacity or random coding exponent of equivalent channels. Duan et al. [23] designed a multilevel coding scheme that approaches AWGN channel capacity by mapping the output of each encoder to an independent signal constellation. Morelos-Zaragoza [24] analysed the performance of multilevel coded modulation and multistage decoding for unequal error protection using non-standard and hybrid set partitioning of 2^M-ary modulation. Besides, theoretical upper bounds were derived for designing good multilevel coding schemes. Isaka et al. [25] investigated asymmetric signal constellations to increase the flexibility of multilevel coding scheme and multistage decoding for unequal error protection. Wachsmann et al. [26] reported that multilevel coding in combination with full maximum-likelihood decoding can be designed using a large space of rate combinations to approach capacity. But, maximum likelihood decoding is much more complex than multistage decoding. Isaka and Imai [27] proposed iterative decoding of multilevel codes due to sub-optimality of multistage decoding in some cases. The sub-optimality is caused by an increase in error multiplicity at lower stages which is further propagated to higher stages. Iterative decoding improves error performance at the cost of complexity.

The combination of multilevel codes and space-time codes further improves the performance of wireless communication. It has the capability to impart maximum possible diversity gain without bandwidth expansion. Yuan et al. [28] combined multilevel coding and multistage decoding with orthogonal space-time block codes (OSTBC) using punctured convolutional codes based on capacity rule. Yuan et al. [29] designed another structure based on the combination of multilevel coding and OSTBC for Rayleigh fading channels. It considers Bose, Chaudhuri, and Hocquenghem (BCH) codes as component codes, block partitioning technique and 8-ASK modulation. It was observed that such a structure shows same spectral efficiency but better power efficiency in comparison to multilevel coding structure without space diversity. Lampe et al. [30] designed multilevel coding with orthogonal space-time block codes as component codes based on binary partitioning of two dimensional signal constellation for the case of single transmit antenna. Martin et al. [31], [32] developed space-time multilevel codes based on multi-dimensional partitioning of $2N_t$ dimensional signal constellation in such a way that each component code spans N_t transmit antennas. In addition, space-time multistage decoder was designed that reduces the decoding complexity in comparison to space-time low density parity check code or turbo space-time code. Diggavi et al. [33] designed multilevel diversity-embedded space-time codes to support applications with different quality of service requirements. Diversity-embedded space-time codes are high-rate space-time codes having multiple levels of reliability. Chui and Calderbank [34] designed multilevel diversity-embedded space-time codes for parallel multiple-input multiple-output (MIMO) channels to implement video-broadcasting in WiMAX. Ma [35] proposed a space-time block code-spatial modulation (STBC-SM) scheme in conjunction with multilevel coding. This scheme shows an improved error performance in comparison to traditional STBC-SM for the same spectral efficiency and space diversity order.

Baghaie Abchuyeh [36] designed a new transmission scheme known as multilevel space-time trellis coding scheme. It is formed by combining multilevel codes and space-time trellis codes. Such a combination can provide high coding gain, spectral efficiency and throughput at a low decoding complexity, even for big constellations and larger number of states. Baghaie Abchuyeh et al. [37] further developed a multilevel space-time trellis coding scheme which involves grouping of transmit antennas. This scheme uses independent space-time trellis code (STTC) for each group. It transmits multiple data symbols in a time slot and provides an enhanced spectral efficiency with manageable decoding complexity.

Sharma [38] extended the work of Baghaie Abchuyeh by designing weighted multilevel space-time trellis coding scheme using channel state information (CSI) at transmitter in order to improve error performance. The transmission signals were weighted by exploiting feedback information from receiver. Jain and Sharma [39] presented another technique of improving the performance of multilevel space-time trellis codes. The generator sequences for component STTC were selected in a dynamic manner based on the current channel profile at receiver. Further, grouped multilevel dynamic space-time trellis coding scheme [40] was designed by grouping the transmit antennas to enhance spectral efficiency and error performance. Furthermore, CSI at transmitter was used to design adaptively grouped multilevel space-time trellis coding scheme [41], [42] based on adaptive grouping of transmit antennas, weighted adaptively grouped multilevel space-time trellis coding scheme [43] based on transmission weighting as well as adaptive grouping of transmit antennas, and weighted adaptively grouped multilevel dynamic space-time trellis coding scheme [44] based on transmission weighting, adaptive grouping of transmit antennas and adaptive selection of generator sequences.

1.5.2 Cooperative Diversity

The underlying idea of cooperative diversity lies in the classical relay channel. Cover and Gamel [45] studied the capacity of degraded, reversely degraded and feedback relay channels for a single sender and receiver. Willems [46] introduced the concept of partially cooperating encoders in a multiple access channel for two senders and single receiver. The partial cooperation is due to limited capacities of channels.

Sendonaris et al. [47], [48] proposed a novel user cooperation diversity technique which creates spatial diversity for single-antenna mobile users through cooperation of in-cell users. Every cell has a partner for each user. The partners receive information of each other, detect it and transmit it along with their own information. The system employing user cooperation diversity shows an increased capacity and robustness, even when the channel between users is noisy.

Laneman and Wornell [49], [50] and Laneman et al. [50] designed energy efficient cooperative transmission protocols, namely ‘amplify and forward protocol’ and ‘decode and forward protocol’ to combat multipath fading in wireless networks. In amplify and forward (AF) cooperative transmission technique, the relay estimates fading coefficient between source and relay, and scales the received signal in order to meet its average power constraint prior to transmission. Decode and forward (DF) cooperative transmission technique can be applied when signal-to-noise ratio (SNR) between source and relay is reasonably high. In this case, the relay decodes received signal and re-encodes it before transmitting to the destination.

Barbarossa and Scutari [51] derived a coding strategy that maximizes the sum of rates from cooperating mobile terminals to base station, under total available power constraint. Yuksel and Erkip [52] investigated diversity order effects for a network with single source, single destination and two amplify and forward relays. This network showed lowest error rate in comparison to direct transmission, traditional multi-hop transmission and well-known transmit diversity methods.

Sendonaris et al. [53] analysed the system based on user cooperation concept in terms of capacity, outage and coverage. The user cooperation concept was implemented to a CDMA system. It was observed that user cooperation results in an increased capacity for each user and, provides system robustness in terms of diversity gain and a low outage probability. In [54], Sendonaris et al. investigated the practical issues related to cooperation concept and observed that user cooperation is advantageous in terms of reduced sensitivity to channel variations and enhanced system throughput and coverage.

Mo and Wang [55] analysed the performance of cooperative diversity system in terms of outage probability and average symbol error probability (SEP) over random fading channels at high SNR. Diversity gain and coding gain parameters were introduced to characterize average SEP and outage probability. Nosratinia et al. [56] presented an overview of the developments in cooperative communication and reported that cooperative diversity has a promising future in wireless networks.

Laneman et al. [57] developed various low-complexity protocols for user cooperation viz. fixed cooperative schemes namely ‘amplify and forward’ and ‘decode and forward’, selection based cooperative schemes that adapt with CSI between cooperating nodes, and incremental relaying that exploits the limited feedback from destination. The performance analysis revealed that these protocols result in large power or energy savings and most of them can reduce outage probability. Nabar et al. [58] analysed the performance of various time-division multiple access based cooperative protocols which vary in degree of broadcasting and receive collision. These protocols were studied for a simple fading relay channel where the relay uses AF or DF cooperative scheme. Further, space-time codes were used for AF based relay. It was reported that full spatial diversity order can be achieved in case of appropriate power control. Ribeiro et al. [59] analysed the performance of AF cooperative diversity protocol in terms of average SEP for a system with multiple cooperating branches and multiple cooperating hops at high SNR. It was observed that error gain of multihop systems is due to lower path loss, and error gain of multibranch systems is due to lower path loss and diversity gain.

Larsson and Vojcic [60] proposed a new cooperative diversity technique based on superposition modulation and multi-user detection. With this technique, relay can transmit the received data as well as its own data to destination simultaneously. It outperforms the classical DF cooperative diversity technique by about 1.5-2 dB at same complexity. Bletsas et al. [61] proposed another cooperative transmission technique based on network path selection. It selects the best relay from a group of relays for cooperation between source and destination. Ribeiro et al. [62] developed a general framework for multi-source cooperation protocols that improves diversity and spectral efficiency in comparison to single-source cooperation, with manageable complexity. Xiao et al. [63] proposed a cooperative diversity technique based on network coding in which cooperating partners transmit algebraic superposition of its own information and relayed information to destination.

Han and Sun [64] investigated security problems in traditional cooperative transmission schemes and designed a secure cooperative transmission scheme that can manage channel estimation errors and relays' misbehaviour. This technique outperforms the traditional cooperative transmission technique under various attacks. Ding et al. [65] designed a cooperative secure transmission system that can approach zero outage probability. The relay transmission was exploited using distributed beamforming and precoding.

Ibrahim et al. [66] proposed another cooperative transmission protocol with same diversity order and high spectral efficiency in comparison to conventional cooperative scheme. The system comprises a number of DF based relays from which the optimal relay is selected on the basis of partial CSI at source and relays. The optimal relay is the one that has maximum instantaneous scaled harmonic mean function of its source-relay and relay-destination channel gains. Liang et al. [67] discussed key design issues of cooperative communication system, such as relaying candidate selection, optimal relay assignment and cooperative transmission. In addition, various numerical protocols for relay selection were analysed and compared.

Capar et al. [68] investigated the broadcast capability of nodes in a cooperative wireless network. It was observed that the broadcast performance is dependent on path loss exponent of medium. For a 1-D infinite network, the probability of broadcasting is zero when path loss exponents are greater than one and non-zero when path loss exponents are less than one.

Zhou and Zhuang [69] analysed network throughput of cooperative communication in a wireless ad-hoc network and studied the trade-off between spatial diversity gain of a single link and spatial frequency reuse of entire network. It was reported that the effectiveness of cooperation depends on link distance.

Korn et al. [70] considered a two-dimensional user distribution scenario to investigate the power saving potential of cooperative communication. For the same SNR at base station, the average transmit power of cooperative transmission and conventional communication were compared. It was observed that power savings per user in a cooperative transmission system increases with an increase in path loss exponent and number of users in the circular cell. Ling et al. [71] proposed an optimal power allocation algorithm for cooperative beamforming networks that outperforms the conventional techniques in terms of energy saving.

Yu et al. [72] proposed an efficient cooperative transmission technique for two user cooperative systems, that achieves signal space diversity using rotated constellation. This technique performs better than the conventional cooperative scheme based on orthogonal signalling when the inter-user channel quality is low.

1.5.3 Coded Cooperation

Hunter and Nosratinia [73] introduced a novel user cooperation scheme for wireless networks, termed as ‘coded cooperation’. It is the combination of channel coding technique and cooperation. The codewords transmitted by cooperative users consist of a portion of their own information and that of other user. The partner transmits the information of other user only when it is decoded correctly. The performance analysis was done for a system with two users having uplink channels of different quality and a common base station. It was observed that a significant gain can be achieved with coded cooperation where each user is benefitted even if the quality of inter-user channel is worse than the uplink channels.

Hunter and Nosratinia [74] further investigated the effects of coded cooperation in slow and fast Rayleigh fading scenarios where the quality of users’ uplink channels is either similar or different. The coded cooperation in slow Rayleigh fading scenario shows a significant improvement even when the inter-user channel is worse, and outperforms AF based cooperative diversity scheme by 1-2 dB. The effects of conventional power control was also analysed for slow Rayleigh fading and it was reported that it fails to allocate the system resources in an optimal manner. Besides, coded cooperation in fast Rayleigh fading scenario improves the performance of user with poorer uplink channel and fails to improve the performance of user with better uplink channel. In [75], [76], Hunter and Nosratinia evaluated the performance of coded cooperation analytically and through simulations by developing tight bounds for bit and block error probabilities. It was observed that coded cooperation can achieve maximal diversity. Stefanov and Erkip [77] designed channel codes capable of achieving full diversity order in a cooperative environment and reported that cooperative coding provides a significant improvement in performance over non-cooperative scheme even when the inter-user channel is noisy.

Laneman and Wornell [78] developed space-time coded cooperative diversity protocol that can achieve full spatial diversity order and higher spectral efficiency in wireless networks. In this protocol, the relay decodes received signal of other user and encodes it using space-time coding before transmitting to the destination.

Janani et al. [79], [80] analysed space-time user cooperation protocol and turbo-coded user cooperation protocol in both slow and fast frequency non-selective fading channels. The performance analysis revealed that full diversity order can be achieved when both users cooperate in slow fading scenario, and higher diversity order in comparison to coded cooperation can be achieved in fast fading scenario. Liu et al. [81] examined user cooperation using punctured turbo codes for a strict decoding delay constraint over quasi-static fading channel. The frame error rate (FER) performance evaluations indicated that cooperative turbo codes show the expected diversity gain in case of good inter-user channel quality. Wang et al. [82] designed a user cooperation protocol based on differential space-time coding scheme when CSI is not available at receiver. The performance analysis was done in terms of diversity gain and diversity product for two users which indicated that this protocol is effective.

Shalvi [83] proposed a new cooperative diversity technique known as ‘multi-source cooperation’ which works by encoding the data from multiple users jointly by one or more cooperating users. It shows higher diversity gain and higher data rates in comparison to single-source coded cooperative diversity technique. Stefanov and Erkip [84] designed a cooperative transmission technique in which cooperative users having multiple antennas use space-time coding. It can achieve full diversity provided by user cooperation and a reduced error rate even for poor quality inter-user channel.

Hunter et al. [85] performed the outage probability analysis of coded cooperation technique for two users which confirms that this technique can achieve full diversity in terms of number of cooperative users. Moreover, it shows that coded cooperation is different from DF based cooperation as the diversity order of latter technique is one. Chen et al. [86] investigated the effect of network coding for user cooperation. It was reported that network coding leads to additional diversity gains with an increase in the number of cooperative users.

Chen et al. [87] performed the comparison of AF, DF and coded cooperation techniques for a convolutional coded system. Coded cooperation outperforms AF and DF cooperation and AF outperforms DF cooperation. Apart from this, two important parameters were determined to analyse the performance of coded cooperation viz. percentage of cooperation and distributed effect for transmitted symbols.

Dayal and Varanasi [88] designed distributed QAM based space-time block coded symbols to enable the single antenna cooperative users in a wireless network to achieve maximum diversity order. Additionally, two coded cooperation schemes were proposed viz. two-phase cooperative scheme and self-information cancelling linear (SCL) scheme that utilises cooperation rule to decide whether a relay cooperates or not. The two-phase scheme has low decoding complexity in comparison to SCL scheme, but SCL scheme shows a better performance.

Yilmaz and Yilmaz [89] proposed a multilevel coded cooperative system using orthogonal signalling in a wireless vehicular network. The performance analysis revealed that multilevel coded cooperative system for two single-antenna users with a perfect inter-user channel shows similar performance to non-cooperative multilevel coded system with two transmit antennas for the same bandwidth and a little increase in complexity.

Zhang and Hanzo [90] proposed a superposition coding (SPC) scheme and a physical layer algebraic network coding (PANC) scheme for multi-source cooperation. Both schemes perform close to the best possible outage probability bound and maintains the same throughput and delay. PANC shows lower complexity in comparison to SPC scheme but at the cost of slight degradation in performance.

Ng et al. [91] presented turbo-trellis coded modulation scheme for cooperative communication which is both power and bandwidth efficient. Yang and Yuan [92] designed a novel superposition modulation based cooperative transmission scheme with iterative decoding. It performs better than the previously proposed cooperative transmit diversity scheme based on superposition modulation in a quasi-static fading environment. Choi et al. [93] proposed a bit-interleaved coded multilevel modulation scheme for non-orthogonal cooperative system which can outperform the conventional cooperation schemes by selecting the appropriate mapping pattern, power scaling and iterative equalization.

Ishibashi et al. [94] presented a dynamic coded cooperation protocol using multiple turbo codes for wireless relay networks which can achieve full diversity order. The relay and destination are fitted with a sensing device, with the help of which relay decides whether it should cooperate or not. Duyck et al. [95] investigated coded cooperation technique using low-density parity-check (LDPC) coding and iterative decoding for block fading relay channels. For two cooperative users, this technique shows near outage limit performance. Norouzi et al. [96] proposed a new version of cooperative diversity technique using embedded space-time coding scheme that performs better than the cooperative diversity technique. The embedded space-time codes were devised by utilising singular value decomposition of circulant matrix.

Li et al. [97] performed an outage probability analysis of coded cooperation system having multiple relays in Rayleigh fading channels. It was observed that diversity gain increases and outage probability reduces with an increase in number of relays, but at the expense of approximately linearly increased complexity.

Ishii et al. [98], [99] proposed a new cooperation protocol based on multilevel coded modulation. The multilevel codes are combined with multistage decoding to provide high spectral efficiency and large coding gain for multiple cooperating nodes with reduced decoding complexity. Each cooperating node utilizes multilevel coding scheme with convolutional codes as component codes to encode its own information and the decoded information of other nodes.

1.6 Problem Formulation

The number of wireless users are increasing day by day, which generates the demand for high data rate, coverage, spectral efficiency and low outage. Currently, the next generation viz. 5G communication systems aim to connect billions of wireless devices. This requires an innovation in the current wireless technology. In this research work, multilevel coding scheme in conjunction with cooperative diversity is investigated in an endeavour to meet these requirements.

Multilevel coding scheme has the potential of providing flexible data transmission rate, coding gain and improved spectral efficiency. Since, the multilevel signals are prone to channel noise, therefore, these are accompanied with suitable error-correcting codes to generate efficient communication systems. The multilevel coding scheme usually involves multistage decoding for the detection of information because of its low decoding complexity.

Cooperative diversity technique is capable of providing diversity gain, better error performance, improved coverage, lower latency, greater reliability of data reception and reduction in outage probability. It creates virtual transmit diversity in single antenna mobile users through mutual cooperation and combats the effects of multipath fading.

Most of the cooperative transmission protocols investigated by researchers fall under TD cooperation protocol and SS cooperation protocol. These protocols are not suitable for multiple cooperative users. Recently, a new cooperation protocol is introduced to overcome the drawbacks of TD and SS cooperation protocol. It uses multilevel coding scheme at each mobile node to transmit the information of nodes to a common destination node in a cooperative manner. So far, the research has been done for a system that uses multilevel coding scheme with convolutional codes as component codes at each cooperative node. This implies that each cooperative node processes its own information as well as the information of other nodes through a set of convolutional encoders. The self-information of each node is processed at the highest level, where self-information is the node's own information. The coded symbols generated by the set of convolutional encoders are mapped to pulse amplitude modulation (PAM) constellation using a modified mapping pattern based on exhaustive search to find the optimum mapping function. The destination node receives the symbols transmitted by each cooperative node and employs multistage decoder with a maximum a posteriori (MAP) decoder at each stage to detect the information of each node. This multilevel coded cooperation system enhances the cooperation probability, spectral efficiency and provides a flexible code design without exponential increase in receiver complexity.

To the best of our knowledge, such a multilevel coded cooperation system has not been investigated yet for other error-correcting codes apart from convolutional codes. In this research work, we have proposed a novel cooperative communication system based on multilevel coding scheme that is less complex than the existing system. We have further investigated the proposed cooperative multilevel coding system for various error-correcting codes such as convolutional codes, pseudo space-time trellis codes (PSTTC), weighted space-time trellis codes (WSTTC), and dynamic space-time trellis codes (DSTTC). These codes show a remarkable performance in improving the quality of service by reducing error rate and outage probability.

1.7 Research Objectives

The objectives for research work are as follows:

- To design a system model by superimposing multilevel coding with cooperative diversity scheme for improved system performance.
- To perform the analysis of proposed system by using various component codes for its evaluation.

1.8 Thesis Outline

The structure of thesis is as follows:

- **Chapter one** presents motivation for research, detailed explanation of multilevel coding scheme and cooperative diversity including literature review, problem formulation, objectives of research, and organization of thesis.
- **Chapter two** deals with the design and analysis of cooperative communication system based on multilevel convolutional codes. It describes the proposed system model, transmission and reception procedure, performance analysis of system and complexity considerations.
- **Chapter three** deals with the design and analysis of cooperative communication system based on multilevel pseudo space-time trellis codes. It analyses the proposed system model both analytically and through simulations. In addition, it discusses the complexity considerations.
- **Chapter four** deals with the design and analysis of cooperative communication system based on multilevel weighted space-time

trellis codes. It describes the proposed system model in detail which includes encoding and transmission weighting at cooperative node and decoding at destination node. It also includes the performance analysis of system and its complexity considerations.

- **Chapter five** deals with the design and analysis of cooperative communication system based on multilevel dynamic space-time trellis codes. It discusses the transmitter and receiver structure of proposed system, system performance and complexity considerations.
- **Chapter six** concludes the research work and presents future scope for further research.

1.9 Summary of the Chapter

In this chapter, we established the background for research in multilevel coding and cooperative diversity. An overview of multilevel coding scheme and cooperative diversity is given which forms the basis for designing the proposed system. The encoding and decoding mechanism of a system using multilevel coding scheme is discussed. The mechanism of various cooperative diversity techniques are discussed and the advantage of coded cooperation is highlighted. An extensive literature survey was carried out to acquire complete knowledge about the current scenario of these technologies. The limitations of existing techniques were highlighted and the objectives for current research were established.

Chapter 2

Cooperative Communication System based on Multilevel Convolutional Codes

Contents

2.1 Introduction

Cooperative diversity is a virtual form of transmit diversity created by single-antenna mobile users that share their antennas for information transmission. It is based on the following principles. The broadcast nature of wireless medium enables multiple users in a network to hear most of the transmissions without requiring additional transmission power and bandwidth. The channel fading statistics between different mobile users and base station are independent. The base station can listen, store and combine signals from different mobile users [100]. A number of techniques given by research community describe the mechanism of user to user cooperation. The transmitting user broadcasts its information to a collection of neighbouring users. The cooperative users can be selected based on their distance from base station [101], mean signal to noise ratio to base station [102] or, partial channel state information [66]. Cooperative diversity provides system robustness in terms of enhanced diversity gain and reduced outage probability. Additionally, it helps in enhancing cell coverage, system throughput and reducing sensitivity to channel variations.

In this chapter, a novel cooperative communication system based on multilevel coding scheme with convolutional codes as component codes, is proposed. Multilevel coding scheme processes the information in levels. There is an encoder at each level that generates error-correcting code. These error-correcting codes are mapped to M-QAM constellation using MRM partitioning and transmitted to base station. The cooperative diversity, when implemented with multilevel coding scheme at mobile users proves beneficial in terms of enhanced cooperation probability, spectral efficiency and flexible code design without exponential increase in receiver complexity.

2.2 Convolutional Codes

Convolutional codes [103]–[105] are generated by processing the data bits through a linear finite-state shift register with K stages and k bits per stage, as shown in figure 2.1. Here, the number of stages in a shift register, K is termed as constraint length. The k-bit data is converted into n-bit coded symbol by using n modulo-2 adders based on n generator polynomials. The generator polynomials are constructed by taking inputs from K stages. At a time, the data is shifted by k bits into each stage and each shift generates n bit coded symbol. Therefore, rate of code is k/n. A convolutional code is commonly specified by (n, k, K). Since the current coded symbol is dependent on kK bits rather than k input bits, it indicates that convolutional codes have memory. The state of convolutional encoder is given by K-1 stages of shift register other than the first stage. In all, a convolutional encoder can have 2^{K-1} states.

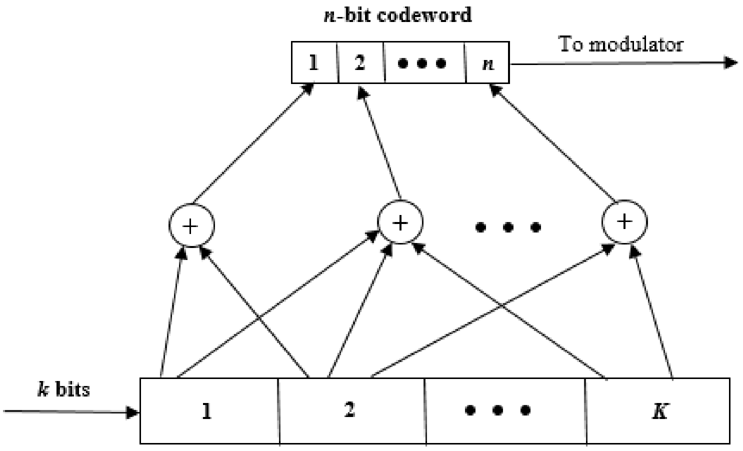

Figure 2.1: Convolutional Encoder

Generally, a convolutional code can be represented in three ways - state diagram, tree diagram and trellis diagram [106]. A state diagram depicts all the states, possible state transitions and corresponding outputs of convolutional encoder. A tree diagram is in the form of a tree with as many unique branches as there are number of states in convolutional encoder. Each branch represents a different state and the corresponding output. A trellis diagram is the most commonly used representation of convolutional code because it represents the time sequencing of events linearly. The time is represented by x-axis and possible states are represented by y-axis. As the time passes, each state is connected to next state for all the possible codewords for that state.

So far, the best procedure to decode a convolutional code is Viterbi algorithm [107], [108]. A Viterbi decoder is based on maximum likelihood principle. It examines the entire received coded sequence and calculates metric for 2^k trellis paths entering each node. Usually, Hamming distance and Euclidean distance metrics are used, which compare the received codeword with the allowable codeword. In case two paths converge at one node, the higher metric path is carried forward and lower metric path is discarded. The selected paths are known as surviving paths. In all, there are $2^{k(K-1)}$ valid surviving paths. Once, the surviving paths are obtained, an estimated value of actual information can be generated. The error-correcting capability of a convolutional code is given by $\lfloor (d_{free} - 1)/2 \rfloor$, where d_{free}, called free distance, is minimum Hamming distance of all the paths through trellis to all zero path.

2.3 System Model of Cooperative Multilevel Coding

Figure 2.2 shows the model of proposed cooperative multilevel coding system. The proposed system considers N single antenna mobile users that transmit information to a common base station B. It is assumed that users are chip synchronized and cooperate with each other by sharing their antennas. The amount of interference caused by other non-cooperative users is negligible and considered as background noise [54]. Each cooperative user receives the coded information transmitted by other users to base station, decodes it and further encodes it along with its own information. The decoding of other users' information can be done using Viterbi decoder. The encoding is done using multilevel coding scheme with convolutional codes as component codes. The decoded information of other users and self-information of cooperative user are passed through a set of convolutional encoders. The coded symbols are mapped to M-QAM constellation using MRM partitioning. Section 2.4 describes multilevel coding of information at each cooperative user in detail. Each cooperative user transmits multilevel coded symbols of its own information as well as that of other users to base station. The coded symbols transmitted by each user experience independent Rayleigh fading. The base station receives the information of each user multiple times. Thus, a virtual spatial diversity namely cooperative diversity is created by single antenna mobile users. It is assumed that the base station has perfect channel state information which can be possible when the channel parameters are not rapidly time-varying. For this, quasi-static flat fading channel is considered. The channel information can be sent to cooperative users through a feedback link in order to decode the information sent by other users correctly. The information of each user is detected by a multistage

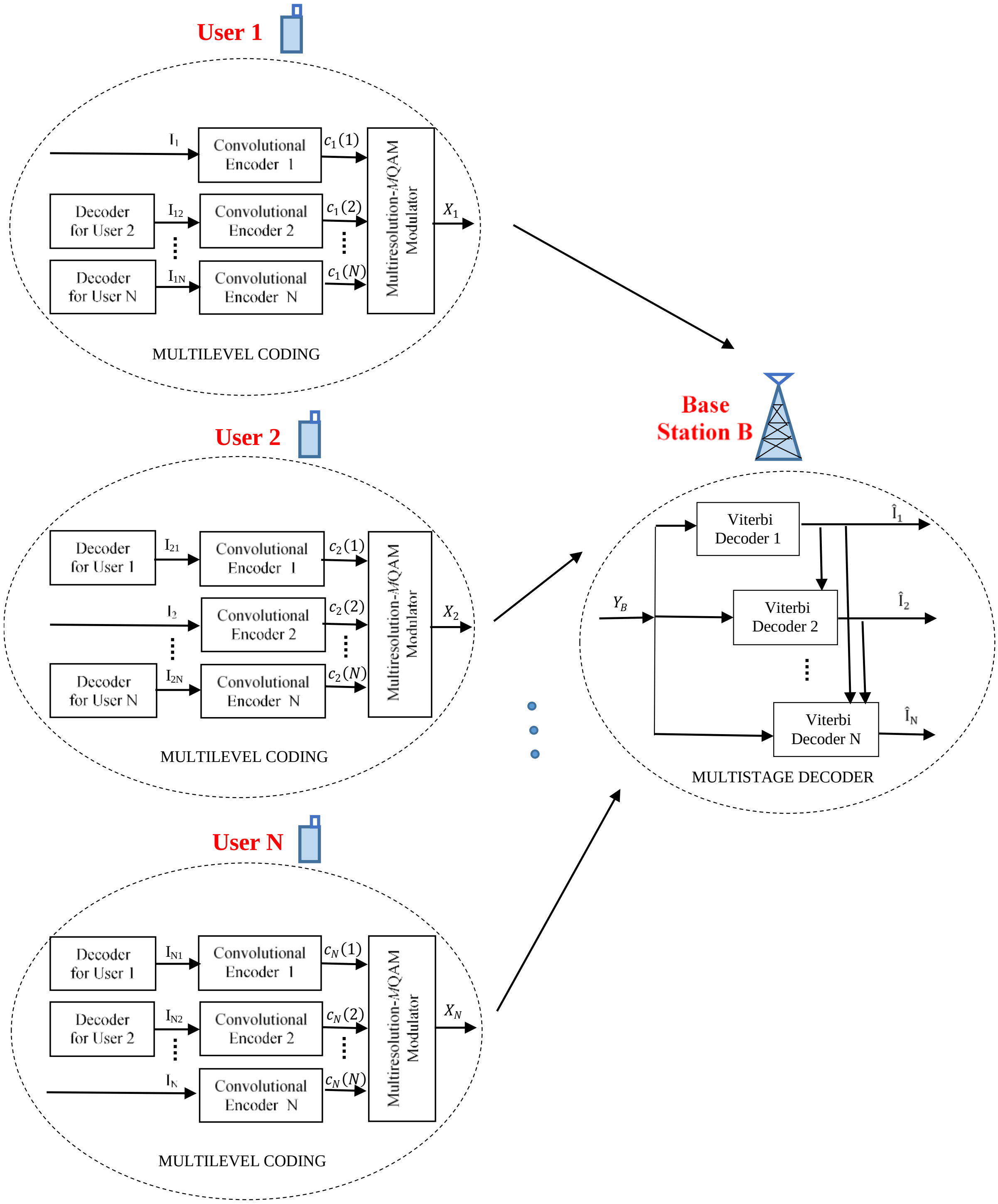

Figure 2.2: System model of cooperative communication using multilevel coding scheme with convolutional codes as component codes

decoder at base station. Section 2.5 describes the information received at base station from cooperative users and decoding procedure followed to detect the information of each user.

2.4 Transmission Process at Cooperative User

The information at cooperative user u (u=1,2,…,N) is processed in L levels. In general, the number of levels, L can be greater than or equal to number of cooperative users, N [99]. In order to reduce complexity, the proposed system considers L to be equal to N. Out of L levels, level u comprises self-information, I_u of user u and remaining L-1 levels comprise the decoded information, I_{uv} of nearby users' v (v=1,2,…,N and $v \neq u$) such that level v comprises the information of user v. There is a rate ½ convolutional encoder at each level of cooperative user that encodes the information available at the respective level. The convolutional encoder k (k=1,2,…,N) generates coded symbols $c_u(k)$ represented as

$$c_u(k) = c^1(x)\, c^2(x) \tag{2.1}$$

where,

$$c^1(x) = (x + x^2)\, I(x) \tag{2.2}$$

$$c^2(x) = (1 + x + x^2)\, I(x) \tag{2.3}$$

The coded symbols are mapped to M-QAM constellation using MRM partitioning. The MRM partitioning of M-QAM constellation involves L resolutions such that $M = 4^L$. The M points in signal constellation are partitioned into 4 clusters of points spaced by certain distance Δ_1. Each of these 4 clusters is further partitioned into 4 sub-clusters of points spaced by certain distance Δ_2. This process is repeated until each sub-cluster is partitioned into 4 constellation points at level L. The clusterization procedure considers each cluster as 4-QAM constellation. This enables the use of convolutional codes designed for 4-QAM at each level. The coded information at first level is mapped to clusters. The coded information at subsequent levels are mapped to sub-clusters. Finally, the coded information at level L (=N) is mapped to constellation points. Each point of M-QAM constellation, denoted by X_u can be represented as

$$X_u = \mathit{\Delta}_1 c_u(1) + \mathit{\Delta}_2 c_u(2) + \cdots + \mathit{\Delta}_N c_u(N)\,; u = 1,2,\dots,N \tag{2.4}$$

where, $\mathit{\Delta}_1,\dots,\mathit{\Delta}_N$ are cluster distances associated with $c_u(1),\dots,c_u(N)$. Therefore, cooperative user u transmits multilevel coded symbol X_{ut} at time t.

$$X_{ut} = \sum_{k=1}^{N} \mathit{\Delta}_k\, c_{ut}(k)\,; u = 1,2,\dots,N \tag{2.5}$$

Equation (2.5) can be expressed in matrix form as

$$[X_{1t}\; X_{2t} \dots X_{Nt}] = [\mathit{\Delta}_1 \quad \mathit{\Delta}_2 \quad \cdots \quad \mathit{\Delta}_N]\begin{bmatrix} c_{1t}(1) & c_{2t}(1) & \cdots & c_{Nt}(1) \\ c_{1t}(2) & c_{2t}(2) & \cdots & c_{Nt}(2) \\ \vdots & \vdots & \ddots & \vdots \\ c_{1t}(N) & c_{2t}(N) & \cdots & c_{Nt}(N) \end{bmatrix} \tag{2.6}$$

In compact form, equation (2.6) can be represented as

$$\boldsymbol{X}_t = \boldsymbol{\Delta C_t} \tag{2.7}$$

where,

$\boldsymbol{X}_t = [X_{1t}\; X_{2t} \dots X_{Nt}]$ represents multilevel coded symbols transmitted by cooperative users 1,2,…,N.

$\boldsymbol{\Delta} = [\mathit{\Delta}_1 \quad \mathit{\Delta}_2 \quad \cdots \quad \mathit{\Delta}_N]$ represents cluster distances at partitioning levels 1,2,…,N , and

$$\boldsymbol{C_t} = \begin{bmatrix} c_{1t}(1) & c_{2t}(1) & \cdots & c_{Nt}(1) \\ c_{1t}(2) & c_{2t}(2) & \cdots & c_{Nt}(2) \\ \vdots & \vdots & \ddots & \vdots \\ c_{1t}(N) & c_{2t}(N) & \cdots & c_{Nt}(N) \end{bmatrix} \tag{2.8}$$

In matrix $\boldsymbol{C_t}$, the columns represent information processed at levels 1,2,…,N for a particular cooperative user u (u=1,2,…,N). Example: first column represents the information processed at cooperative user 1 at levels 1 to N. The rows represent information processed at a particular level for cooperative users 1,2,…,N. Example: first row represent the information processed at level 1 at cooperative users 1 to N. For simplicity, it is considered that each cooperative user performs error-free decoding of other users' information. Therefore, the proposed system considers user 1's information at level 1, user 2's information at level 2 and so on with user N's information at level N for each cooperative user. This implies

$$c_{1t}(k) = c_{2t}(k) = \cdots = c_{Nt}(k) = c_t(k)\,; k = 1,2,\dots,N \tag{2.9}$$

Considering equation (2.9), the matrix $\boldsymbol{C_t}$ in (2.8) becomes

$$\boldsymbol{C_t} = \begin{bmatrix} c_t(1) & c_t(1) & \cdots & c_t(1) \\ c_t(2) & c_t(2) & \cdots & c_t(2) \\ \vdots & \vdots & \ddots & \vdots \\ c_t(N) & c_t(N) & \cdots & c_t(N) \end{bmatrix} \tag{2.10}$$

Therefore, equation (2.6) can be represented as

$$[X_{1t}\, X_{2t} \ldots X_{Nt}] = [\Delta_1 \quad \Delta_2 \quad \cdots \quad \Delta_N] \begin{bmatrix} c_t(1) & c_t(1) & \cdots & c_t(1) \\ c_t(2) & c_t(2) & \cdots & c_t(2) \\ \vdots & \vdots & \ddots & \vdots \\ c_t(N) & c_t(N) & \cdots & c_t(N) \end{bmatrix} \tag{2.11}$$

2.5 Reception Process at Base Station

The multilevel coded symbols transmitted by each cooperative user to base station experience independent Rayleigh fading which is quasi-static and frequency non-selective. The base station receives a noisy superposition of independent Rayleigh faded signals transmitted by cooperative users. In Rayleigh fading, scatterers present in the vicinity of mobile users eliminate the line of sight between mobile users and base station, and the signal transmitted by mobile users gets scattered along multiple paths before it arrives at base station. This necessitates the use of multiple antennas at base station to create receive diversity in order to improve the quality and reliability of wireless link. The multiple receive antennas enable the base station to obtain several observations of same signal. Since, each antenna receives an independently faded copy of same signal, therefore, it is likely that if one antenna is experiencing a deep fade, other antenna has an adequate signal.

The signal received at r-th receive antenna of base station at time t, denoted by Y_t^r is given as

$$Y_t^r = \sum_{u=1}^{N} h_{ru} X_{ut} + n_t^r \,; r = 1,2, \ldots, N_r \tag{2.12}$$

where, h_{ru} is fading coefficient between user u and r-th receive antenna of base station, n_t^r is additive white Gaussian noise (AWGN) at r-th receive antenna of base station.

Equation (2.12) can be represented in matrix form as

$$\begin{bmatrix} Y_t^1 \\ Y_t^2 \\ \vdots \\ Y_t^{N_r} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & h_{22} & \cdots & h_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN} \end{bmatrix} \begin{bmatrix} X_{1t} \\ X_{2t} \\ \vdots \\ X_{Nt} \end{bmatrix} + \begin{bmatrix} n_t^1 \\ n_t^2 \\ \vdots \\ n_t^{N_r} \end{bmatrix} \tag{2.13}$$

In compact form, equation (2.13) can be represented as

$$\boldsymbol{Y}_t = \boldsymbol{H_t X_t^T} + \boldsymbol{n_t} \tag{2.14}$$

where,

$\boldsymbol{Y}_t = \begin{bmatrix} Y_t^1 & Y_t^2 & \cdots & Y_t^{N_r} \end{bmatrix}^T$ represents the signals received at antenna 1,2,..., N_r at base station.

$$\boldsymbol{H_t} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & h_{22} & \cdots & h_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN} \end{bmatrix} \tag{2.15}$$

In channel matrix $\boldsymbol{H_t}$, the columns represent fading coefficients between a particular cooperative user and receive antennas 1,2,..., N_r at base station. Example: first column represents fading coefficients between cooperative user 1 and receive antennas 1 to N_r. The rows represent fading coefficients between a particular receive antenna and cooperative users 1,2,...,N. Example: first row represents the fading coefficients between receive antenna 1 and cooperative users 1 to N.

$\boldsymbol{n_t} = \begin{bmatrix} n_t^1 & n_t^2 & \cdots & n_t^{N_r} \end{bmatrix}^T$ represents the noise associated with receive antennas 1,2,..., N_r at base station.

Substituting equation (2.7) in equation (2.14),

$$\boldsymbol{Y}_t = \boldsymbol{H_t C_t^T \varDelta^T} + \boldsymbol{n_t} \tag{2.16}$$

Equation (2.16) can be represented in matrix form as follows

$$\begin{bmatrix} Y_t^1 \\ Y_t^2 \\ \vdots \\ Y_t^{N_r} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & h_{22} & \cdots & h_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN} \end{bmatrix} \begin{bmatrix} c_t(1) & c_t(2) & \cdots & c_t(N) \\ c_t(1) & c_t(2) & \cdots & c_t(N) \\ \vdots & \vdots & \ddots & \vdots \\ c_t(1) & c_t(2) & \cdots & c_t(N) \end{bmatrix} \begin{bmatrix} \varDelta_1 \\ \varDelta_2 \\ \vdots \\ \varDelta_N \end{bmatrix} + \begin{bmatrix} n_t^1 \\ n_t^2 \\ \vdots \\ n_t^{N_r} \end{bmatrix} \tag{2.17}$$

In equation (2.17), $\boldsymbol{H_t}$ shows the use of multiple receive antennas at base station to receive multiple copies of same signal in order to create receive diversity, $\boldsymbol{C_t}$ shows the transmission of each user's information N times through cooperative users 1 to N in order to create virtual transmit diversity. The combination of cooperative diversity created by single antenna mobile users and receive diversity created by multiple antennas at base station plays a significant role in mitigating the detrimental effects of multipath fading. From equation (2.17), the signal received at r-th receive antenna of base station can be represented as,

$$Y_t^r = \sum_{u=1}^{N} h_{ru} \left(\sum_{k=1}^{N} \Delta_k \, c_t(k) \right) + n_t^r \, ; r = 1,2, \dots, N_r \tag{2.18}$$

or,

$$Y_t^r = \sum_{u=1}^{N} \sum_{k=1}^{N} h_{ru} \, \Delta_k c_t(k) + n_t^r \, ; r = 1,2, \dots, N_r \tag{2.19}$$

2.5.1 Multistage Decoding at Base Station

The received signal at base station, Y_t is passed through a multistage decoder to detect the information of each user. The multistage decoder consists of N stages with a Viterbi decoder at each stage. The Viterbi decoder computes branch metrics for a data frame by executing a search based on maximising the likelihood function. Firstly, the output of first component code, c(1) is decoded. The Viterbi decoder at stage 1 gives the estimated value of user 1's information i.e., $\hat{c}(1)$. The estimate $\hat{c}(1)$ is passed to decoding stages 2,…,N. The Viterbi decoder at stage 2 decodes the output of second component code, c(2) by using the estimate $\hat{c}(1)$. The estimate $\hat{c}(2)$ at second stage is passed to decoding stages 3,…,N. The similar decoding procedure is followed for decoding stages 3,…,N. Finally, the Viterbi decoder at stage N decodes the output of component code c(N) using estimates $\hat{c}(1), \dots, \hat{c}(N-1)$ to give the estimated value of user N's information i.e., $\hat{c}(N)$. The conditional PDF of received signal, Y_{Bt} conditioned on channel matrix H_t and output of N encoders is

$$P(Y_t | c_t(1), \dots, c_t(N), H_t) \tag{2.20}$$

The decoding operation followed at each stage of multistage decoder is explained in the following sub-sections.

2.5.1.1 ***Decoding operation at stage* 1:** The Viterbi decoder at stage 1 executes a search based on maximising the likelihood function over hypothesized value of c(1). Since stage 1 decoder has no knowledge of the values c(2),…,c(N), therefore, it considers them as nuisance variables and average them out. Based on (2.20), the conditional PDF is

$$P(Y_t|c_t(1),H_t) = \sum_{\substack{c_t(k)\\ k=2,\dots,N}} P(c_t(2),\dots,c_t(N)|c_t(1),H_t)\,P(Y_t|c_t(1),c_t(2),\dots,c_t(N),H_t) \qquad (2.21)$$

It is assumed that the convolutional encoder at each level is independent. This implies that $c_t(1), c_t(2), \dots, c_t(N)$ are mutually independent. It is also assumed that the channel is independent of component codes and the probability of transmitting $c_t(k)$; k=1,2…N is same. Therefore, first term in the right hand side of equation (2.21) reduces to a constant. This term can be ignored while maximizing the likelihood function. Considering equation (2.19), second term in the right hand side of equation (2.21) becomes

$$P(Y_t|c_t(1),c_t(2),\dots,c_t(N),H_t) = \frac{1}{\sqrt{2\pi\sigma_n^2}} exp\left(\sum_{r=1}^{N_r} \frac{|Y_t^r - \sum_{u=1}^{N}\sum_{k=1}^{N} h_{ru}\Delta_k c_t(k)|^2}{2{\sigma_n}^2}\right) \qquad (2.22)$$

Substituting equation (2.22) in (2.21) and ignoring constant term, the likelihood function can be represented as

$$L\big(x_t(1)\big) = P(Y_t|c_t(1),H_t) \propto \sum_{\substack{c_t(k)\\ k=2,\dots,N}} exp\left(\sum_{r=1}^{N_r} \frac{\left|Y_t^r - \sum_{u=1}^{N}\sum_{k=1}^{N} h_{ru}\Delta_k c_t(k)\right|^2}{2{\sigma_n}^2}\right) \qquad (2.23)$$

Taking logarithm of above equation, the branch metric is obtained.

$$L\big(x_t(1)\big) = log\left(\sum_{\substack{c_t(k)\\ k=2,\dots,N}} exp\left(\sum_{r=1}^{N_r} \frac{|Y_t^r - \sum_{u=1}^{N}\sum_{k=1}^{N} h_{ru}\Delta_k c_t(k)|^2}{2{\sigma_n}^2}\right)\right) \qquad (2.24)$$

The branch metric complexity can be reduced by using max-log approximation [36], which states

$$log \sum_j \exp a_j = \max_j a_j \qquad (2.25)$$

Considering the above approximation, equation (2.24) becomes

$$L\big(x_t(1)\big) = \max_{\substack{c_t(k)\\ k=2,\dots,N}} \sum_{r=1}^{N_r} |\, Y_t^r - \sum_{u=1}^{N}\sum_{k=1}^{N} h_{ru}\,\Delta_k c_t(k)\,|^2 \qquad (2.26)$$

The branch metrics in equation (2.26) are used to obtain the estimated information of first component code i.e., $\hat{c}(1)$. Thus, the information of user 1 is detected.

2.5.1.2 ***Decoding operation at stage s*****:** The Viterbi decoder at stage s ($1<s<N$) executes a search based on maximising the likelihood function by considering hypothesized value of c(s). The estimates of stages 1 to s-1 are taken into account. Stage s decoder has no knowledge of the values c(s+1),…,c(N), therefore, it considers them as nuisance variables and average them out. The branch metric at stage s is

$$L\big(x_t(s)\big) = \max_{\substack{c_t(k)\\ k=s+1,\ldots,N}} \sum_{r=1}^{N_r} \Big| Y_t^r - \sum_{k=s}^{N} \sum_{u=1}^{N} h_{ru}\, \mathit{\Delta}_k c_t(k) - \sum_{u=1}^{N} \sum_{p=1}^{s-1} h_{ru}\, \mathit{\Delta}_p \hat{c}_t(p) \Big|^2 \tag{2.27}$$

where, $\hat{c}_t(p)$ is the estimated information by decoder at stage p. The branch metrics in equation (2.27) are used to obtain the estimated information of component codes at levels 2 to N-1 i.e., $\hat{c}(2), \ldots, \hat{c}(N-1)$. Thus, the information of users 2 to N-1 are detected.

2.5.1.3 ***Decoding operation at stage N*****:** Finally, the Viterbi decoder at stage N uses estimates $\hat{c}(1), \ldots, \hat{c}(N-1)$ to find the estimated information of component code at level N i.e., $\hat{c}(N)$. The branch metric at stage N is

$$L\big(x_t(N)\big) = log\left(exp\Big(\sum_{r=1}^{N_r} \Big| Y_t^r - \sum_{u=1}^{N} h_{ru}\, \mathit{\Delta}_N c_t(N) - \sum_{u=1}^{N} \sum_{p=1}^{N-1} h_{ru}\, \mathit{\Delta}_p \hat{c}_t(p) \Big|^2\Big)\right) \tag{2.28}$$

The branch metrics in equation (2.28) are used to obtain $\hat{c}(N)$. Thus, the information of user N is detected.

2.6 Theoretical Analysis of System Performance

In this section, a theoretical analysis of system performance is done by considering arbitrary number of cooperative users. Consider the case when user 1’s information is transmitted by user 1 itself and other cooperative users 2,…,N to base station B. This implies that users 2,…,N act as relay nodes for the transmission of user 1’s information. Thus, the information of user 1 is transmitted through N independent fading paths to base station.

Let the channel power on i-th fading path be $\alpha_i = |h_{iD}|^2$; i=1,...,N and it is modelled as a Gaussian random variable with zero mean and unit variance. Since channel fading is assumed to be quasi-static (slowly varying) and frequency non-selective (flat), the error probability for a modulation scheme can be obtained by averaging its error probability in a time-invariant channel over the fading distribution. The error probability of M-QAM in a time-invariant channel is given by [104]

$$P_M = 1 - \left[2\left(1-\frac{1}{\sqrt{M}}\right).Q\left(\sqrt{\left(\frac{3}{M-1}\right).SNR_{av}}\right)\right]^2 \tag{2.29}$$

where, $SNR_{av} = E_{av}/N_o$ is average symbol energy to noise ratio. The average error probability for the transmission of user 1's information through N independent fading paths can be expressed as

$$P_e = \int_0^\infty \left[1 - \left[2\left(1-\frac{1}{\sqrt{M}}\right).Q\left(\sqrt{\left(\frac{3}{M-1}\right).\sum_{i=1}^{N} y_i}\right)\right]^2\right] f_\Sigma\,(\alpha)d\alpha \tag{2.30}$$

where, y_i is a random variable representing receive SNR at base station on i-th path; $f_\Sigma\,(\alpha)$ is probability density function (PDF) of $\sum_{i=1}^{N} y_i$. Since the fading paths from cooperative users to base station are independent, PDF of $\sum_{i=1}^{N} y_i$ can be obtained by the method of moment generating function. The unconditional PDF, $f_{y_i}(\alpha)$ represents i-th path to base station. In case of erroneous user-to-user transmission, the relay node may incorrectly decode the information of transmitting user. Considering the cases of incorrect as well as correct decoding at relay node, $f_{y_i}(\alpha)$ can be expressed as

$$f_{y_i}(\alpha) = f_{y_i|incorrect\ dec}(\alpha)\,Pr[incorrect\ dec] + \\ f_{y_i|correct\ dec}(\alpha)\ Pr[correct\ dec] \tag{2.31}$$

where, $f_{y_i|incorrect\ dec}(\alpha)$ and $Pr[incorrect\ dec]$ are conditional pdf and probability respectively in the case of incorrect decoding at relay node;

$f_{y_i|correct\ dec}(\alpha)$ and $Pr[correct\ dec]$ are conditional pdf and probability respectively in the case of correct decoding at relay node. It can be observed from equation (2.30) that probability of error reduces by increasing the cooperative users N. This implies that an increase in number of cooperative users results in an improved error performance of cooperative communication system. The performance improvement in cooperative communication system is due to an increase in throughput, diversity gain, coding gain and decrease in outage probability. Equations (2.30) and (2.31) indicate that an erroneous user-to-user transmission increases probability of error due to incorrect decoding at relay node. If the relay node sends erroneous information of transmitting user to base station, the performance of cooperative communication system gets degraded. However, if the system is designed in a manner that the relay node sends the information of transmitting user only when it is correctly decoded, then the benefits of cooperative diversity can be achieved.

2.7 Performance Analysis of Cooperative Multilevel Coding System

The proposed cooperative multilevel coding system is modelled and analysed in matrix laboratory (MATLAB) for two and three cooperative users and a common base station. The information at each cooperative user is processed in two levels in the case of two cooperative users and three levels in the case of three cooperative users. One level comprises the self-information of cooperative user and other levels comprise the overheard information of nearby users. The overheard information of nearby users is decoded to extract the original information. Each level has an identical ½ rate convolutional encoder that generates coded information corresponding to self-information of user and decoded information of nearby users. The coded symbols are mapped to multi-resolution 16-QAM constellation in the case of two cooperative users and 64-QAM constellation in the case of three cooperative users. Considering each cluster as 4-QAM constellation, the clusterization of 16-QAM and 64-QAM constellations involve 2 and 3 levels of resolution respectively. Therefore, the convolutional encoder at each level of cooperative user is designed for 4-QAM constellation. Each cooperative user transmits multilevel coded information to base station. The information is transmitted in frames (1 frame=130 symbols). The signals transmitted by cooperative users experience independent Rayleigh fading. For simplicity reasons, quasi-static frequency non-selective Rayleigh fading is considered [13], [109], where channel parameters are constant for a frame and change independently after the transmission of a frame [36], [37]. Such a fading environment helps in the reliable estimation of nearby users' information at the cooperative user resulting in an ease in the implementation of cooperative mechanism. The fading coefficients are uncorrelated and modelled as complex Gaussian random variables. The path gains over the channel are modelled as complex Gaussian random variables with zero mean and unit variance. The base station receives a noisy superposition of Rayleigh faded signals transmitted by cooperative users. It is assumed that perfect CSI is available at base station. The decoding of received signal is done by a multistage decoder which employs Viterbi decoder at each stage to detect the information of each user. The proposed cooperative multilevel coding system has the capability of providing diversity gain, coding gain, improved throughput and spectral efficiency and, reduced outage probability and system complexity.

The error performance of proposed cooperative multilevel coding system is compared with the non-cooperative multilevel coding system as shown in figure 2.3. This comparison is done by considering two cooperative users, single transmit antenna at each user and varying the number of receive antennas (N_r) at base station. In case of 1 antenna at base station, cooperative multilevel coding system outperforms non-cooperative multilevel coding system by ~0.5 dB at FER of 10^{-1}.

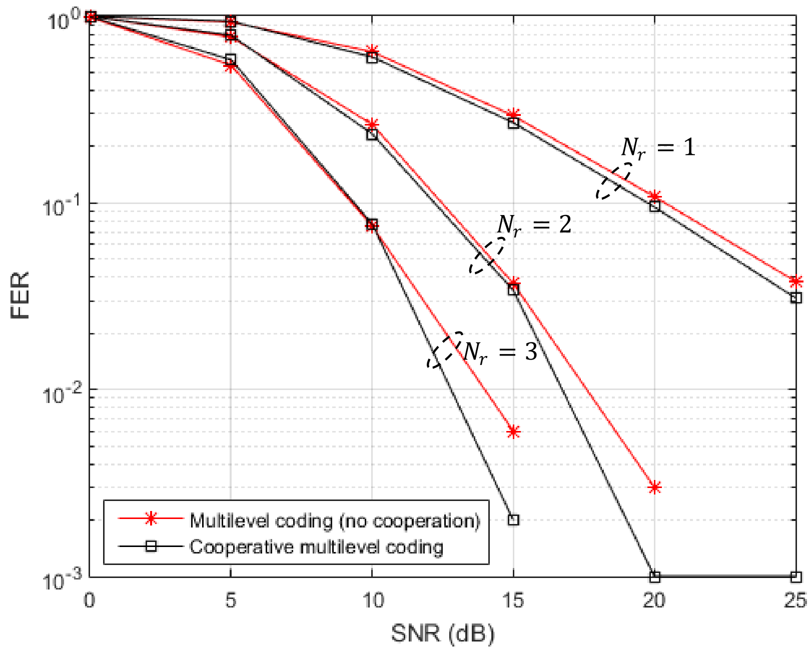

Figure 2.3: FER performance comparison of the proposed cooperative multilevel coding system with the non-cooperative multilevel coding system for $N_r = 1$, 2 and 3 receive antennas at base station

In case of 2 antennas at base station, cooperative multilevel coding system outperforms non-cooperative multilevel coding system by ~1 dB at FER of 10^{-2}. In case of 3 antennas at base station, cooperative multilevel coding system outperforms non-cooperative multilevel coding system by ~1.5 dB at FER of 6×10^{-3}. The SNR requirement of proposed cooperative multilevel coding system is ~19.8 dB at FER=10^{-1}, ~16.7 dB at FER=10^{-2} and ~13.7 dB at FER=6×10^{-3} for 1, 2 and 3 antennas respectively at base station. Clearly, the performance of cooperative multilevel coding system is superior to non-cooperative multilevel coding system.

Figure 2.4 illustrates the effect of increasing the number of cooperative users on the performance of cooperative multilevel coding system in the case of single antenna at base station. The cooperative multilevel coding system with three cooperative users outperforms cooperative multilevel coding system with two cooperative users by ~0.8 dB and non-cooperative multilevel coding system by ~1.5 dB at FER of 10^{-1}. This implies that the performance of proposed cooperative multilevel coding system can be improved by increasing the number of cooperative users. As the number of cooperative users increase, the system throughput and diversity gain increases and outage probability reduces. Therefore, desired FER can be achieved at a lower SNR.

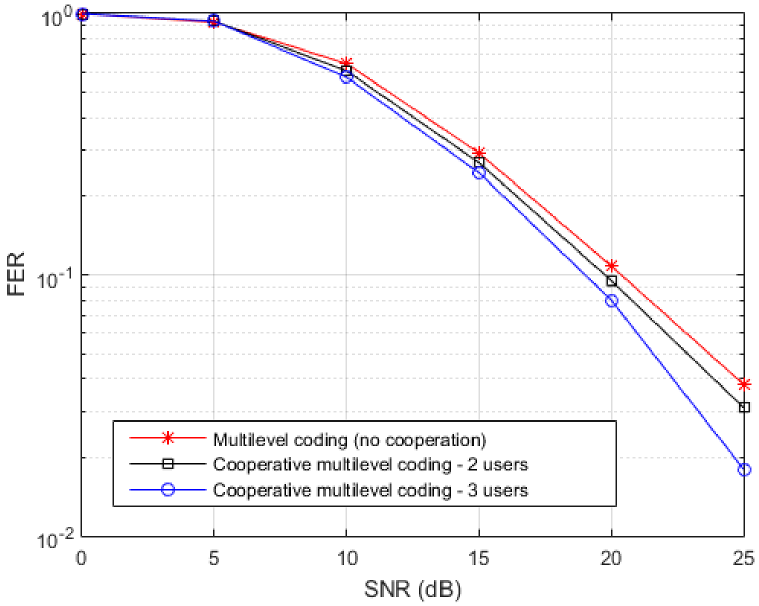

Figure 2.4: FER performance comparison of non-cooperative multilevel coding system with the proposed cooperative multilevel coding system for 2 and 3 cooperative users and a single antenna at base station

Figure 2.5 shows the comparison of outage performance of non-cooperative multilevel coding system and proposed cooperative multilevel coding system with two and three cooperative users in the case of single antenna at base station. For every 5 dB increase in SNR, the reduction in outage probability is greater for cooperative multilevel coding system in comparison to non-cooperative multilevel coding system. At an outage probability of 10^{-1}, the cooperative multilevel coding system results in an energy saving of 4 - 5.5 dB over non-cooperative multilevel coding system. Furthermore, outage probability reduces significantly with an increase in the number of cooperative users. This implies that user cooperation improves the performance of wireless communication.

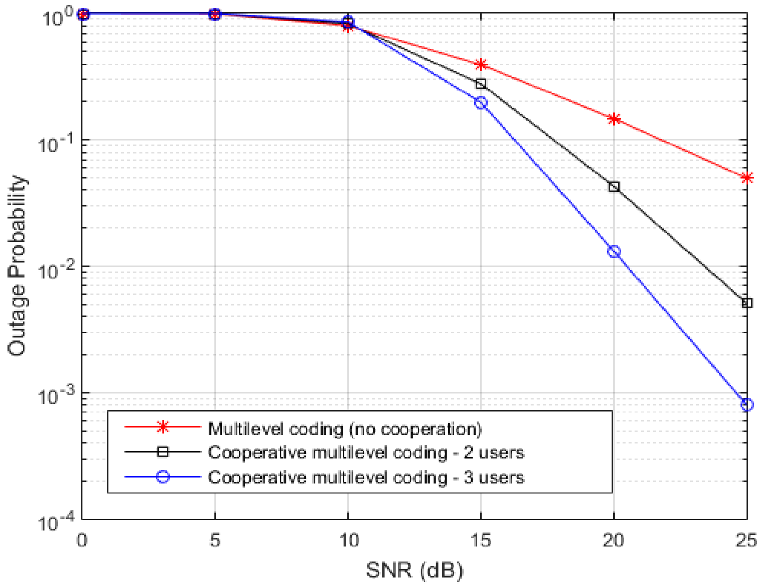

Figure 2.5: Outage probability of non-cooperative multilevel coding system and the proposed cooperative multilevel coding system for 2 and 3 cooperative users and a single antenna at base station

Table 2.1 compares the specifications of proposed cooperative multilevel coding system and existing cooperative multilevel coding system [99]. The existing system considers 3 cooperative users with self-information of each user processed at the highest level. ¾ rate punctured convolutional codes are used at each level. The coded symbols are mapped to 8-PAM constellation. This system uses a modified mapping pattern by performing an exhaustive search to find the optimum mapping function at target SNR. Once the target SNR is changed, another optimum mapping function needs to be found. The mapped symbols are transmitted in frames (1 frame=396 symbols). The receiver detects the information of each user by using a multistage decoder based on MAP decoding.

In contrast, the proposed cooperative multilevel coding system considers 3 cooperative users with self-information of user u processed at level u. The processing of self-information at their respective levels provides an ease in the detection of each user's information while decoding. ½ rate convolutional codes are used at each level. The trellis complexity of ½ rate convolutional codes is less than ¾ rate convolutional codes. Further, MRM partitioning technique is used for mapping the coded symbols to 64 QAM constellation. MRM partitioning enables the use of convolutional codes designed for 4-QAM at each level.

Table 2.1: Comparison in specifications of proposed cooperative multilevel coding system and existing cooperative multilevel coding system

Parameter	**Proposed cooperative multilevel coding system**	**Cooperative multilevel coding system** [99]
Component code for multilevel coding	½ rate convolutional code with $G=[6,7]_8$	¾ rate punctured convolutional code using ½ rate convolutional code with $G=[133,171]_8$
Information of User	Self-information of cooperative user *u* is processed at level *u*	Self-information of cooperative user is processed at the highest level
Mapping Technique	MRM mapping	Modified mapping pattern based on exhaustive search to find optimum mapping function.
Modulation	QAM MRM enables the use of convolutional codes designed for 4-QAM at each level	PAM
Antennas	Single antenna at mobile user. 1,2 or 3 antennas at base station	Single antenna at mobile node. Single antenna at destination node
Frame Size	1 frame=130 symbols	1 frame=396 symbols
Decoder	Multistage decoder with ML based Viterbi decoder at each stage	Multistage decoder with MAP decoder at each stage

The advantage of using MRM is that it allows the use of lower order constellation with relatively more spacing between the points. Moreover, there is no need of exhaustive search for MRM mapping. In comparison to PAM, QAM provides high speed data transmission, better anti-noise performance and full bandwidth usage [104]. The mapped symbols are transmitted in frames (1 frame=130 symbols). Instead of multistage decoder based on MAP decoding, the proposed system provides lower decoding complexity with multistage decoder based on ML Viterbi decoding. The max-log approximation provides further reduction in branch metric complexity.

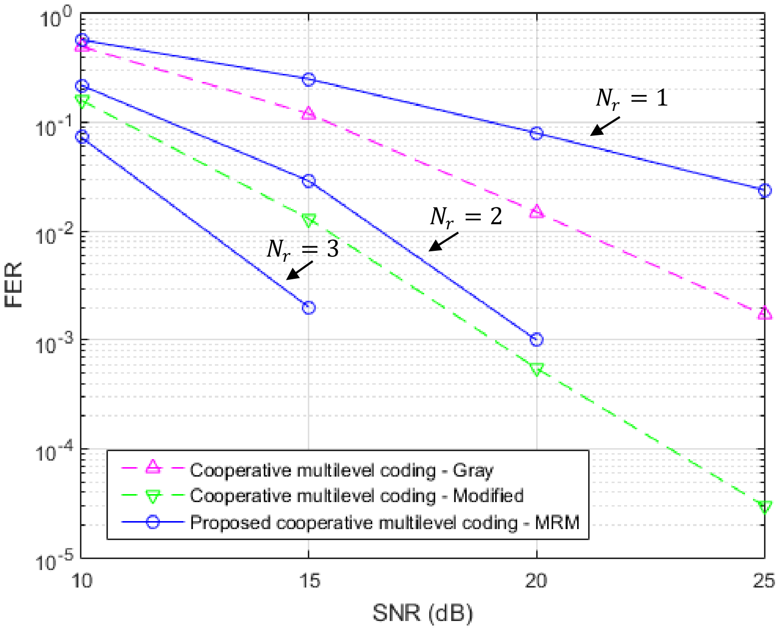

Figure 2.6: FER performance comparison of proposed cooperative multilevel coding system using MRM mapping with the existing cooperative multilevel coding system using Gray mapping and modified mapping

Figure 2.6 compares the error performance of proposed cooperative multilevel coding system using MRM mapping with the system given in [99] using Gray mapping and modified mapping. The error performance of proposed cooperative multilevel coding system with 1 antenna at base station is worse than the other two systems. However, the proposed system with 2 antennas at base station, provides ~4.5 dB improvement in SNR at

FER of 10^{-2} over the system with Gray mapping. The proposed system with 3 antennas at base station, provides ~2.8 dB improvement in SNR at FER of 10^{-3} over the system with modified mapping.

2.8 Complexity Considerations

The minimum computational complexities of non-cooperative multilevel coding and proposed cooperative multilevel coding are discussed below.

The multilevel coding scheme uses convolutional codes as component codes. Consider a (n, k, K) convolutional code where n is the length of codeword, k is the length of dataword and K is the constraint length. The decoding of n-bit codeword by Viterbi decoder involves the comparison of branch metrics over two state transitions into each state, for each of the 2^{K-1} states. This includes 2^K comparisons at each time step giving a total complexity of $n.2^K$ for decoding n-bit codeword. The multilevel coding operation involves the partitioning of M-QAM constellation in L levels. At each level a convolutional encoder is employed. Therefore, the minimum complexity of multilevel convolutional coding is $L.n.2^K$.

The proposed cooperative multilevel coding system is designed using multilevel convolutional coding at each cooperative user. So, the minimum computational complexity of proposed system can be obtained by considering the complexities due to multilevel coding, decoding at mobile user and cooperative diversity. The minimum complexity of multilevel convolutional coding is $L.n.2^K$. The decoding of other users' information at each cooperative user results in an increase in complexity by $(L-1).n.2^K$ due to L-1 decoders at each cooperative node. For N cooperative users, the minimum complexity becomes $N.\left[(L.n.2^K)+\left((L-1).n.2^K\right)\right]$ or, $N.[(2L-1).n.2^K]$.

2.9 Summary of the Chapter

In this chapter, we have proposed a system where mobile users transmit their information cooperatively to the common base station. Each mobile user receives the coded information of other users, detects it and further encodes it along with its own information. The encoding is done using multilevel coding scheme with convolutional codes as component codes. Each cooperative user transmits the multilevel coded symbols of its own information as well as that of other users to the base station. The base station receives a noisy superposition of independent Rayleigh faded signals transmitted by the cooperative users. The received signal is passed through a multistage decoder that employs maximum likelihood based Viterbi decoder at each stage to detect the information of each user. In order to provide a reduction in branch metric complexity, max-log approximation is used. The proposed system has the capability of providing diversity gain, coding gain, improved throughput and spectral efficiency and, reduced outage probability and system complexity.

The proposed cooperative multilevel coding system for 2 cooperative users outperforms non-cooperative multilevel coding system by ~0.5 dB at FER of 10^{-1}, ~1 dB at FER of 10^{-2}, and ~1.5 dB at FER of 6×10^{-3} for 1, 2 and 3 antennas respectively at base station. Additionally, the performance of the proposed system improves by increasing the number of cooperative users in terms of reduced error probability and outage probability. The cooperative multilevel coding system with three cooperative users outperforms the cooperative multilevel coding system with two cooperative users by ~0.8 dB and non-cooperative multilevel coding system by ~1.5 dB at FER of 10^{-1}. At an outage probability of 10^{-1}, the cooperative multilevel coding system results in an energy saving of ~5.5 dB in the case of three cooperative users and ~4 dB in the case of two cooperative users over non-cooperative multilevel coding system.

Chapter 3

Cooperative Communication System based on Multilevel Pseudo Space-Time Trellis Codes

Contents

3.1 Introduction

The combination of multilevel codes and space-time codes proves beneficial in combating the adverse effects of multipath fading to improve the quality of information transmission. The multilevel codes, when combined with space-time block codes, is capable of providing maximum possible diversity gain without bandwidth expansion [28], [29]. In order to obtain an enhanced coding gain in addition to diversity gain, multilevel space-time trellis codes (MLSTTC) are designed in [36] which use component STTC in multilevel coding scheme. MLSTTC are capable of providing an improved spectral efficiency, coding gain, diversity gain and a low decoding complexity even for big constellations and high throughput. However, STTC require multiple transmit antennas for their operation.

Recently, pseudo space-time trellis codes are invented for single antenna nodes [110]. PSTTC encoder comprises a serial to parallel converter to convert input information bitstream into parallel bitstreams, which are processed to generate sets of encoded symbols. The output encoded symbol sets are combined to produce a linear combination of output symbols that can be transmitted by single antenna nodes.

To the best of our knowledge, the use of space-time codes for multilevel coding of information in a cooperative communication system, has not been investigated yet. In this chapter, a cooperative transmission technique for single-antenna mobile users using novel multilevel pseudo space-time trellis coding (MLPSTTC) scheme, is proposed. Each cooperative user encodes its own information and decoded information of other users using multilevel coding scheme with PSTTC as component codes. The resultant MLPSTTC symbols are transmitted to base station by each cooperative user. The proposed cooperative diversity technique based on MLPSTTC is referred to as cooperative multilevel pseudo space-time trellis coding (CMLPSTTC) technique.

3.2 Pseudo Space-Time Trellis Codes

Pseudo space-time trellis codes are an extension of space-time trellis codes, so a brief overview of STTC is given prior to the description of PSTTC.

STTC [109], [111], [112] are error-correcting codes that are used for multiple-antenna nodes to provide coding gain as well as diversity gain without bandwidth expansion. STTC combats multipath fading by transmitting multiple copies of trellis code span over time and space (transmit antennas). Figure 3.1 shows the operation of space-time trellis coding scheme for a system with n transmit antennas. The m-bit information stream at a time t is simultaneously passed through m shift-registers, where it is multiplied with the corresponding generator sequences.

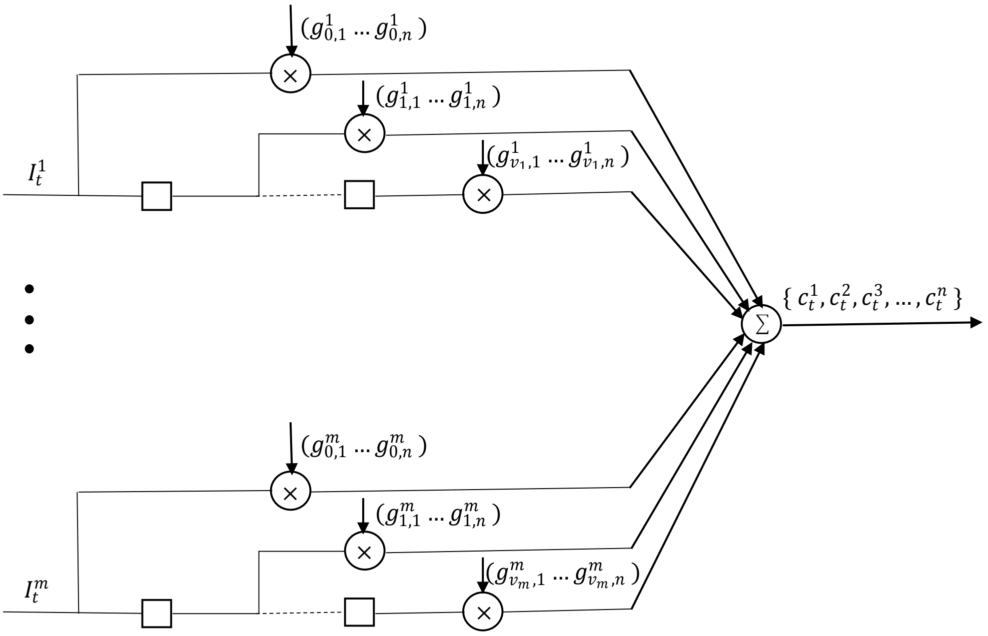

Figure 3.1: Space-time trellis coding scheme

The generator sequences of shift registers are of the following form:

$$g^1 = [(g^1_{0,1} \cdots g^1_{0,n,}), (g^1_{1,1} \cdots g^1_{1,n,}) \cdots (g^1_{v_1,1} \cdots g^1_{v_1,n,})]$$

$$g^2 = [(g^2_{0,1} \cdots g^2_{0,n}), (g^2_{1,1} \cdots g^2_{1,n}) \cdots (g^2_{v_2,1} \cdots g^2_{v_2,n})]$$

$$g^m = [(g^m_{0,1} \cdots g^m_{0,n}), (g^m_{1,1} \cdots g^m_{1,n}) \cdots (g^m_{v_m,1} \cdots g^m_{v_m,n})] \tag{3.1}$$

where, $g^w_{v,a}$ is a M-QAM symbol, a = 1,2,…,n ; v = 0,1,…,v_w ; w= 1,2,…,m and v_w is memory order of shift register w. The STTC encoder output x_t^i for transmit antenna i and time t is given as

$$c_t^i = \sum_{u=1}^{m} \sum_{v=0}^{v_u} g^u_{v,a}\, I^u_{t-v} \ (mod\ M) \tag{3.2}$$

The output $\{c_t^1, c_t^2, c_t^3, \dots, c_t^n\}$ is a space-time trellis coded symbol which is transmitted simultaneously through corresponding *n* transmit antennas. The decoding of STTC is done using Viterbi algorithm based on maximum-likelihood principle.

Recently, Orlik et al. [110] invented pseudo space-time trellis coding for single antenna nodes. The PSTTC encoder converts input bitstreams of information to parallel bitstreams of information using a serial to parallel (S/P) convertor. Each of the parallel bitstreams processes through branches of shift registers where code generating weights are multiplied with information bits to produce *n* sets of encoded symbols for transmission by *n* virtual antennas. In order to use a single antenna transmitter, the output coded symbols are multiplied with a complex number ε_i(t) (*i* represents virtual antennas) at each time slot, which are then added to form a linear combination of output symbols. Figure 3.2 illustrates PSTTC scheme for *n* virtual transmit antennas. As shown in figure, the encoded symbols $c_t^1, \ldots, c_t^n$ are multiplied with linear coefficients $\varepsilon_1(t), \ldots, \varepsilon_n(t)$ at each time slot, which are added to form a linear combination of output symbols $\sum_{i=1}^{n} c_t^i \varepsilon_i(t)$. The interested reader can go through reference [110] for an elaborate explanation of PSTTC encoder.

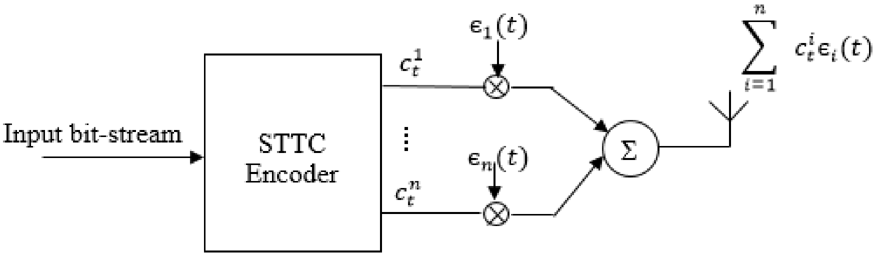

Figure 3.2: Pseudo Space-Time Trellis Coding Scheme

3.3 System Model of Cooperative Multilevel Pseudo Space-Time Trellis Coding

Figure 3.3 shows the system model of proposed cooperative diversity technique based on multilevel pseudo space-time trellis coding. The system comprises *N* single-antenna mobile users and a common base station. Each mobile user behave as a cooperative user to transmit the information of other users along with its own information to base station. Due to the broadcast nature of wireless medium, each cooperative user overhears the information transmitted by other users to base station and detects the information of each user using a set of decoders.

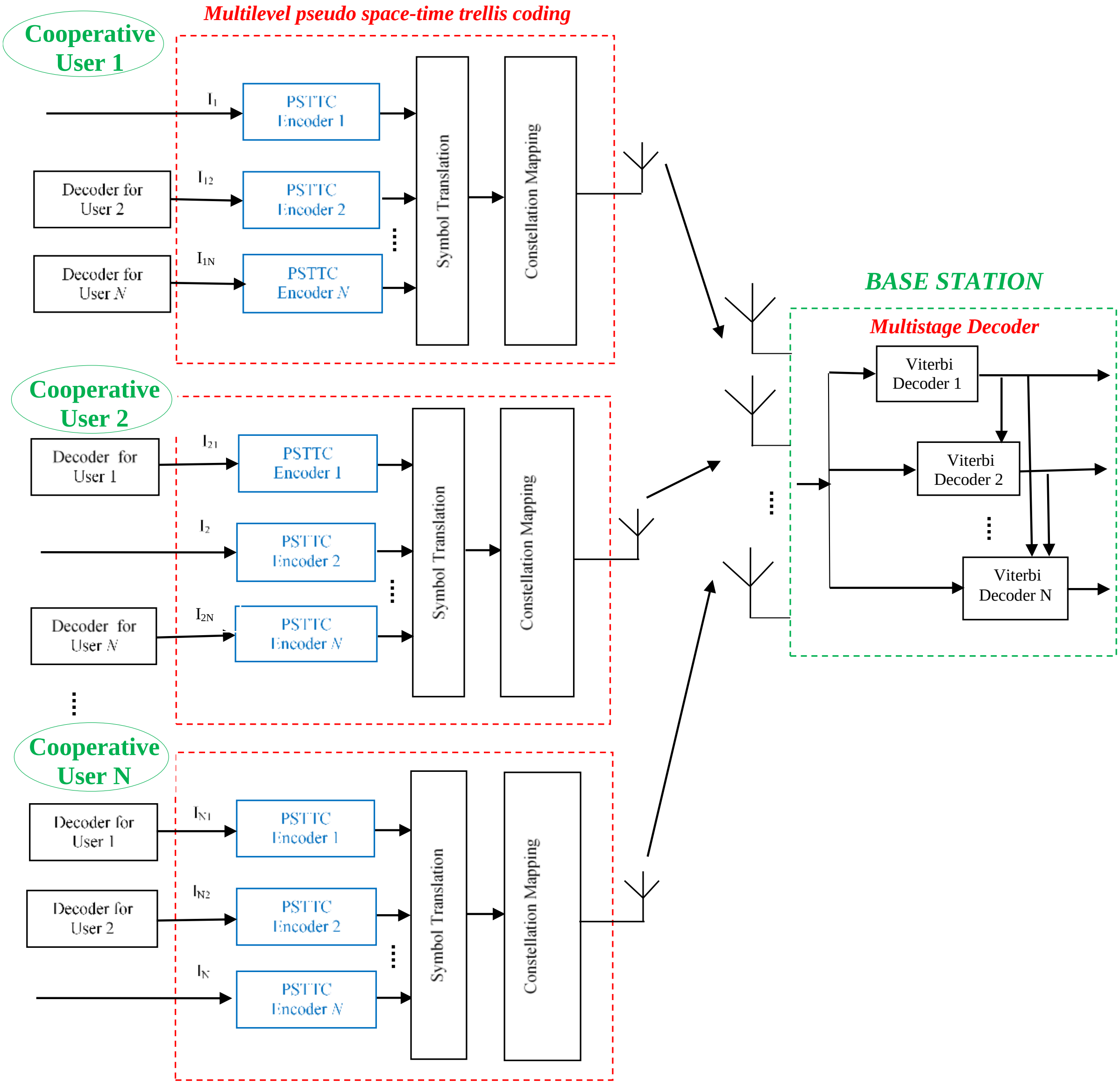

Figure 3.3: System model of proposed cooperative multilevel pseudo space-time trellis coding technique

Each cooperative user employs multilevel coding scheme with PSTTC as component codes to encode its own information and the detected information of other users. For simplicity reasons, it is assumed that number of levels are equal to number of cooperative users. This implies that each cooperative user has N levels of information corresponding to N users and there is a PSTTC encoder at each level to encode the information of respective user. For example, user 1 has a set of decoders to detect the information transmitted by users 2 to N, and a set of PSTTC encoders to encode self-information of user 1 and decoded information of other cooperative users. The self-information of user 1 is represented by I_1, and decoded information of users 2 to N at node 1 is represented by $I_{12}, I_{13}, \ldots, I_{1N}$.

PSTTC encoder converts input bitstreams of information to parallel bitstreams of information using a serial to parallel (S/P) convertor. Each of the parallel bitstreams processes through branches of shift registers where code generating weights are multiplied with information bits to produce n sets of encoded symbols for transmission by n virtual antennas. In order to use a single antenna transmitter, the output encoded symbols are multiplied with a complex number $\varepsilon_i(t)$ (i represents virtual antenna) at each time slot, which are then added to form a linear combination of output symbols. The resultant PSTTC symbols are passed through a symbol translator to generate translated symbols which are mapped to M-QAM constellation using MRM partitioning. The mapped symbols are transmitted by single antenna cooperative users to base station. Section 3.4 elaborates the transmission process at each cooperative user. The multilevel coded information transmitted by each cooperative user is assumed to experience statistically independent quasi-static frequency non-selective Rayleigh fading. The base station receives Rayleigh faded signals transmitted by each cooperative user and detects the information of each user using a multistage decoder based on Viterbi algorithm. Section 3.5 elaborates the reception process at base station.

3.4 Transmission Process at Cooperative User

The following sub-sections explain the encoding operation at cooperative users 1,…,*N*.

3.4.1 Encoding at Cooperative User 1

As shown in figure 3.3, user 1 employs *N* PSTTC encoders to produce coded symbols corresponding to input data streams at each level. The encoding operation at PSTTC encoder is as follows.

Firstly, a set of *n* space-time trellis coded symbols, $\{c_{1t}^{1}, \dots, c_{1t}^{n}\}$ are generated for *n* virtual transmit antennas.

$$S_1(e) = \{c_{1t}^{1}, \dots, c_{1t}^{n}\} = \boldsymbol{I}\,\boldsymbol{G} \tag{3.3}$$

where, $S_1(e)$ represents the set of *n* space-time trellis coded symbols generated by PSTTC encoder *e* (e=1,2,…,*N*) at user 1.

I represents the input information at PSTTC encoder and is given by

$$\boldsymbol{I} = \left\{ \begin{matrix} I_1 \text{ at encoder 1} \\ I_{12}, I_{13}, \dots, I_{1N} \text{ at encoders } 2,3,\dots,N\ respectively \end{matrix} \right\} \tag{3.4}$$

G represents generator polynomial given by

$$\boldsymbol{G} = \{\boldsymbol{g_e^1}, \boldsymbol{g_e^2}, \dots, \boldsymbol{g_e^m}\} \tag{3.5}$$

$$\boldsymbol{g_e^1} = \left[\left(g_{0,1}^{1} \cdots g_{0,n}^{1}\right), \left(g_{1,1}^{1} \cdots g_{1,n}^{1}\right), \dots, \left(g_{v_1,1}^{1} \cdots g_{v_1,n}^{1}\right)\right] \tag{3.6}$$

$$\boldsymbol{g_e^2} = \left[\left(g_{0,1}^{2} \cdots g_{0,n}^{2}\right), \left(g_{1,1}^{2} \cdots g_{1,n}^{2}\right), \dots, \left(g_{v_2,1}^{2} \cdots g_{v_2,n}^{2}\right)\right] \tag{3.7}$$

$$\boldsymbol{g_e^m} = \left[\left(g_{0,1}^{m} \cdots g_{0,n}^{m}\right), \left(g_{1,1}^{m} \cdots g_{1,n}^{m}\right), \dots, \left(g_{v_m,1}^{m} \cdots g_{v_m,n}^{m}\right)\right] \tag{3.8}$$

In the above equations, $\{\boldsymbol{g_e^1}, \boldsymbol{g_e^2}, \dots, \boldsymbol{g_e^m}\}$ represents generator sequences for PSTTC encoder *e* where $m = \log_2 M$. $g_{v,a}^{w}$ (*w*=1,2,…,*m* ; *v*=0,1,…,v_w ; a=1,2,…,*n*) is a part of *M*-QAM signal constellation where v_w is the memory order of *w*-th shift register and *a* represents virtual antenna.

In order to use a single antenna transmitter, the set of *n* space-time trellis coded symbols $\{c_{1t}^{1}, \dots, c_{1t}^{n}\}$ are multiplied with linear coefficients $\{\varepsilon_1(t), \dots, \varepsilon_n(t)\}$ which are added to generate a linear combination of output symbols. The resultant pseudo space-time trellis coded symbol is given by

$$x_{1t}(e) = \sum_{i=1}^{n} c_{1t}^{i}\, \varepsilon_i(t) \tag{3.9}$$

where, $x_{1t}(e)$ represents pseudo space-time trellis code generated by encoder e of cooperative user 1 at time t.

The pseudo space-time trellis coded symbols generated at levels 1,…,N are passed through a symbol translator which performs transpose operation on coded symbols to produce translated symbols $x_{1t}(1)$,…, $x_{1t}(N)$. The translated symbols are mapped to M-QAM constellation using MRM partitioning. The MRM partitioning involves L levels of partition such that M=4^L, which indicates that 4-cluster is used as elementary unit of resolution. By considering each cluster as 4-QAM signal constellation, the component PSTTC are designed for 4-QAM. The output of PSTTC encoder at first level is mapped to clusters, output of PSTTC encoder at subsequent levels is mapped to sub-clusters and the output of PSTTC encoder at level L is mapped to constellation points. The multilevel coded symbol transmitted by single transmit antenna of cooperative user 1 at time t is given by

$$Q_{1t} = \Delta_1 x_{1t}(1) + \Delta_2 x_{1t}(2) + \cdots + \Delta_N x_{1t}(N) \tag{3.10}$$

where, $\Delta_1, \ldots, \Delta_N$ are cluster distances corresponding to $x_{1t}(1), \ldots, x_{1t}(N)$ respectively during MRM partitioning.

3.4.2 Encoding at Cooperative User 2

Cooperative user 2 behaves in a similar way. It uses second level for encoding its own information and remaining levels for encoding the information of other mobile users. The PSTTC encoder at each level works as follows.

Initially, a set of n space-time trellis coded symbols, $\{c_{2t}^1, \ldots, c_{2t}^n\}$ are generated for n virtual transmit antennas.

$$S_2(e) = \{c_{2t}^1, \ldots, c_{2t}^n\} = \boldsymbol{I}\,\boldsymbol{G} \tag{3.11}$$

where $S_2(e)$ represents the set of n space-time trellis coded symbols generated by PSTTC encoder e (e=1,2,…,N) at user 2.

$\boldsymbol{I}$ represents the input information at PSTTC encoder and is given by

$$\boldsymbol{I} = \begin{Bmatrix} I_2 \text{ at encoder 2} \\ I_{21}, I_{23}, \ldots, I_{2N} \text{ at encoders } 1,3,\ldots,N \; respectively \end{Bmatrix} \tag{3.12}$$

G represents generator polynomial and is the same as considered for cooperative user 1.

In order to use a single antenna transmitter, the set of n space-time trellis coded symbols $\{c_{2t}^1, \ldots, c_{2t}^n\}$ are multiplied with linear coefficients $\{\varepsilon_1(t), \ldots, \varepsilon_n(t)\}$ which are added to generate a linear combination of output symbols. The resultant pseudo space-time trellis coded symbol is given by

$$x_{2t}(e) = \sum_{i=1}^{n} c_{2t}^{i}\, \varepsilon_i(t) \qquad (3.13)$$

where $x_{2t}(e)$ represents pseudo space-time trellis code generated by encoder e of cooperative user 2 at time t.

The pseudo space-time trellis coded symbols generated at levels 1,…,N are passed through a symbol translator to produce translated symbols $x_{2t}(1)\ldots x_{2t}(N)$. The translated symbols are mapped to M-QAM constellation using MRM partitioning. The multilevel coded symbol transmitted by single transmit antenna of cooperative user 2 at time t is given by

$$Q_{2t} = \Delta_1 x_{2t}(1) + \Delta_2 x_{2t}(2) + \cdots + \Delta_N x_{2t}(N) \qquad (3.14)$$

where $\Delta_1, \ldots, \Delta_N$ are cluster distances corresponding to $x_{2t}(1), \ldots, x_{2t}(N)$ respectively during MRM partitioning.

3.4.3 Encoding at Cooperative User *N*

Cooperative user N uses level N for encoding its own information and remaining levels for encoding the information of other mobile users. First of all, each PSTTC encoder generates a set of n space-time trellis coded symbols, $\{c_{Nt}^1, \ldots, c_{Nt}^n\}$ for n virtual transmit antennas.

$$S_N(e) = \{c_{Nt}^1, \ldots, c_{Nt}^n\} = \boldsymbol{I}\,\boldsymbol{G} \qquad (3.15)$$

where $S_N(e)$ represents the set of n space-time trellis coded symbols generated by PSTTC encoder e (e=1,2,…,N) at user N.

I represents the input information at PSTTC encoder and is given by

$$\boldsymbol{I} = \begin{Bmatrix} I_N \text{ at encoder } N \\ I_{N1}, I_{N2}, \ldots, I_{N(N-1)} \text{ at encoders } 1,2,\ldots,(N-1)\ respectively \end{Bmatrix} \qquad (3.16)$$

G represents generator polynomial and is same for all cooperative users.

In order to use a single antenna transmitter, the set of n space-time trellis coded symbols $\{c_{Nt}^1, \ldots, c_{Nt}^n\}$ are multiplied with linear coefficients $\{\varepsilon_1(t), \ldots, \varepsilon_n(t)\}$ which are added to generate a linear combination of output symbols. The resultant pseudo space-time trellis coded symbol is given by

$$x_{Nt}(e) = \sum_{i=1}^{n} c_{Nt}^i \, \varepsilon_i(t) \tag{3.17}$$

where, $x_{Nt}(e)$ represents pseudo space-time trellis code generated by encoder e of cooperative user N at time t.

The pseudo space-time trellis coded symbols generated at levels 1,…,N are passed through a symbol translator to produce translated symbols $x_{Nt}(1) \ldots x_{Nt}(N)$. The translated symbols are mapped to M-QAM constellation using MRM partitioning.

The multilevel coded symbol transmitted by single transmit antenna of cooperative user N at time t is given by

$$Q_{Nt} = \Delta_1 x_{Nt}(1) + \Delta_2 x_{Nt}(2) + \cdots + \Delta_N x_{Nt}(N) \tag{3.18}$$

where, $\Delta_1, \ldots, \Delta_N$ are cluster distances corresponding to $x_{Nt}(1), \ldots, x_{Nt}(N)$ respectively during MRM partitioning.

3.5 Reception Process at Base Station

The signals transmitted by cooperative users experience independent Rayleigh fading over the wireless channel such that the base station receives a noisy superposition of signals. The signal received at base station B at time t is given by

$$r_t = {h_{1B}}^t Q_{1t} + {h_{2B}}^t Q_{2t} + \ldots + {h_{NB}}^t Q_{Nt} + n_t \tag{3.19}$$

where, ${h_{1B}}^t, {h_{2B}}^t, \ldots, {h_{NB}}^t$ are fading coefficients between base station B and cooperative users 1,2,…,N respectively, and n_t is the noise at receive antenna of base station. Perfect channel state information is assumed at base station.

Substituting values of $Q_{1t}, Q_{2t}, \ldots, Q_{Nt}$ from equations (3.10), (3.14) and (3.18) in equation (3.19),

$$\begin{aligned} r_t = {} & h_{1B}\{\Delta_1 x_{1t}(1) + \Delta_2 x_{1t}(2) + \cdots + \Delta_N x_{1t}(N)\} + h_{2B}\{\Delta_1 x_{2t}(1) + \\ & \Delta_2 x_{2t}(2) + \cdots + \Delta_N x_{2t}(N)\} + h_{NB}\{\Delta_1 x_{Nt}(1) + \\ & \Delta_2 x_{Nt}(2) + \ldots + \Delta_N x_{Nt}(N)\} + n_t \end{aligned} \tag{3.20}$$

Error-free decoding of other users' information at each cooperative user is assumed, which implies

$$x_{1t}(e) = x_{2t}(e) = \ldots = x_{Nt}(e) = x_t(e)\ ;\ e=1,2,\ldots,N \tag{3.21}$$

Therefore, equation (3.20) can be represented as

$$r_t = \{h_{1B} + h_{2B} + \ldots + h_{NB}\}\,\Delta_1 x_{1t}(1) + \{h_{1B} + h_{2B} + \ldots + h_{NB}\}\,\Delta_2 x_{2t}(2) + \cdots + \{h_{1B} + h_{2B} + \ldots + h_{NB}\}\,\Delta_N x_{Nt}(N) + n_t \tag{3.22}$$

$$r_t = \sum_{e=1}^{N}\sum_{u=1}^{N} h_{uB}\Delta_e x_t(e) + n_t \tag{3.23}$$

where, e represents PSTTC encoder and u represents cooperative user.

3.5.1 Multistage Decoding

The signal received at base station is passed through a low complexity multistage decoder which employs Viterbi decoder at each stage to detect the information of corresponding cooperative user. The number of stages in multistage decoder is equal to the number of levels in multilevel coding. The received signal is fed to all the stages of multistage decoder. Each Viterbi decoder decodes the corresponding component code by deriving branch metrics for a data frame by executing a search based on maximising the likelihood function. The multistage decoder starts its operation at stage 1 which involves decoding the component code corresponding to PSTTC encoder 1 and finding the estimated value of $x_t(1)$. The estimated value of $x_t(1)$ is passed to stage 2 to contribute in the decoding of component code corresponding to PSTTC encoder 2 and to find the estimated value of $x_t(2)$. The estimated values of $x_t(1)$ and $x_t(2)$ are passed to stage 3 to estimate $x_t(3)$. This process is followed for subsequent stages. Finally, stage N uses the estimates of stage 1 to N-1 to obtain the estimated value of $x_t(N)$.

The Viterbi decoder at stage 1 has no knowledge of the values of $x_t(2)$ to $x_t(N)$, so it considers them as nuisance variables and average them out. It executes a search based on maximising the likelihood function by considering hypothesized value of $x_t(1)$. The likelihood function to estimate $x_t(1)$ in the form of branch metric is

$$L\big(x_t(1)\big) = log\left(\sum_{\substack{x_t(e)\\ e=2,\dots,N}} exp\left[\frac{|\, r_t - \sum_{e=1}^{N}\sum_{u=1}^{N} h_{uB}\Delta_e x_t(e)\,|^2}{2{\sigma_n}^2}\right]\right) \tag{3.24}$$

The Viterbi decoder at stage s ($1 < s < N$) executes a search based on maximising the likelihood function by considering hypothesized value of $x_t(s)$. Since the output of stages 1 to s-1 decoders are available, the estimated values of $x_t(1),\dots,x_t(s-1)$ contribute in estimating the value of $x_t(s)$. Stage s has no knowledge of values $x_t(s+1),\dots,x_t(N)$, so it considers them as nuisance variables and average them out. The likelihood function that estimates $x_t(s)$ in the form of branch metric is

$$L\big(x_t(s)\big) = log\left(\sum_{\substack{x_t(e)\\ e=s+1,\dots,N}} exp\left[\frac{|\, r_t - \sum_{e=s}^{N}\sum_{u=1}^{N} h_{uB}\Delta_e x_t(e) - \sum_{p=1}^{s-1}\sum_{u=1}^{N} h_{uB}\Delta_p \hat{x}_t(p)\,|^2}{2{\sigma_n}^2}\right]\right) \tag{3.25}$$

where, $\hat{x}_t(p)$ is the estimated output of encoder p.

Finally, Viterbi decoder at stage N uses the estimated values of $x_t(1),\dots,x_t(N-1)$. The likelihood function to estimate $x_t(N)$ in the form of branch metric is

$$L\big(x_t(N)\big) = log\left(exp\left[\frac{|\, r_t - \sum_{u=1}^{N} h_{uB}\Delta_N x_t(N) - \sum_{p=1}^{N-1}\sum_{u=1}^{N} h_{uB}\Delta_p \hat{x}_t(p)|^2}{2{\sigma_n}^2}\right]\right) \tag{3.26}$$

In this way, each stage of multistage Viterbi decoder detects the corresponding component code and gives the information of user at that particular level.

3.6 Performance Analysis of Cooperative Multilevel Pseudo Space-Time Trellis Coding

The performance of proposed cooperative multilevel pseudo space-time trellis coding technique is evaluated for two mobile users that cooperate with each other to transmit their information to a common base station. Each cooperative user encodes its own information and the other user’s information using MLPSTTC scheme. The cooperative user has two levels of information – one for its own information and the second for other user’s information. There is a PSTTC encoder at each level that encodes the information at respective level. For simplicity, it is assumed that

PSTTC encoder uses complex number $\varepsilon_i(t) = 1$ for linear combination of output symbols. Furthermore, predefined generator sequences for PSTTC encoder are considered. The coded symbols are mapped to 16-QAM signal constellation using MRM partitioning, which enables the use of 4-QAM at each level with $\Delta_1/\Delta_2 = 2$. The single antenna cooperative users transmit mapped symbols to common base station in frames with 130 symbols in each frame. The channel between each cooperative user and base station undergo quasi-static Rayleigh fading. The path gains are modelled as complex Gaussian random variables with zero mean and unit variance. The fading coefficients for each cooperative user are uncorrelated and statistically independent. The channel is assumed to be constant over a frame and changes independently after the transmission of a frame. The base station uses multistage Viterbi decoder to detect the information of each mobile node. The performance evaluation of proposed CMLPSTTC system is done in MATLAB.

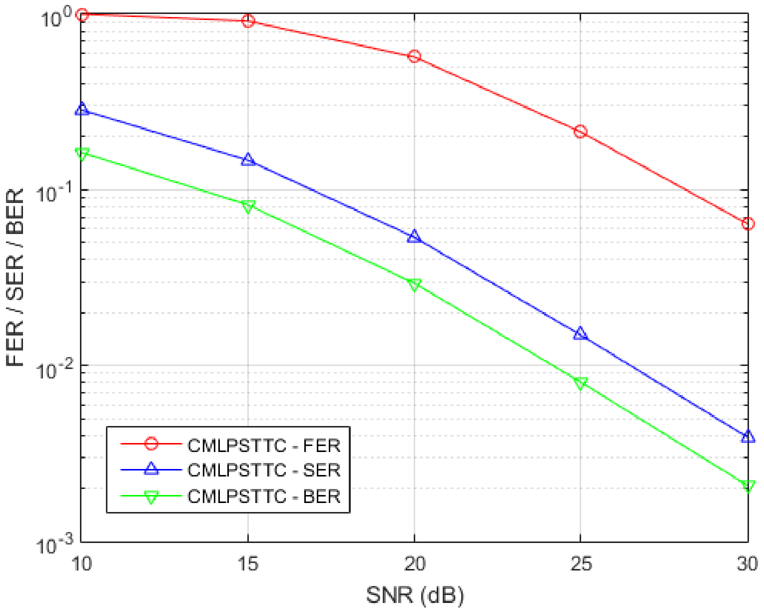

Figure 3.4: Performance of proposed cooperative multilevel pseudo space-time trellis coding technique

Figure 3.4 shows the performance of CMLPSTTC system in terms of FER, symbol error rate (SER) and bit error rate (BER) v/s SNR. The CMLPSTTC system requires SNR of ~28.2 dB to achieve FER of 10^{-1},

~26.5 dB to achieve SER of 10^{-2} and ~24.2 dB to achieve BER of 10^{-2}.

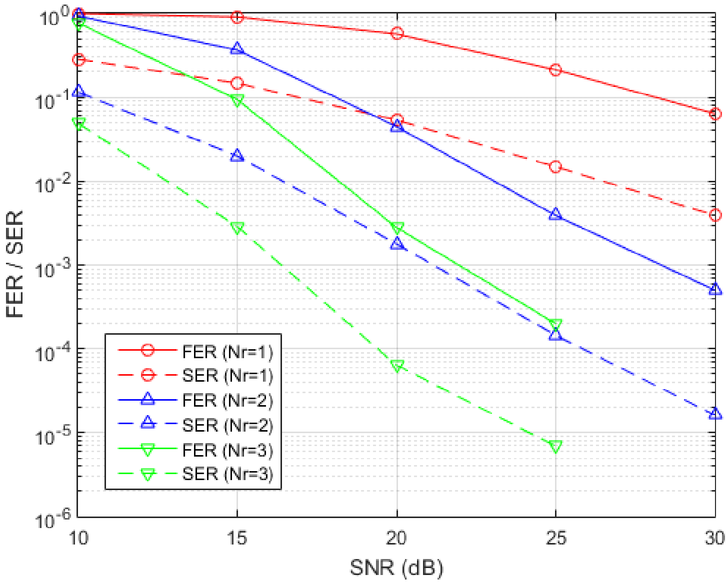

Figure 3.5: Performance of proposed cooperative multilevel pseudo space-time trellis coding technique for $N_r = 1$, 2 and 3 receive antennas at base station

Figure 3.5 shows the performance of CMLPSTTC system for 1, 2 and 3 receive antennas at base station. The CMLPSTTC system can achieve FER of 10^{-1} at SNR ~28.2 dB, ~18.2 dB and ~15 dB for 1, 2 and 3 receive antennas respectively at base station. The SER of 10^{-2} can be achieved at SNR ~26.5 dB, ~16.5 dB and ~12.8 dB for 1, 2 and 3 receive antennas respectively at base station. This implies that the performance of CMLPSTTC system improves with an increase in number of antennas at destination node.

Figure 3.6 compares the performance of proposed CMLPSTTC technique with the existing multilevel space-time trellis coding techniques viz. MLSTTC [36], grouped multilevel space-time trellis coding (GMLSTTC) [37], grouped multilevel dynamic space-time trellis coding (GMLDSTTC) [40], adaptively grouped multilevel space-time trellis coding (AGMLSTTC) [41], weighted adaptively grouped multilevel space-time trellis coding (WAGMLSTTC) [43], weighted adaptively grouped multilevel dynamic space-time trellis coding (WAGMLDSTTC) [44].

MLSTTC technique consider the case of at least two transmit antennas, and GMLSTTC, GMLDSTTC, AGMLSTTC, WAGMLSTTC and WAGMLDSTTC techniques consider the case of at least four transmit antennas. Since these techniques require multiple transmit antennas for operation, they can't be used for mobile users with size, cost or hardware limitations.

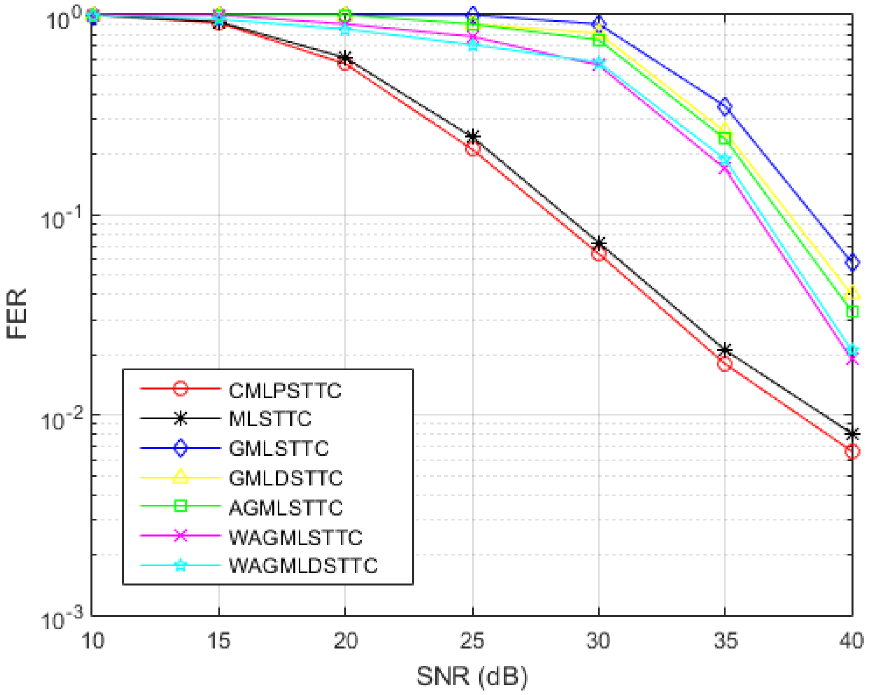

Figure 3.6: Performance comparison of proposed cooperative multilevel pseudo space-time trellis coding technique with the existing multilevel space-time trellis coding techniques viz. MLSTTC, GMLSTTC, GMLDSTTC, AGMLSTTC, WAGMLSTTC and WAGMLDSTTC

The proposed CMLPSTTC technique improves the performance of wireless communication for single antenna mobile users. CMLPSTTC system enables the mobile users to share their antennas in order to create a virtual multiple-input single-output (MISO) or virtual MIMO system. The spatial diversity generated by cooperative users, known as cooperative diversity helps in a reliable information transmission. The performance of proposed CMLPSTTC technique is superior to existing MLSTTC technique by ~0.9 dB at FER of 10^{-2}. Furthermore, CMLPSTTC technique outperforms GMLSTTC, GMLDSTTC, AGMLSTTC, WAGMLSTTC and WAGMLDSTTC techniques by ~10.4 dB, ~9.4 dB, ~ 9.1 dB, ~8.2 dB and ~8.4 dB respectively at FER of 10^{-1}. This implies that CMLPSTTC technique helps to improve the performance of wireless systems in terms of enhanced coding gain, diversity gain, system throughput, network capacity, spectral efficiency and transmission reliability.

3.7 Complexity Considerations

In this section, the minimum computational complexity of MLSTTC and proposed CMLPSTTC are computed in terms of trellis complexity. The trellis complexity involves $N_s \times N_b$ calculations, where N_s is the number of states in component STTC and N_b is the number of branches per state.

MLSTTC system involves the partitioning of M-QAM constellation into L 4-QAM subsets using MRM. The multilevel coding will result in minimum $L \times N_s$ $(= L \times 4)$ states with N_b $(= 4)$ branches leaving each state due to 4-QAM subsets. Therefore, the minimum complexity of MLSTTC system is $L \times N_s \times N_b$ $(= L \times 4 \times 4)$.

CMLPSTTC system is formed by using MLPSTTC scheme at each cooperative node. So, the minimum complexity of CMLPSTTC system is obtained by considering the complexity due to MLSTTC, pseudo space-time trellis coding operation, decoding at cooperative node and cooperative diversity. For M-QAM constellation, the minimum complexity due to MLSTTC at each cooperative node is $L \times N_s \times N_b$. PSTTC encoder generates a linear combination of output symbols by multiplying n space-time trellis coded symbols with linear coefficients as shown in equation (4.15). This leads to an increase in minimum complexity by n. Each cooperative node employs a decoder prior to multilevel coding for detecting the overheard information of other nodes. This results in an increase in minimum complexity by $(L-1) \times N_s \times N_b$ $[= (L-1) \times 4 \times 4]$ for L-1 decoders at cooperative node. For N cooperative nodes employing MLPSTTC scheme, the minimum complexity becomes $N.[(L \times N_s \times N_b) + n + \{(L-1) \times N_s \times N_b\}]$ or, $N.[\{(2L-1) \times N_s \times N_b\} + n]$.

3.8 Summary of the Chapter

In this chapter, a novel cooperative communication system is proposed which uses multilevel coding scheme with pseudo space-time trellis codes as component codes at each mobile user. The new CMLPSTTC system enables single antenna mobile users to share their antennas for the transmission of information. The mobile users act as cooperative users by transmitting their own information as well as the information of other users to the common base station. The cooperative users achieve the benefits of spatial diversity by creating a virtual MISO or virtual MIMO system. The base station receives the multilevel coded information transmitted by each cooperative user and detects the information of each user using multistage Viterbi decoder.

The simulation results imply that proposed CMLPSTTC technique is better in performance than the existing MLSTTC technique by ~0.9 dB at FER of 10^{-2}. Moreover, CMLPSTTC technique outperforms the existing GMLSTTC, GMLDSTTC, AGMLSTTC, WAGMLSTTC and WAGMLDSTTC techniques by ~10.4 dB, ~9.4 dB, ~ 9.1 dB, ~ 8.2 dB and ~8.4 dB respectively at FER of 10^{-1}. The performance of CMLPSTTC technique can be ameliorated further by installing more antennas at base station.

Chapter 4

Cooperative Communication System based on Multilevel Weighted Space-Time Trellis Codes

Contents

4.1 Introduction

Multilevel space-time trellis coding scheme [36] avail the benefits of multilevel codes and space-time trellis codes. It has the potential of providing spectral efficiency, coding gain, diversity gain at a low decoding complexity even for big constellations and high throughput. In [37], grouped MLSTTC are designed that can provide high throughput of multilayered schemes while realizing larger diversity gains. MLSTTC and grouped MLSTTC consider CSI at receiver only.

In [113], [114], researchers have shown that CSI at transmitter can be used to improve the performance of space-time transmission. In [115], weighted STTC are proposed that consider CSI at transmitter to provide beamforming. These codes involve proper weighting of signals based on available channel information, thus providing receive SNR gain in addition to coding gain and diversity gain. Based on this concept, weighted MLSTTC [38] are designed that consider transmit CSI in MLSTTC scheme for transmission weighting. Weighted MLSTTC provides an improved system performance in comparison to MLSTTC. However, various MLSTTC schemes discussed above, consider the case of single transmitting node and receiving node, and the transmitting node sends only its own information to the receiving node.

This chapter proposes a cooperative communication system which consider the case of multiple transmitting nodes relaying information for each other to common destination node. Each cooperative node uses component STTC for multilevel coding of information. It considers CSI at transmitting nodes to provide proper weighting of signals in order to achieve receive SNR gain. The proposed system avail the benefits of weighted MLSTTC at each cooperative node. It has the capability of providing an improved throughput, spectral efficiency, coding gain, diversity gain, reduced outage probability, receive SNR gain and a low decoding complexity.

4.2 Weighted Space-Time Trellis Codes

Beamforming [116] is a technique widely used in wireless communication at the transmitting or receiving node to achieve spatial selectivity. It is implemented by weighting transmit or receive signals with appropriate beamforming coefficients such that signals in the desirable direction experience constructive interference and rest of the signals experience destructive interference. This increases receive SNR at destination node and hence improves the error performance.

Jongren et al. [117] proposed OSTBC scheme combined with beamforming by considering partial CSI at transmitter. It was observed that this scheme shows significant gains over conventional OSTBC scheme. Liu and Gunawan [118] implemented beamforming for Alamouti space-time block codes (STBC) using perfect transmit CSI and reported significant performance gain over conventional STBC.

Li et al. [115] designed novel weighted space-time trellis codes by performing adaptive weighting of coded symbols at the transmitting end. WSTTC consider perfect or partial transmit CSI for transmission weighting. It outperforms the conventional STTC in terms of system performance and capacity. WSTTC provides receive SNR gain in addition to coding gain and diversity gain. Figure 4.1 shows transmission weighting for space-time trellis coded symbols for a node with N_t transmit antennas. The coded symbols $c_t^1, \dots, c_t^{N_t}$ generated by STTC encoder are multiplied with suitable beamforming coefficients $w_1, w_2, \dots, w_{N_t}$ based on the partial or perfect CSI prior to transmission.

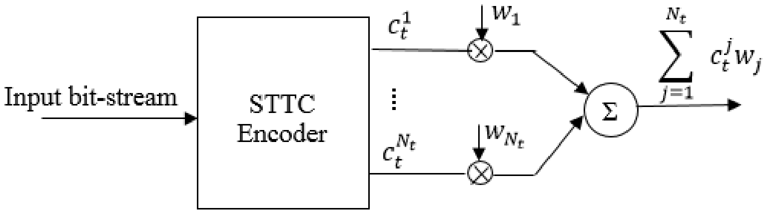

Figure 4.1: Transmission weighting of space-time trellis coded symbols

4.3 System Model of Cooperative Multilevel Weighted Space-Time Trellis Coding

Figure 4.2 shows the system model of proposed cooperative multilevel weighted space-time trellis coding (CMLWSTTC) technique. The proposed system consists of N cooperative nodes communicating with a common destination node *D*. Due to broadcast nature of wireless medium, each cooperative node overhears the information transmitted by other *N*-1 nodes to the destination node. Each cooperative node passes the overheard information through a set of *N*-1 decoders to detect the information of *N*-1 nodes. The decoded information of other nodes and self-information of cooperative node are encoded using multilevel coding scheme with STTC as component codes.

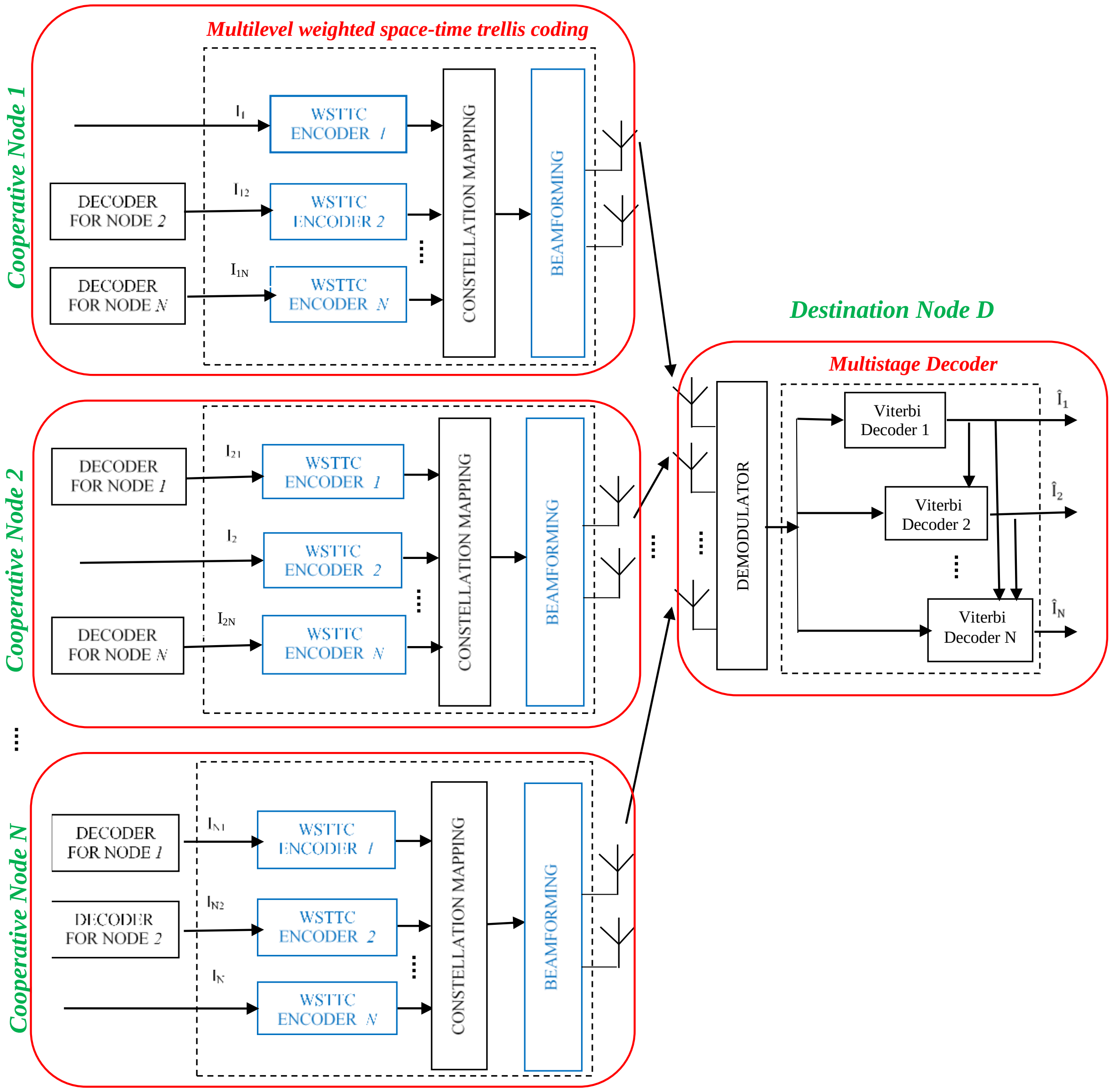

Figure 4.2: System model of Cooperative multilevel weighted space-time trellis coding (CMLWSTTC) technique

This involves processing of decoded information as well as self-information of cooperative node at L levels. For multilevel coded cooperation, number of levels at each cooperative node should be greater than or equal to number of nodes, i.e., $L \geq N$ [99]. For simplicity reasons, L=N is considered. The information at each level is passed through a STTC encoder to generate coded symbols. This implies that there is a set of N STTC encoders at each cooperative node. The coded symbols generated by STTC encoders are passed through a symbol translator which performs a transpose operation. The translated symbols are mapped to M-QAM constellation using MRM partitioning technique. It is assumed that perfect CSI is available at the transmitting and receiving end. Based on the available CSI at cooperative node, mapped symbols are weighted by proper beamforming coefficients prior to transmission. The weighted symbols are transmitted to destination node through N_t=2 transmit antennas. Thus, each transmitting node cooperates by sending its own information as well as the information of other nodes to common destination node. Section 4.4 explains the encoding operation, symbol translation, MRM partitioning, constellation mapping and weighting of mapped symbols at each cooperative node. The communication link between each transmitting node and destination node is assumed to experience statistically independent Rayleigh fading which is quasi-static frequency non-selective. The fading coefficients are uncorrelated and modelled as complex Gaussian random variable. If the information of other nodes is correctly decoded at cooperative node, then destination node receives the information of each node N times through independent fading channels and a diversity order of N is achieved. The destination node employs a low complexity multistage decoder that uses Viterbi algorithm based on ML decoding to detect the information of each mobile node. Section 4.5 explains the decoding operation at destination node.

4.4 Transmission Process at Cooperative Node

At c-th cooperative node (c=1,2,…,N), the information given to a set of N STTC encoders is I_c (own information of node c) and I_{cd} (decoded information of other nodes d =1,2,…,N and $d≠c$). I_c is processed on c-th level and $I_{cd}$is processed on d^{th} level of c-th cooperative node. For example, at cooperative node 1, the information given to a set of encoders is I_1 (its own information at level 1) and I_{12},…, I_{1N} (decoded information of rest of the nodes) at levels 2,…,N respectively. There is a STTC encoder at each level of c-th cooperative node. The output of STTC encoder e (e=1,2,…,N) at time t, $S_c(e)$ is given as

$$S_c(e) = x_{ct}^1(e), x_{ct}^2(e) \; ; \; c,\, e=1,2,\ldots,N \tag{4.1}$$

The encoded outputs $x_{ct}^1(e), x_{ct}^2(e)$ form a space-time trellis coded symbol, whereby symbol $x_{ct}^j(e)$; j=1,2 is to be transmitted by j-th transmit antenna of c-th cooperative node. Each STTC used in multilevel coding is designed for a 4-QAM constellation. The complex form of STTC output symbol $x_{ct}(e)$ is a+ib ; a, b ∈ {1,-1}.

The STTC output from N levels $S_c(1), \ldots, S_c(N)$ are given as an input to symbol translator to produce translated symbols.

$$T_c(1) = \; x_{ct}^1(1)\, x_{ct}^1(2) \ldots \, x_{ct}^1(N) \tag{4.2}$$

$$T_c(2) = x_{ct}^2(1)\, x_{ct}^2(2) \ldots \, x_{ct}^2(N) \tag{4.3}$$

The translated symbols get mapped to M-QAM constellation through MRM partitioning strategy. This involves partitioning of M-QAM constellation into L levels of resolution such that M=4^L considering each resolution as a 4-QAM constellation. Because of L levels of partition, the information data stream at each node traverses through a set of L STTC encoders. This enables the use of STTC designed for 4-QAM in the mapping procedure. Since L=N, therefore, there are N STTC encoders.

Prior to transmission, mapped symbols are weighted based on the available CSI at cooperative node to provide beamforming. The beamforming scheme is used to dynamically allocate transmit power to transmit antennas. The weighting coefficient for j-th transmit antenna, w_j is given as

$$w_j = \frac{h_{ij}^t}{\sqrt{\sum_{j=1}^{N_t} |h_{ij}^t|^2}} \tag{4.4}$$

where, h_{ij} is fading coefficient between i-th receive antenna and j-th transmit antenna. The weighting coefficients satisfy the normalization constraint $\sum_{j=1}^{N_t} |w_j|^2 = 1$ such that average signal energy is unity.

The weighted symbols are transmitted through N_t=2 transmit antennas. The symbol transmitted by c-th cooperative node and j-th (j=1, 2) transmit antenna at time t, Q_{ct}^j is given as

$$Q_{ct}^j = w_j \left[\sum_{e=1}^{N} \mathit{\Delta}_e x_{ct}^j(e)\right] \tag{4.5}$$

where, $\mathit{\Delta}_1, \dots, \mathit{\Delta}_N$ are cluster distances during MRM partitioning.

4.5 Reception Process at Destination Node

The signal received at i-th (i=1,2,…,N_r) receive antenna of destination node *D*, r_{Dt}^i is a noisy superposition of faded signals transmitted by cooperative users.

$$\begin{aligned} r_{Dt}^i &= \sum_{c=1}^{N} h_{Dc}^t Q_{ct}^j + n_{Dt}^i \\ &= \sum_{c=1}^{N} h_{Dc}^t\, w_j \left[\sum_{e=1}^{N} \mathit{\Delta}_e x_{ct}^j(e)\right] + n_{Dt}^i \\ &= \sum_{c=1}^{N} \sum_{e=1}^{N} h_{Dc}^t w_j \mathit{\Delta}_e x_{ct}^j(e) + n_{Dt}^i \end{aligned} \tag{4.6}$$

where, h_{Dc} is fading coefficient between destination node *D* and cooperative node c and n_{Dt}^i is noise associated with i-th receive antenna of destination node *D*. This research work considers error-free decoding of other nodes' information at each cooperative node, which implies

$$x_{1t}(e) = x_{2t}(e) = \cdots = x_{Nt}(e) = x_t(e) \tag{4.7}$$

Thus, equation (4.6) can be expressed as

$$r_{Dt}^i = \sum_{e=1}^{N} \sum_{c=1}^{N} h_{Dc}^t\, w_j \mathit{\Delta}_e x_t^j(e) + n_{Dt}^i \tag{4.8}$$

4.5.1 Multistage Decoding

In order to detect the information of each mobile node, destination node uses a multistage decoder having low computational complexity. The received signal is fed to all the stages of multistage decoder. The number of stages in multistage decoder are equal to the number of levels in multilevel coding. There is a Viterbi decoder at each stage to decode the corresponding component code. It decodes the received signal by deriving branch metrics for a data frame. The coded information by encoder 1 is decoded by decoder at stage 1 which executes a search based on maximising likelihood function by considering hypothesized value of $x_t(1)$. Stage 1 decoder has no knowledge of values $x_t(2), \dots, x_t(N)$, so it considers them as nuisance variables and average them out. The likelihood function to estimate $x_t(1)$ in the form of branch metric is

$$L\big(x_t(1)\big) = log\left(\sum_{\substack{x_t(e)\\ e=2,\dots,N}} exp\left[\frac{|\, r_{Dt}^{i} - \sum_{e=1}^{N}\sum_{c=1}^{N} h_{Dc}^{t} w_j \Delta_e x_t^{j}(e)\,|^2}{2{\sigma_n}^2}\right]\right) \tag{4.9}$$

Once $x_t(1)$ is estimated, its value is passed to subsequent decoding stages. The decoder at stage 2 utilises the estimated information of $x_t(1)$ to decode the coded information of encoder 2 i.e., to estimate $x_t(2)$. The similar procedure is followed to decode the coded information of encoders 3 to N. At decoding stage s ($1 < s < N$), Viterbi decoder executes a search based on maximising likelihood function by considering hypothesized value of $x_t(s)$. Stage s decoder has no knowledge of values $x_t(s+1), \dots, x_t(N)$, so it considers them as nuisance variables and average them out. Since decoding starts from stage 1, the outputs of stage 1 to s-1 decoders are available. The likelihood function to estimate $x_t(s)$ in the form of branch metric is

$$L\big(x_t(s)\big) = log\left(\sum_{\substack{x_t(e)\\ e=s+1,\dots,N}} exp\left[\frac{|\, r_{Dt}^{i} - \sum_{e=s}^{N}\sum_{c=1}^{N} h_{Dc}^{t} w_j \Delta_e x_t^{j}(e) - \sum_{p=1}^{s-1}\sum_{c=1}^{N} h_{Dc}^{t} w_j \Delta_p \hat{x}_t^{j}(p)\,|^2}{2{\sigma_n}^2}\right]\right) \tag{4.10}$$

where, $\hat{x}_t(p)$ is the estimated output of encoder p.

Finally, the estimated values of $x_t(1)$ to $x_t(N-1)$ from stages 1 to N-1 are used at stage N decoder to estimate $x_t(N)$. The likelihood function to estimate $x_t(N)$ in the form of branch metric is

$$\mathrm{L}\big(x_t(N)\big) = log\left(exp\left[\frac{|\, r_{Dt}^{i} - \sum_{c=1}^{N} h_{Dc}^{t} w_j \varDelta_N x_t(N) - \sum_{p=1}^{N-1} \sum_{c=1}^{N} h_{Dc}^{t} w_j \varDelta_p \hat{x}_t^{j}(p)|^2}{2{\sigma_n}^2}\right]\right) \qquad (4.11)$$

Thus, destination node decodes the component code at each level and thereby, obtains the information of user at that particular level.

4.6 Performance Analysis of Cooperative Multilevel Weighted Space-Time Trellis Coding

The performance of proposed CMLWSTTC system is evaluated in MATLAB for two cooperative nodes communicating with a common destination node. The information at each node is passed through two levels with STTC encoder at each level that produces coded information. The encoder at each level is assumed to be identical for both nodes such that full diversity gain can be achieved. The modulation scheme considered is 16-QAM. The constellation mapping is done using MRM partitioning technique which enables the use of 4-QAM constellation as basic unit with $\varDelta_1/\varDelta_2$=2. Each cooperative node has 2 transmit antennas and destination node has 1, 2 or 3 receive antennas. The information is transmitted in frames with 130 symbols in each frame. It is assumed that the channel characteristics are constant for a frame and change independently after the transmission of a frame. The channel between transmitting nodes and destination node is statistically independent from one antenna to other antenna and experience quasi-static Rayleigh fading. The path gains over channel are modelled as zero mean complex Gaussian random variables with unit variance. The channel state information is available at both transmitting and destination node. A multistage Viterbi decoder is used at destination node to extract the information of each node. The performance evaluation is done through FER and SNR curves.

Figure 4.3 shows the comparison of FER performance of proposed CMLWSTTC system and non-cooperative multilevel weighted space-time trellis coding (MLWSTTC) system [38]. It can be observed that the performance of CMLSTTC system is superior to non-cooperative

MLWSTTC system and is further enhanced with the number of receive antennas at destination node. The CMLWSTTC system shows an improvement of 2 dB SNR over non-cooperative MLWSTTC system at FER of 0.4×10^{0}, 10^{-1} and 0.6×10^{-2} for N_r=1, 2 and 3 respectively. The proposed CMLWSTTC system with two cooperative mobile nodes, requires SNR of ~24 dB when $N_r = 2$ and ~18.5 dB when $N_r = 3$ to achieve FER of 10^{-2}. Thus, the proposed system can achieve desired error performance at a moderate SNR.

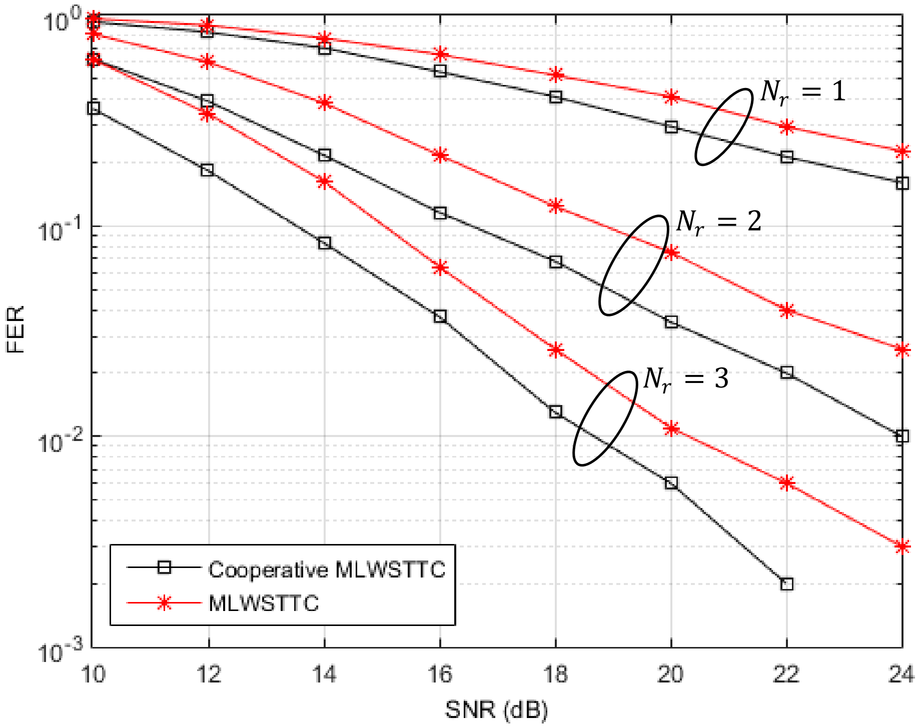

Figure 4.3: FER performance comparison of cooperative MLWSTTC (CMLWSTTC) and non-cooperative MLWSTTC systems having 2 transmit and 1, 2 and 3 receive antennas

Table 4.1 shows the improvement in performance of CMLWSTTC system over non-cooperative MLWSTTC system in terms of FER at various SNR values. It can be observed that as the number of receive antennas at destination node increases, the performance of CMLWSTTC system over non-cooperative MLWSTTC system improves further due to receive diversity. Additionally, a significant improvement in FER can be observed with a 2 dB increase in SNR. An increase in SNR indicates an improvement in the quality of signals transmitted by both cooperative nodes to destination node. This intensifies the effect of cooperative diversity and, results in reliable reception of dual copies of each mobile node’s information at destination node. Thus, the accuracy of decoder to detect each mobile node’s information increases and as a result, FER decreases.

Table 4.1: FER vs SNR values for cooperative multilevel weighted space-time trellis coding (CMLWSTTC) and multilevel weighted space-time trellis coding (MLWSTTC) systems with $N_r = 1$, 2 and 3 receive antennas at destination node

SNR (dB)	**FER**					
	$N_r = 1$		$N_r = 2$		$N_r = 3$	
	CMLWSTTC	MLWSTTC	CMLWSTTC	MLWSTTC	CMLWSTTC	MLWSTTC
10	0.933	0.967	0.623	0.817	0.361	0.621
12	0.834	0.899	0.391	0.601	0.183	0.341
14	0.702	0.781	0.217	0.384	0.083	0.163
16	0.541	0.654	0.116	0.217	0.037	0.064
18	0.411	0.521	0.068	0.124	0.013	0.026
20	0.297	0.411	0.035	0.075	0.006	0.011
22	0.213	0.296	0.02	0.04	0.002	0.006
24	0.161	0.227	0.01	0.026	0	0.003

4.7 Complexity Considerations

In this section, the minimum computational complexity of MLWSTTC and CMLWSTTC systems are calculated.

MLWSTTC system is formed by combining MLSTTC and transmission weighting. The minimum complexity of MLSTTC as given in section 4.6 is $L \times N_s \times N_b$. To create beamforming, the mapped symbols are weighted by appropriate coefficients prior to transmission. The calculation of weighting coefficients for N_t transmit antennas is shown in equation (4.4).

This results in an increase in minimum complexity by N_t. Therefore, the minimum complexity of MLWSTTC is $(L \times N_s \times N_b) + N_t$.

CMLWSTTC system is formed by using MLWSTTC scheme at each cooperative node. So, the minimum complexity of CMLWSTTC system is obtained by considering the complexity due to MLSTTC, transmission weighting, decoding at cooperative node and cooperative diversity. For M-QAM constellation, the minimum complexity due to MLWSTTC at each cooperative node is $(L \times N_s \times N_b) + N_t$. Each cooperative node employs a decoder prior to multilevel coding for detecting the overheard information of other nodes. This results in an increase in minimum complexity by $(L-1) \times N_s \times N_b$ for L-1 decoders at cooperative node. For N cooperative nodes employing MLWSTTC scheme, the minimum complexity becomes $N.[(L \times N_s \times N_b) + N_t + \{(L-1) \times N_s \times N_b\}]$ or, $N.[\{(2L-1) \times N_s \times N_b\} + N_t]$.

4.8 Summary of the Chapter

This chapter proposed a system where each mobile node uses multilevel coding scheme with space-time trellis codes as component codes for cooperative transmission. Each cooperative node decodes the information sent by other nodes to destination node and further encodes it. The coded symbols are mapped using MRM partitioning to M-QAM constellation. Based on the available CSI at cooperative nodes, the mapped symbols are weighted prior to transmission. The weighted symbols are sent through two transmit antennas. The destination node extracts the information of each node using multistage Viterbi decoder.

The performance of proposed CMLWSTTC system is compared to non-cooperative MLWSTTC system. It is observed that the performance of CMLWSTTC system is superior to non-cooperative MLWSTTC system by 2 dB at FER= 0.4×10^{0}, 10^{-1} and 0.6×10^{-2} for N_r=1, 2 and 3 respectively. The performance of CMLWSTTC system improves further with the number of receive antennas at destination node. The proposed system contributes in improving the performance of wireless communication.

Chapter 5

Cooperative Communication System based on Multilevel Dynamic Space-Time Trellis Codes

Contents

5.1 Introduction

Dynamic space-time codes [119], invented by Blanz *et al.*, select the optimum code set of generator sequences in a time-variant manner with or without feedback from receiver. The space-time codes are selected according to current channel conditions by using feedback information from receiver. The receiver can send feedback information in the form of an index of predefined channel profile that best matches the current channel profile. In [39], the concept of dynamic space-time codes is utilised to design dynamic space-time trellis codes. These are used as component codes in multilevel coding scheme. DSTTC consider CSI at transmitting and receiving end and outperform predefined STTC. They utilize the feedback information from receiver to adapt to current channel conditions. The current channel profile is compared with a number of predefined channel profiles in terms of power gain. The index of predefined channel profile that is the closest match is fed back by the receiver. Based on the feedback information, DSTTC encoder choose optimum code set of generator sequences. Multilevel dynamic space-time trellis codes (MLDSTTC) provide better performance than MLSTTC by using component DSTTC for multilevel coding and CSI at both transmitter and receiver. However, MLSTTC and MLDSTTC consider the case of single transmitting node and destination node. The transmitting node comprises its own information and utilizes multilevel coding scheme with STTC or DSTTC as component codes to generate coded information.

This chapter proposes a cooperative communication system which considers multiple transmitting nodes relaying information for each other to common destination node. Each transmitting node comprises its own information as well as the overheard information of neighbouring nodes. The system utilizes MLDSTTC at each transmitting node for cooperative transmission. The coded symbols are mapped to M-QAM constellation and transmitted to destination node. Cooperative transmission enables the mobile nodes to exploit spatial diversity without increasing the number of transmit antennas. It plays a contribution in enhancing the system performance by improving system throughput and robustness.

5.2 Dynamic Space-Time Trellis Codes

Blanz *et al.* [119] invented dynamic space-time codes, which can select the optimum code set of generator sequences in a time-variant manner with or without feedback from receiver. The dynamic space-time codes with no feedback can use a code-set with number of space-time codes out of which each code can be selected for a specific time interval. The dynamic space-time codes with feedback information from receiver can select a code-set in accordance with the present channel conditions. The receiver can send feedback information in the form of an index of predefined channel profile that best matches the current channel profile. It is to be noted that dynamic space-time coding scheme is different from a fully adaptive scheme. It utilises the information of current channel profile to select the best match of space-time code from predefined code-set instead of defining the space-time code. This simplifies the operation and reduces the signalling.

Jain and Sharma [39] proposed dynamic space-time trellis codes based on the concept of dynamic space-time codes. DSTTC consider CSI at both transmitting and receiving end, and as a result, outperform predefined STTC. These codes adapt to the current channel conditions on the basis of feedback information sent by receiver. The current channel profile is compared with the predefined channel profiles in terms of power gain. The index of predefined channel profile that is in close proximity to current channel profile is fed back to the transmitter. DSTTC encoder selects optimum code-set of generator sequences based on the feedback information. Figure 5.1 shows the working of DSTTC encoder with feedback information.

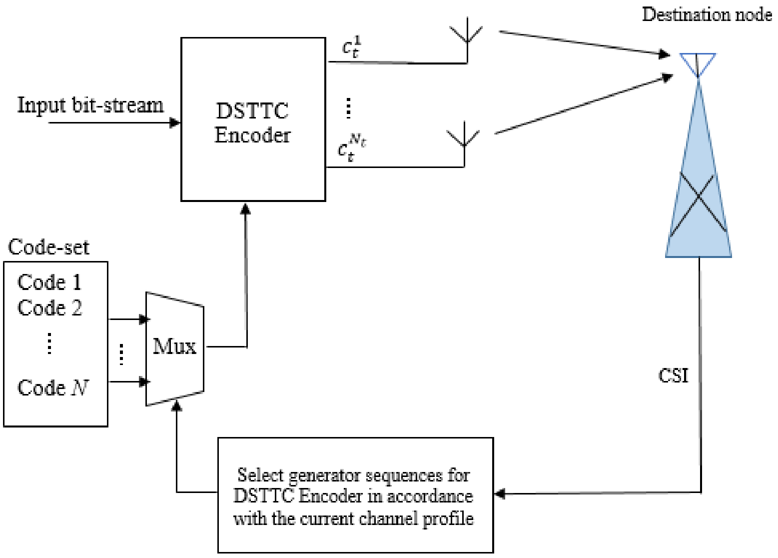

Figure 5.1: Dynamic space-time trellis coding scheme

5.3 System Model of Cooperative Multilevel Dynamic Space-Time Trellis Coding

Consider a system with N cooperative mobile nodes communicating with a common destination node D. Each mobile node acts as a cooperative node by transmitting its own information as well as the information of nearby mobile nodes to destination node. The structure of proposed cooperative multilevel dynamic space-time trellis coding (CMLDSTTC) system is shown in figure 5.2.

The transmitter structure shows the implementation of multilevel coding scheme with DSTTC as component codes for sending the information of mobile nodes. MLDSTTC can adapt to channel conditions and provide coding gain, diversity gain and spectral efficiency without bandwidth expansion. Each mobile node c (c=1,2,…,N) has L levels of information, out of which 1 level is comprised of self-information of mobile node and L-1 levels are comprised of overheard information transmitted by nearby mobile nodes d (d=1,2,…,N and $d \neq c$) to destination node. For convenience, it is assumed that the number of levels, L and cooperative mobile nodes, N are equal. The mobile node c uses c-th level for self-information and d-th level for the information of other mobile nodes. The coded information of other mobile nodes is first passed through a set of N-1 decoders to extract their respective information. The decoded information of other mobile nodes, I_{cd} and self-information, I_c are passed through a set of DSTTC encoders e (e=1,2,…,N). The coded information at each level is given to symbol translator that performs a transpose operation to produce translated symbols. These are mapped to M-QAM constellation with MRM partitioning technique. The modulated symbols are sent through N_t (=2) transmit antennas. It should be noted that each mobile node can have $\log_2 M$ levels of information, i.e., $L=\log_2 M=N$. In the proposed system, cooperative diversity plays the role of enhancing system throughput and robustness. The system throughput is enhanced when each mobile node's information is transmitted by itself as well as by other cooperative nodes. This way, the probability of successful delivery of mobile node's information at the destination node increases. The system robustness is enhanced in terms of increased diversity gain and reduced outage probability. The diversity gain of a non-cooperative mobile node with 2 transmit antennas is 2. On the other hand, diversity gain of N cooperative mobile nodes is $2N$. The outage probability of a mobile node's

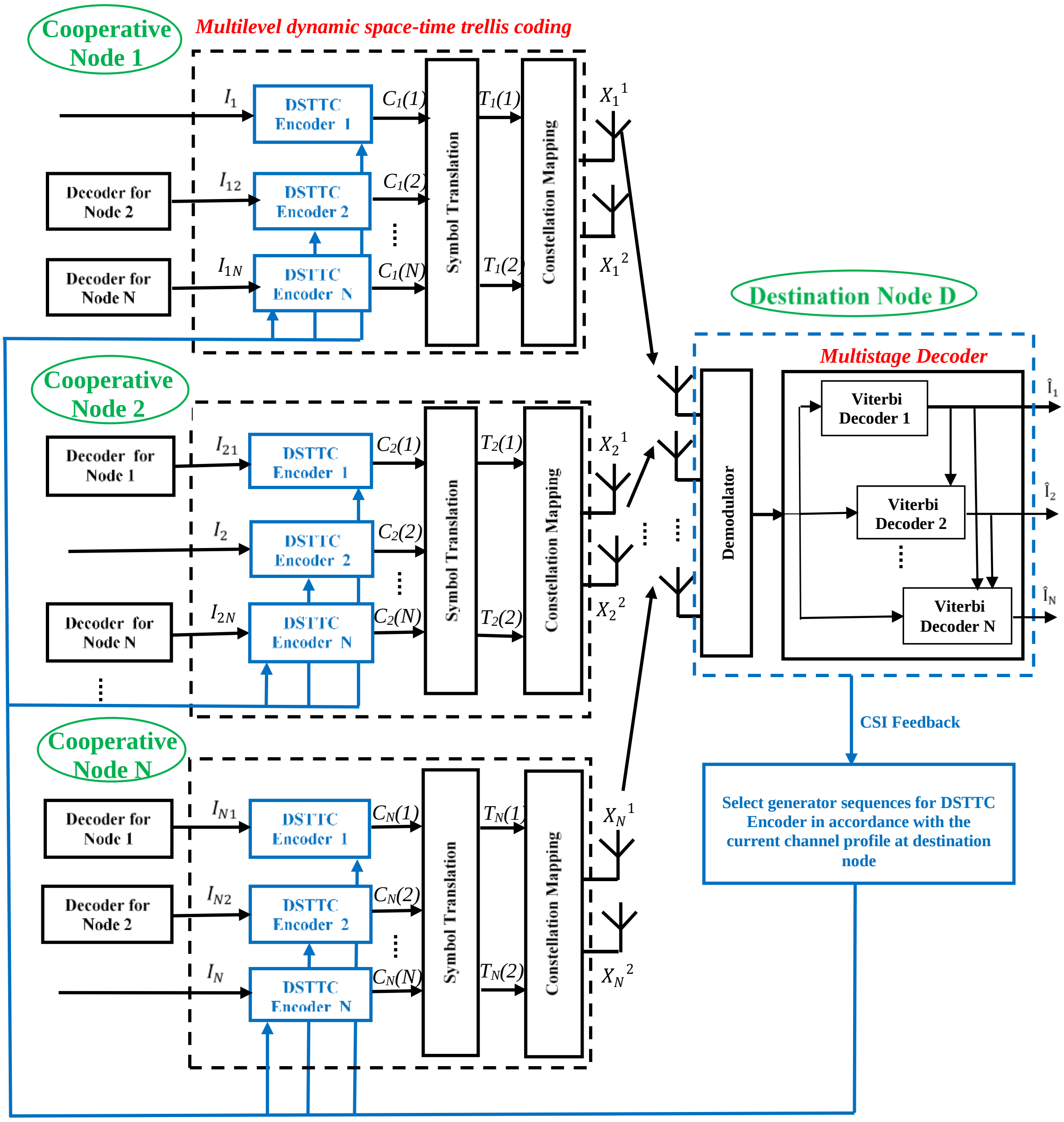

Figure 5.2: Transmitter and receiver structure of Cooperative multilevel dynamic space-time trellis coding (CMLDSTTC) system

information transmission to destination node can be represented as $\mathrm{Pr}_{\mathrm{outage}} \sim 1/(\mathrm{SNR})^{\mathrm{N}}$ in case of high SNR [120]. It indicates that outage probability reduces with an increase in the number of cooperative nodes.

5.4 Transmission Process at Cooperative Node

Each cooperative node uses a set of N encoders which perform dynamic space time trellis coding of input information at their respective levels. Instead of using predefined generator sequences, DSTTC encoder selects generator sequences according to the channel conditions. The channel between each cooperative node and destination node experiences independent Rayleigh fading which is quasi-static and frequency non-selective. It is assumed that perfect CSI is available at transmitting and receiving end. The cooperative node enables DSTTC encoder at each level to choose optimum code-set of generator sequences by using feedback information from destination node. The same feedback information reaches every DSTTC encoder, ensuring same generator sequences at each information level of cooperative node.

The algorithm for selecting code-set of generator sequences computes total channel power gain G_P between transmit and receive antennas for current channel profile at destination node.

$$G_P = \sum_{j=1}^{N_t} \sum_{i=1}^{N_r} \sum_{c=1}^{N} \left| h_{cij}{}^{t} \right|^2 \tag{5.1}$$

where, $h_{cij}{}^{t}$ is path-gain for j-th (j=1,2,…, N_t) transmit antenna of cooperative node c and i-th (i=1,2,…, N_r) receive antenna of destination node. The path-gains $h_{cij}{}^{t}$ are uncorrelated and modelled as complex Gaussian random variables with mean zero and variance half per dimension. The current channel profile is compared with predefined channel profiles in terms of power gain. The index of predefined channel profile which is the best match is fed back to cooperative nodes. It is assumed that there is no feedback delay from destination node to cooperative nodes. Based on this feedback information, each cooperative node selects an optimum code-set of generator sequences G^{cp}.

$$G^{cp} = [(\boldsymbol{g}_1^{1,cp}, \boldsymbol{g}_1^{2,cp}, \dots \boldsymbol{g}_1^{m,cp}), (\boldsymbol{g}_2^{1,cp}, \boldsymbol{g}_2^{2,cp}, \dots \boldsymbol{g}_2^{m,cp}), \dots, (\boldsymbol{g}_N^{1,cp}, \boldsymbol{g}_N^{2,cp}, \dots \boldsymbol{g}_N^{m,cp})] \tag{5.2}$$

where, $m = \log_2 M$ represents binary input sequences corresponding to I_c or I_{cd} received by DSTTC encoder e ; $(\boldsymbol{g}_e^{1,cp}, \boldsymbol{g}_e^{2,cp} \dots \boldsymbol{g}_e^{m,cp})$ represents generator sequences for DSTTC encoder e at channel profile cp.

$$\boldsymbol{g}_e^{1,cp} = [(g_{0,1}^{1,cp} \dots g_{0,N_t}^{1,cp}), (g_{1,1}^{1,cp} \dots g_{1,N_t}^{1,cp}) \dots (g_{v_1,1}^{1,cp} \dots g_{v_1,N_t}^{1,cp}] \tag{5.3}$$

$$\boldsymbol{g}_e^{2,cp} = [(g_{0,1}^{2,cp} \dots g_{0,N_t}^{2,cp}), (g_{1,1}^{2,cp} \dots g_{1,N_t}^{2,cp}) \dots (g_{v_2,1}^{2,cp} \dots g_{v_2,N_t}^{2,cp})\ ] \tag{5.4}$$

$$\boldsymbol{g}_e^{m,cp} = [(g_{0,1}^{m,cp} \dots g_{0,N_t}^{m,cp}), (g_{1,1}^{m,cp} \dots g_{1,N_t}^{m,cp}) \dots (g_{v_m,1}^{m,cp} \dots g_{v_m,N_t}^{m,cp})] \tag{5.5}$$

where, $\mathrm{g}_{\mathrm{v,a}}^{\mathrm{w,cp}}$ (w=1,2,…,m ; v=0,1,…,v_w ; a = 1, 2…N_t) is an element of M-QAM constellation set and v_w is the memory order of w-th shift register. The binary input sequences corresponding to I_c or I_{cd} are multiplied by selected generator sequences for DSTTC encoder e. The multiplier outputs from all shift registers are then added modulo M to generate the encoded output. The output of DSTTC encoders at levels 1 to N at channel profile cp and time t is given by

$$S_c(\mathrm{e}) = x_{c,t}^{cp}(e)^1, x_{c,t}^{cp}(e)^2 \ ;\ c,\ e=1,\ 2\dots N \tag{5.6}$$

The encoded symbols from N levels, $S_c(1),\dots,S_c(N)$ are given as an input to symbol translator to produce translated symbols.

$$T_c(1) = x_{c,t}^{cp}(1)^1\, x_{c,t}^{cp}(2)^1 \dots x_{c,t}^{cp}(N)^1 \tag{5.7}$$

$$T_c(2) = x_{c,t}^{cp}(1)^2\, x_{c,t}^{cp}(2)^2 \dots x_{c,t}^{cp}(N)^2 \tag{5.8}$$

These symbols get mapped to M-QAM constellation with the help of MRM partitioning technique, which is followed for L levels of partition with M=4^L. The MRM partitioning of constellation considers each cluster as a 4-QAM constellation. As a result, component DSTTC designed for 4-QAM can be directly used in the mapping process. The output of DSTTC encoder at first level is mapped to clusters, the output of DSTTC encoders at subsequent levels are mapped to sub-clusters, and the output of DSTTC encoder at level L is mapped to constellation points. The coded output symbols from DSTTC encoder at each level are drawn from a 4-QAM constellation. Therefore, each point in M-QAM constellation can be expressed as

$$X = \Delta_1 x^{cp}(1) + \Delta_2 x^{cp}(2) + \cdots + \Delta_L x^{cp}(L) \tag{5.9}$$

Considering equation (5.9) and $L=N$, the symbol transmitted by c-th cooperative node at time t by j-th (j=1, 2) transmit antenna can be represented as

$$X_{c,t}^{j} = \sum_{e=1}^{N} \Delta_e\, x_{c,t}^{cp}(e)^j \tag{5.10}$$

where, $\Delta_1, \ldots, \Delta_N$ are cluster distances corresponding to $x_{c,t}^{cp}(1), x_{c,t}^{cp}(2) \ldots x_{c,t}^{cp}(N)$ respectively during partitioning.

5.5 Reception Process at Destination Node

The receiver structure of figure 5.2 shows the destination node receiving noisy superposition of statistically independent Rayleigh faded signals transmitted by cooperative nodes. In case of successful decoding of other nodes information at cooperative node, the destination node receives the information of each cooperative node as many times as there are number of cooperative nodes, thus achieving full diversity order.

$$Y_{D,t}^{i} = \sum_{c=1}^{N} h_{D,c}^{t} X_{c,t}^{j} + n_{D,t}^{i} = \sum_{c=1}^{N}\sum_{e=1}^{N} h_{D,c}^{t}\, \Delta_e x_{c,t}^{cp}(e)^j + n_{D,t}^{i} \tag{5.11}$$

where, ${Y_{D,t}}^{i}$ is the signal received at i-th receive antenna of destination node D at time t. Error-free decoding of other nodes' information at each cooperative node is considered which implies,

$$x_{1,t}^{cp}(e) = x_{2,t}^{cp}(e) = \cdots = x_{N,t}^{cp}(e) = x_{t}^{cp}(e) \tag{5.12}$$

Substituting equation (5.12) in (5.11),

$$Y_{D,t}^{i} = \sum_{e=1}^{N}\sum_{c=1}^{N} h_{D,c}^{t}\, \Delta_e x_{t}^{cp}(e)^j + {n_{D,t}}^{i} \tag{5.13}$$

where, $x_{t}^{cp}(e)$ is the encoded output of DSTTC encoder e at channel profile cp and time t.

The received signal is demodulated to extract the coded signal, which is then fed to multistage decoder to extract the information of each cooperative node. The multistage decoder performs in various stages, starting from stage 1 and terminating after the decoding operation at stage N. A Viterbi decoder is used at each stage that computes branch metrics for a data frame by performing a search based on maximising the likelihood function in order to detect the information. The Viterbi decoder at stage 1 detects the value of $x_t^{cp}(1)$ by considering hypothesized value of $x_t^{cp}(1)$. It has no knowledge of values $x_t^{cp}(2), \ldots, x_t^{cp}(N)$, therefore, it considers them as nuisance variables and average them out. The likelihood function to estimate $x_t^{cp}(1)$ in the form of branch metric is

$$L\left(x_t^{cp}(1)\right) = log\left(\sum_{\substack{x_t^{cp}(e) \\ e=2\ldots N}} exp\left[\frac{|\,Y_{D,t}^{i} - \sum_{e=1}^{N}\sum_{c=1}^{N} h_{D,c}^{t}\Delta_e x_t^{cp}(e)^j\,|^2}{2{\sigma_n}^2}\right]\right) \tag{5.14}$$

The estimated information at stage 1 is passed to decoding stages 2 to N. The similar procedure is followed for remaining stages. The Viterbi decoder at stage s ($1 < s < N$) uses the estimated information of stages 1 to s-1 and hypothesized value of $x_t^{cp}(s)$. It has no knowledge of values $x_t^{cp}(s+1), \ldots, x_t^{cp}(N)$, so these are considered as nuisance variables and averaged out.The likelihood function to estimate $x_t^{cp}(s)$ in the form of branch metric is

$$L\left(x_t^{cp}(s)\right) =$$

$$log\left(\sum_{\substack{x_t^{cp}(e) \\ e=s+1\ldots N}} exp\left[\frac{|\,Y_{D,t}^{i} - \sum_{e=s}^{N}\sum_{c=1}^{N} h_{D,c}^{t}\Delta_e x_t^{cp}(e)^j - \sum_{p=1}^{s-1}\sum_{c=1}^{N} h_{D,c}^{t}\Delta_p \hat{x}_t^{cp}(p)^j\,|^2}{2{\sigma_n}^2}\right]\right) \tag{5.15}$$

where, $\hat{x}_t^{cp}$(p) is the estimated output of encoder p.

Finally, $x_t^{cp}(N)$ is detected by Viterbi decoder at stage N using estimated information of stages 1 to N-1. The likelihood function to estimate $x_t^{cp}(N)$ in the form of branch metric is given by

$$L\left(x_t^{cp}(N)\right) = log\left(exp\left[\frac{|\,Y_{D,t}^{i} - \sum_{c=1}^{N} h_{D,c}^{t}\Delta_N x_t^{cp}(N) - \sum_{p=1}^{N-1}\sum_{c=1}^{N} h_{D,c}^{t}\Delta_p \hat{x}_t^{cp}(p)^j|^2}{2{\sigma_n}^2}\right]\right) \tag{5.16}$$

Thus, the information of each cooperative node is extracted at each stage of multistage decoder.

5.6 Performance Analysis of Cooperative Multilevel Dynamic Space-Time Trellis Coding

The performance of proposed CMLDSTTC system is analysed for two cooperative mobile nodes communicating with a common destination node. Each mobile node has two levels of information, one for its own information and other for the information of nearby cooperative node. A DSTTC encoder is employed at each level to produce the coded information according to current channel conditions. The proposed system considers 16-QAM scheme and MRM partitioning for mapping of signal points. MRM partitioning allows the usage of 4-QAM constellation at each information level of cooperative node with Δ_1/Δ_2=2. Each cooperative node has two transmit antennas to send the information in frames with 130 symbols in each frame. The channel between cooperative node and destination node is statistically independent from one antenna to other antenna and experience quasi-static frequency non-selective Rayleigh fading. Each cooperative node and destination node has the availability of perfect CSI. The destination node receives the coded information of cooperative nodes using 1 or 2 receive antennas, which is demodulated and finally detected by a multistage Viterbi decoder. The power gain of current channel profile at destination node is compared with the power gains of two predefined channel profiles. The closest match of current channel profile is selected and its index is fed back to cooperative nodes. Based on the feedback information, each cooperative node chooses the optimum code-set of generator sequences.

The assumption of perfect CSI at transmitting node holds only if the feedback link from destination to transmitting node has no delay and errors [2]. Practically, the perfect estimation of CSI and zero-delay error free feedback to transmitting nodes are not possible, particularly in environments where channel parameters are rapidly time-varying [117]. Perfect CSI and zero-delay error-free feedback are considered as an ideal case [118]. An imperfect CSI at transmitting node signifies that the feedback information from destination node is not estimated correctly. A delayed feedback at transmitting node indicates the variations in channel conditions and signifies that the feedback information does not correspond to current channel profile. Thus, the transmitting node receives feedback information corresponding to old channel profile. Therefore, imperfect transmit CSI and erroneous feedback with delay, hamper the dynamic mechanism and result in a loss in system performance. For simplicity reasons, quasi-static frequency non-selective Rayleigh fading environment is considered, where the channel parameters are constant for a frame and changes after the transmission of frame. Such a fading environment helps in a reliable estimation of feedback information at the transmitting node, resulting in an ease in the implementation of dynamic mechanism.

The performance of proposed system is evaluated in MATLAB in terms of FER and SNR curves. The performance of proposed CMLDSTTC system, CMLSTTC system and existing non-cooperative MLDSTTC system [39] is compared using 1 bit of feedback information from destination node, as shown in figure 5.3.

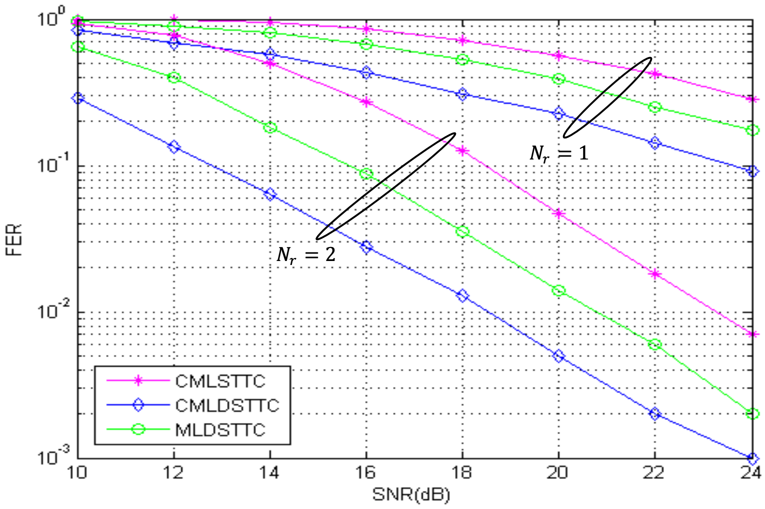

Figure 5.3: FER performance comparison of CMLSTTC, CMLDSTTC and MLDSTTC systems having 2 transmit and 1, 2 receive antennas using 1 bit CSI feedback

The specifications of these three systems are given in table 5.1. It can be observed that CMLDSTTC system outperforms CMLSTTC system by

~5.6 dB and MLDSTTC system by ~3.1 dB at FER of 3×10^{-1} when 1 receive antenna is used at the destination node. In case of two receive antennas at destination node, CMLDSTTC system outperforms CMLSTTC system by ~5 dB and MLDSTTC system by ~2.5 dB at FER of 10^{-2}. The FER values of these three systems at SNR of 18 dB and 20 dB is given in table 5.2 for 1 and 2 receive antennas at destination node. The results indicate that the error performance of CMLDSTTC system is superior to CMLSTTC system and existing MLDSTTC system. The performance of CMLDSTTC system improves further by increasing the receive antennas at destination node.

Table 5.1: Comparison of multilevel dynamic space-time trellis coding (MLDSTTC) system, cooperative multilevel space-time trellis coding (CMLSTTC) system and cooperative multilevel dynamic space-time trellis coding (CMLDSTTC) system

Parameter	**MLDSTTC**	**CMLSTTC**	**CMLDSTTC**
Cooperation	no	yes	yes
Component Code for multilevel coding	dynamic STTC	predefined STTC	dynamic STTC
Channel State Information	perfect CSI at both transmitter and receiver	perfect CSI at receiver only	perfect CSI at both transmitter and receiver
Feedback information from destination node	yes	no	yes
Minimum Complexity	38	96	106
SNR requirement at $FER=10^{-2}$ *(two transmit and two receive antennas)*	21 dB	23.5 dB	18.5 dB

Table 5.2: FER values of MLDSTTC, CMLSTTC and CMLDSTTC systems at a given SNR for $N_r = 1$ and 2 receive antennas at destination node

SNR (dB)	FER					
	$N_r = 1$			$N_r = 2$		
	MLDSTTC	CMLSTTC	CMLDSTTC	MLDSTTC	CMLSTTC	CMLDSTTC
18	0.532	0.716	0.309	0.035	0.126	0.013
20	0.39	0.568	0.226	0.014	0.047	0.005

The performance evaluation of proposed CMLDSTTC system is also done for varying bits of feedback information from destination node. The CMLDSTTC system with P predefined channel profiles requires $\log_2 P$ bits to be fed back to the transmitting node in order to select the optimum generator sequences. Example, a system with 2, 4 or 8 predefined channel profiles requires 1, 2 or 3 bits of feedback information respectively.

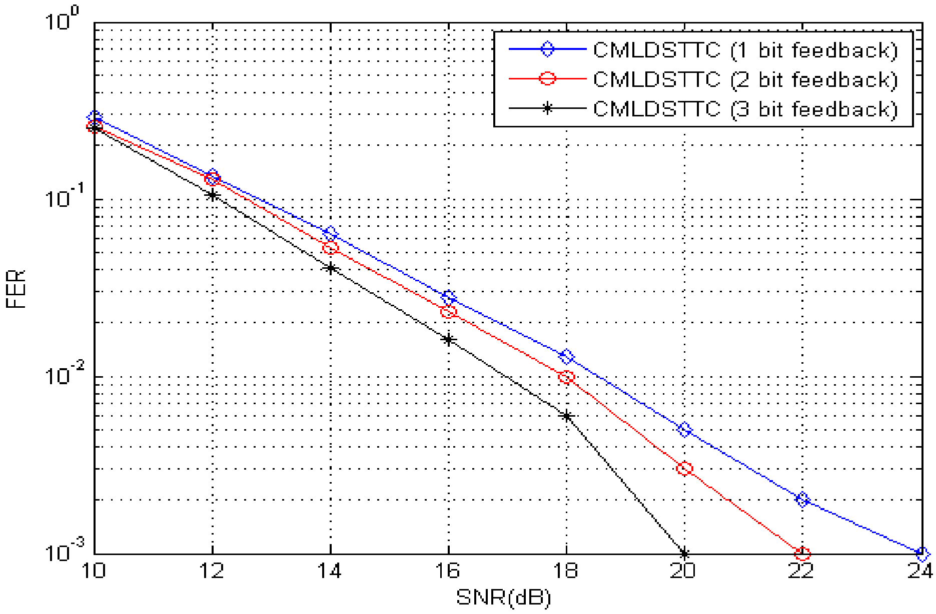

Figure 5.4: FER performance comparison of CMLDSTTC system having 2 transmit and 2 receive antennas for 1, 2 and 3 bits of feedback information from destination node

Figure 5.4 shows FER performance comparison of CMLDSTTC system having two transmit and two receive antennas for 1, 2 and 3 bits of feedback information. The code sets corresponding to predefined channel profiles for 1, 2 and 3 feedback bits are given in tables 5.3, 5.4 and 5.5 respectively. It can be observed from figure 5.4 that system performance improves by increasing the feedback bits of information. CMLDSTTC system with 1, 2 and 3 bits of feedback information requires SNR of 21 dB, 20 dB and 19 dB respectively at FER of 3×10^{-2}. At SNR of 20 dB, FER values of CMLDSTTC system with 1, 2 and 3 bits of feedback information are 0.005, 0.003 and 0.001 respectively.

Table 5.3: Code sets for predefined channel profiles with 1 bit of feedback information

Code set	**Set of generator sequences for DSTTC encoder**
1	g1=[(02),(20)] g2=[(01),(10)]
2	g1= [(02),(22)] g2= [(01),(22)]

Table 5.4: Code sets for predefined channel profiles with 2 bits of feedback information

Code set	**Set of generator sequences for DSTTC encoder**
1	g1=[(02),(20)] g2=[(01),(10)]
2	g1= [(02),(21)] g2= [(11),(20)]
3	g1= [(12),(20)] g2= [(01),(20)]
4	g1= [(02),(22)] g2= [(01),(22)]

Table 5.5: Code sets for predefined channel profiles with 3 bits of feedback information

Code set	**Set of generator sequences for DSTTC encoder**
1	g1=[(02),(20)] g2=[(01),(10)]
2	g1= [(02),(21)] g2= [(11),(20)]
3	g1= [(12),(20)] g2= [(01),(20)]
4	g1= [(02),(21)] g2= [(11),(20)]
5	g1= [(12),(20)] g2= [(01),(20)]
6	g1= [(02),(21)] g2= [(11),(20)]
7	g1= [(12),(20)] g2= [(01),(20)]
8	g1= [(02),(22)] g2= [(01),(22)]

The improvement in performance of CMLDSTTC system with number of feedback bits of information is due to the increase in number of predefined channel profiles. Since the dynamic mechanism operates by comparing power gain of current channel profile and predefined channel profiles, therefore system can choose the closest match for current channel profile by increasing the number of predefined channel profiles. This improves the accuracy of dynamic mechanism. As a result, the transmitting node can select a better code-set of generator sequences. Thus, an increase in number of feedback bits improves the performance of CMLDSTTC system. However, the system complexity increases with an increase in number of feedback bits. This implies that there is a trade-off between improving system performance by increasing number of feedback bits and reducing system complexity. Hence, the appropriate option can be chosen according to the system requirements.

5.7 Complexity Considerations

In this section, the complexity of proposed CMLDSTTC system, CMLSTTC system and existing non-cooperative MLDSTTC system are computed considering 1 bit of feedback information from destination node.

MLDSTTC system is formed by using dynamic mechanism of optimum generator sequence selection in MLSTTC system. So, the minimum complexity of MLDSTTC system is obtained by considering the complexity due to MLSTTC and dynamic mechanism. The minimum complexity of MLSTTC as given in section 4.6 is $\mathrm{L} \times \mathrm{N_s} \times \mathrm{N_b}$. The dynamic mechanism for selecting the optimum generator sequences of component STTC at cooperative node requires CSI feedback from destination node. This involves computation of power gain at current channel profile. The power gain formula in equation (6.1) for non-cooperative case becomes

$$G_P = \sum_{j=1}^{N_t} \sum_{i=1}^{N_r} \left| h_{ij}^{t} \right|^2 \tag{5.17}$$

For N_t transmit and N_r receive antennas, it results in an increase in minimum complexity by $N_t \times N_r$. The comparison of power gain at current channel profile with power gains at P predefined channel profiles results in an increase in minimum complexity by P. So, the minimum complexity of MLDSTTC system is $(\mathrm{L} \times \mathrm{N_s} \times \mathrm{N_b}) + (N_t \times N_r) + P$.

CMLSTTC system is formed by using MLSTTC scheme at each cooperative node. So, the minimum complexity of CMLSTTC system is obtained by considering the complexity due to MLSTTC, decoding at cooperative node and cooperative diversity. For M-QAM constellation, the minimum complexity due to MLSTTC at each cooperative node is $\mathrm{L} \times \mathrm{N_s} \times \mathrm{N_b}$. Each cooperative node employs a decoder prior to multilevel coding for detecting the overheard information of other nodes. This results in an increase in minimum complexity by $(L-1) \times N_s \times N_b$ for L-1 decoders at cooperative node. For N cooperative nodes employing MLSTTC scheme, the minimum complexity becomes $N.[(L \times N_s \times N_b) + \{(L-1) \times N_s \times N_b\}]$ or, $N.\{(2L-1) \times N_s \times N_b\}$.

CMLDSTTC system is formed by using MLDSTTC scheme at each cooperative node. So, the minimum complexity of CMLDSTTC system is obtained by considering the complexity due to MLSTTC, decoding at cooperative node, dynamic operation, and cooperative diversity. For M-QAM constellation, the minimum complexity due to CMLSTTC system is $N.\{(2L-1) \times N_s \times N_b\}$. The dynamic mechanism for selecting the optimum generator sequences of component STTC at each cooperative node requires CSI feedback from destination node. For N cooperative nodes with N_t transmit antennas and a destination node with N_r receive antennas, the computation of power gain at current channel profile according to equation (5.1) results in an increase in minimum complexity by $N \times N_t \times N_r$. The comparison of power gain at current channel profile with power gains at P predefined channel profiles results in an increase in minimum complexity by P. So, the minimum complexity of CMLDSTTC system is $N.\{(2L-1) \times N_s \times N_b\} + (N \times N_t \times N_r) + P$.

5.8 Summary of the Chapter

This chapter proposed a system where cooperative nodes transmit their information cooperatively to a common destination node using multilevel dynamic space-time trellis coding scheme. The DSTTC encoder at each information level of cooperative node takes CSI feedback from destination node and adapts to the current channel conditions by modifying its generator sequences. The selected code-set of generator sequences is in accordance with the predefined channel profile that closely matches the current channel profile at destination node. The performance of proposed CMLDSTTC system, CMLSTTC system with predefined STTC and existing non-cooperative MLDSTTC system is compared using 1 bit of CSI feedback. The CMLDSTTC system outperforms CMLSTTC and MLDSTTC systems by ~5.6 dB and ~3.1 dB respectively at FER of 3×

10^{-1}, N_r=1 and, by ~5 dB and ~2.5 dB respectively at FER of 10^{-2}, N_r=2. SNR requirement of proposed CMLDSTTC system reduces with an increase in bits of CSI feedback. CMLDSTTC system with 1, 2 and 3 bits of CSI feedback requires SNR of 21 dB, 20 dB and 19 dB respectively at FER of 3×10^{-2}, N_r=2.

Chapter 6

Concluding Remarks and Future Scope

Contents

6.1 Concluding Remarks

In this research work, multilevel coding scheme in conjunction with cooperative diversity is investigated in an endeavour to meet the requirements of next generation communication system such as high spectral efficiency, high data rates, low error rates, low outage probability and improved coverage.

The proposed system considers a number of mobile nodes that transmit their information cooperatively to a common destination node. Each cooperative node employs multilevel coding scheme to process their own information as well as the information of nearby nodes. The self-information of a cooperative node u is encoded at level u and the information of nearby nodes are encoded at remaining levels. The coded symbols get mapped to M-QAM constellation with the help of a partitioning scheme based on multi-resolution modulation, which reduces the system complexity. The mapped symbols are modulated and transmitted to destination node by all cooperative nodes. Thus, the destination node receives multiple copies of information of each mobile node. It demodulates the received signal and decodes it using a multistage decoder based on Viterbi algorithm. The Viterbi decoder at each stage performs maximum likelihood decoding to detect the information of each mobile node at a low decoding complexity. The proposed cooperative multilevel coding system is investigated for various error-correcting codes such as convolutional codes, pseudo space-time trellis codes, weighted space-time trellis codes, and dynamic space-time trellis codes. Figure 6.1 shows the methodology followed to design the proposed cooperative multilevel coding system.

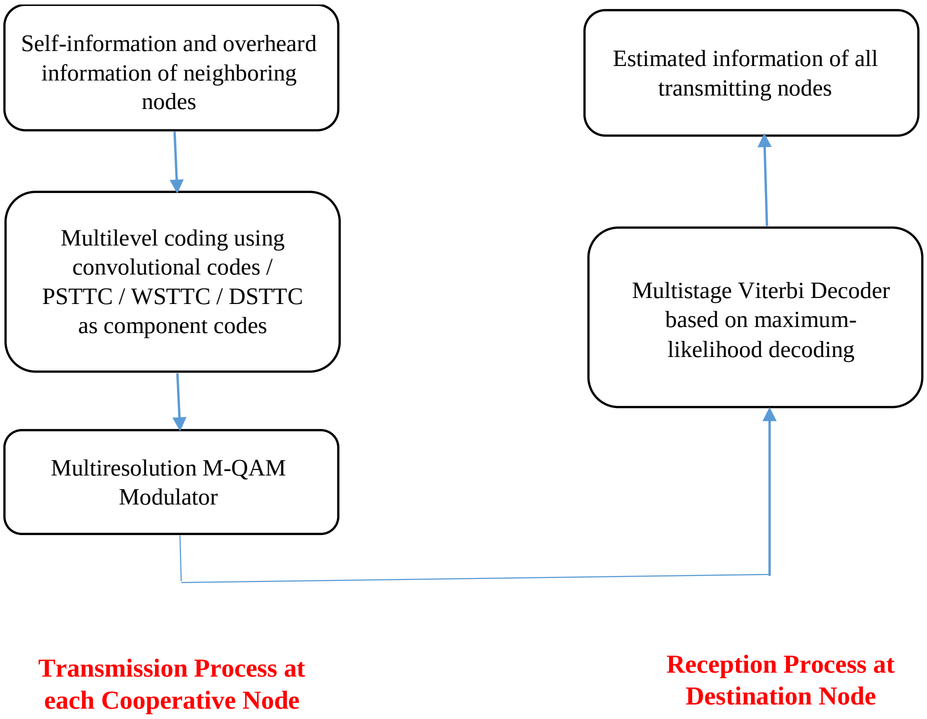

Figure 6.1: Methodology used to design the proposed cooperative multilevel coding system

The cooperative multilevel convolutional coding system is designed for single antenna mobile nodes. Each cooperative mobile node employs multilevel coding scheme with convolutional codes as component codes to generate the coded symbols. The multilevel convolutional coded symbols are mapped and transmitted to destination node. The simulation results indicate that cooperative multilevel convolutional coding system outperforms non-cooperative multilevel convolutional coded system by ~0.5 dB at FER of 10^{-1} using one transmit and one receive antenna.

The cooperative multilevel pseudo space-time trellis coding system is also designed for single antenna mobile nodes. Each cooperative node employs novel multilevel pseudo space-time trellis coding scheme to generate the coded symbols. MLPSTTC use the recently invented PSTTC as component codes. The MLPSTTC symbols generated at each cooperative node are transmitted to the destination node. The simulation results show that the performance of proposed CMLPSTTC technique is superior to existing non-cooperative MLSTTC technique by ~0.7 dB at FER of 3×10^{-1} using one transmit and one receive antenna.

The cooperative multilevel weighted space-time trellis coding system is designed in the following manner. The cooperative nodes employ multilevel coding scheme with STTC as component codes to encode the information of neighboring nodes along with its own information. The coded symbols are mapped and weighted by appropriate beamforming coefficients to achieve receive SNR gain. The weighted symbols are transmitted to the destination node. The simulation results show that the performance of CMLWSTTC system is superior to non-cooperative MLWSTTC system by ~2 dB at FER of 3×10^{-1} using two transmit and one receive antenna.

The cooperative multilevel dynamic space-time trellis coding system is designed by employing multilevel coding scheme with dynamic space-time trellis codes as component codes at each cooperative node. DSTTC adapt to the current channel conditions by selecting the optimum code-set of generator sequences. The MLDSTTC symbols generated at each cooperative node are transmitted to the destination node. The CMLDSTTC system outperforms non-cooperative MLDSTTC system by ~3.1 dB at FER of 3×10^{-1} using 1 bit feedback information in the case of two transmit and one receive antenna.

Hence, the proposed cooperative multilevel coding system with various error-correcting codes shows a significant improvement in performance over existing non-cooperative multilevel coding system. The proposed system is capable of providing flexible data transmission rates, high spectral efficiency, coding gain, diversity gain, improved coverage, low error probability, low outage probability, and a low decoding complexity.

It has the potential to form the basis for next generation communication system.

6.2 Future Scope

The research work for proposed cooperative multilevel coding system can be extended in various directions.

- The proposed system can be analysed for fast fading environment and other fading models such as Rician fading and Nakagami fading.
- The effects of other partitioning strategies and modulation schemes on system performance can be studied.
- Besides, the case of erroneous decoding of other nodes' information at cooperative node can be studied.
- Other possible area of future research can be to find alternative decoding techniques for proposed cooperative multilevel coding system without compromising performance and complexity.

List of Publications

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[1] S. Aneja and S. Sharma, "Cooperative multilevel dynamic space–time trellis coding scheme for improved system performance," *IET Commun,* vol. 10, no. 4, pp. 416-424, March 2016. (SCI Indexed; Impact Factor: 0.742)

[2] S. Aneja and S. Sharma, "Multilevel space–time trellis coded cooperation with channel state information at transmitter," *Int J Commun Syst,* vol. 29, no. 18, pp. 2622-2631, DOI: 10.1002/dac.3123, Feb. 2016. (SCI Indexed; Impact Factor: 1.099)

[3] S. A. Sharma and S. Sharma, "A Novel Cooperative Diversity Technique Based on Multilevel Pseudo Space–Time Trellis Coding," *Wirel. Pers. Commun.,* pp. 1-14, DOI: 10.1007/s11277-016-3634-9, Aug. 2016. (SCI Indexed; Impact Factor: 0.701)

[4] S. Aneja and S. Sharma, "A Novel Cooperative Communication System Based on Multilevel Convolutional Codes," *Wirel. Pers. Commun.,* pp. 1-18, DOI: 10.1007/s11277-017-4011-z, Feb. 2017. (SCI Indexed; Impact Factor: 0.701)

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