İSTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DESIGN AND PERFORMANCE ANALYSIS OF ENHANCED NETWORK CODED COOPERATIVE COMMUNICATION SYSTEMS

M.Sc. THESIS

Rida KHAN

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Thesis Advisor: Prof. Dr. İbrahim ALTUNBAŞ

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Rida KHAN
504131324

Elektronik ve Haberleşme Mühendisliği Anabilim Dalı

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Tez Danışmanı: Prof. Dr. İbrahim ALTUNBAŞ

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Thesis Advisor : **Prof. Dr. İbrahim ALTUNBAŞ** ....
Istanbul Technical University

Jury Members : **Assoc. Prof. Dr. Güneş Karabulut KURT** ....
Istanbul Technical University

Assoc. Prof. Dr. Serhat ERKÜÇÜK ....
Kadir Has University

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To my family and teachers

FOREWORD

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Rida KHAN
(Telecommunication Engineer)

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ABBREVIATIONS

MIMO : Multiple Input Multiple Outputs
AAF : Amplify and Forward
DAF : Decode and Forward
NC : Network Coding
RLNC : Random Linear Network Coding
CFNC : Complex Field Network Coding
XOR : Exclusive-OR
OFDM : Orthogonal Frequency Division Multiplexing
BER : Bit Error Ratio
PLNC : Physical Layer Network Coding
GFNC : Galois Field Network Coding
CPF : Compute and Forward
SLNC : Symbol Level Network Coding
SDF : Selective Decode and Forward
ML : Maximum Likelihood
OFDMA : Orthogonal Frequency Division Multiple Access
EM : Electromagnetic
BPCU : Bits per Channel Use
SNR : Signal to Noise Ratio
SC : Sub-carrier
IFFT : Inverse Fast Fourier Transform
CP : Cyclic Prefix
FFT : Fast Fourier Transform
LAR : Link Adaptive Relay
CU : Channel Uses
RS : Relay Selection
BPSK : Binary Phase Shift Keying
LLR : Log-Likelihood Ratios
SOVA : Soft Output Viterbi Algorithm
PR : Parallel Relay
CRC : Cyclic Redundancy Check
TS : Time Slots
QPSK : Quadrature Phase Shift Keying

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DESIGN AND PERFORMANCE ANALYSIS OF ENHANCED NETWORK CODED COOPERATIVE COMMUNICATION SYSTEMS

SUMMARY

A wireless communication system consists of multiple wireless nodes that can move around and communicate with each other. Fading is one of major degrading factors that can limit the performance of wireless communication systems. In order to achieve reliable communication in fading environments, channel coding and diversity techniques were proposed and implemented. Multiple input multiple output (MIMO) is one of the diversity techniques which uses multiple transmission and reception nodes per terminal to obtain diversity gains for reduced errors in the transmission of data. But cooperative diversity techniques can realize this purpose without installing multiple transmission antennas per terminal. The broadcasting nature of wireless medium allows neighbouring relay nodes to cooperate in communication by forwarding information from source nodes to destination nodes for fading mitigation. Therefore, cooperative communication system utilizes multiple communication routes created by relay nodes and exploits the inherent spatial diversity of the channel for information transmission. While classical single hop communication systems use direct transmission in which a receiver recovers the information using the direct signal only and regarding the reflected signal as interference, the cooperative communication systems consider the other signal as contribution. Therefore, cooperative diversity retrieves information from the combination of two or more signals. In other words, cooperative diversity is a virtual antenna diversity technique that uses distributed antennas belonging to each node in a wireless network for communication. Cooperative diversity is particularly considered useful in wireless ad hoc and sensor networks, where power/bandwidth/size restrictions of the mobile nodes may prevent the use of other diversity techniques to combat channel fading. In all scenarios, cooperation among mobile users of a wireless system has the potential to provide an increased capacity in comparison with the systems without using cooperation.

However, in most cases, cooperative communication attains this improvement in error performance by sacrificing the throughput of wireless network. In such cases, network coding technique can substantially improve the data rate of cooperative wireless networks by intelligently combining the forwarded packets of information at the relay nodes. Network coding was originally proposed for lossless communication systems to increase the throughput of routing networks. But the integration of network coding with cooperative wireless networks has the potential to ensure more efficient usage of resources with improved error performance in fading environments. Network coding can ensure the capability to address the ever increasing number of users and devices in wireless networks, in beyond 5G standards. The broadcast nature of wireless systems allows the joint implementation of cooperative communication and network coding, exploiting the benefits of both techniques. In this context, several types of network coding have been discussed in

literature in the recent years but each type involves the concept of combining and transmitting the functions of information packets at the relay nodes. In this thesis, random linear network coding, complex field network coding and exclusive-OR (XOR) network coding are simulated and analyzed in different perspectives.

In the first part of this thesis, the performance of random linear network coding systems is investigated for Rayleigh and Rician fading channels in terms of decoding failure probabilities at destination nodes. In random linear network coding systems, the information bits at the intermediate nodes are received as packet vectors and the intermediate nodes encode the information data by linearly combining the received packets, with coefficients randomly extracted from the Galois field of a particular size, with equal probability. The setup considered in this section consists of multiple source, relay and destination nodes, with no direct links between sources and destinations. The communication channel outage and hence the packet loss in the given system occurs due to fading. The simulation results for the supposed system model show that the packet decoding failure probabilities are not only determined by the fading environment but also by the coefficients used in the network coding at the relay nodes. In fading channels, decoding failure probabilities can be reduced by increasing the size of the Galois field that contains random coefficients for linear combination of packets at relay nodes.

In the second part of this thesis, the bit error rate performance of complex field network coding is analyzed with orthogonal frequency division multiplexing (OFDM) for frequency selective Rayleigh fading channels. In previous literatures, this analysis is performed for flat fading channels. The system model used in the performance evaluation contains multiple source nodes, single or multiple relay nodes and a single destination node. Both amplify and forward as well as decode and forward types of relays are assumed to obtain error performance results and for multi-relay system, relay selection is also taken into account for both amplify and forward and decode and forward relay types. Convolutional channel codes are also optionally integrated in the given system to boost the system performance and hard decision Viterbi decoding is used to decode source bits. In addition to this, asymmetric link environments, with relay nodes at different distances from sources and destination, are also considered. Multiuser detection rules with OFDM are employed at destination node and/or relay nodes to retrieve each source bits at the same time, for the above mentioned scenarios. The simulation results indicate that amplify and forward relay nodes outperform decode and forward relay nodes in all cases but are not very suitable from the implementation perspective since they require the storage of analog waveform at relays. Moreover, a considerable improvement is error performance can be observed when relay selection is provided in the system model with both amplify and forward and decode and forward types of relays. Finally, in asymmetric network, better error performance can be achieved by placing relay nodes closer to the source nodes.

The third part of this thesis proposes the channel coded complex field network coding with OFDM, combining the mutual benefits of all the techniques involved and the performance evaluation is made in terms of bit error rate. This work is the extension of the convolutional channel coded complex field network coding with OFDM and hard decision Viterbi decoding, presented in the second part. The system model is same as the second part with slow and frequency selective Rayleigh fading channel. Again, both amplify and forward and decode and forward types of relays are considered in this context and relay selection is employed in scenarios with multiple relays. However, this part uses soft decision Viterbi and Max-Log-MAP decoding techniques for obtaining coded source bits and therefore, in this case, the multiuser detection rules provide log likelihood ratios for coded source bits. Moreover, the performance analysis is provided for convolutional codes with different code rates and number of states in the trellis as well as for asymmetric link environments. From simulation results, it is seen that both soft decision Viterbi and Max-Log-MAP channel decoding techniques provide almost same bit error performance in the given system model. Amplify and forward performs better than decode and forward in all cases and relay selection techniques results in a noticeable performance gain. Convolutional codes with lower code rate and more number of trellis states can enhance the system performance considerably and asymmetric links also serve the similar purpose of performance improvement.

The final part of thesis is related to an enhanced version of XOR network coding scheme for two-way relay networks, combined with OFDM. Compared to other conventional strategies for two-way relay networks, this strategy performs Galois field addition or bit-wise XOR coding of multiple information packets at sources. The XOR coded packet is transmitted to the relay nodes along with the information packets which facilitates redundancy to acquire transmit diversity gain for improving error performance of the two-way relay network. The system model consists of two source and different number of relay nodes with convolutional channel encoding in the system to obtain desired error performance. Relay selection is also provided when there are multiple relays in the system and this provision not only improves the error performance but also gives better throughput. The results show that the redundancy provided at the transmission end of two-way relay network enhances bit error performance of the system.

GELİŞMİŞ AĞ KODLAMALI İŞBİRLİKLİ HABERLEŞME SİSTEMLERİNİN TASARIMI VE PERFORMANS ANALİZİ

ÖZET

Kablosuz haberleşme sistemi birbiriyle haberleşebilen birçok hareketli düğüm noktasından oluşmaktadır. Sönümleme ise kablosuz haberleşme sistemlerinin performansını olumsuz yönde etkileyen önemli faktörlerden biridir. Sönümlemenin mevcut olduğu ortamlarda güvenilir bir haberleşme için kanal kodlama ve çeşitleme teknikleri önerilmiş ve uygulanmıştır. Bunlardan biri, çeşitleme kazancı elde ederek olabildiğince hatasız veri iletimi gerçekleştirmek üzere her bir terminalde çoklu verici ve alıcı düğümleri kullanan çok girişli çok çıkışlı çeşitleme (MIMO) tekniğidir. Fakat işbirlikli çeşitleme tekniği bunu her bir terminalde birden çok verici anten kullanmadan gerçekleştirebilmektedir. Kablosuz yayın ortamı komşu röle düğümlerin işbirliği yapmasına imkan sağlayarak verinin kaynak düğümlerden hedef düğümlere aktarılması sırasındaki sönümleme etikisini azaltmaktadır. Bu sebeple, işbirlikli haberleşme sistemi veri iletimi sırasında röle düğümler ile oluşturulan birden çok haberleşme ağının kullanılmasını ve kendiliğinden oluşan uzaysal kanal çeşitlemesinden faydalanılmasını mümkün kılmaktadır. Doğrudan veri iletimi kullanan klasik tek atlamalı haberleşme sistemlerinde bir alıcı doğrudan gelen işaretin içerisindeki veriyi elde ederek yansıyan işaretleri girişim olarak algılarken, işbirlikli haberleşme sistemleri diğer işaretleri katkı olarak değerlendirmektedir. Böylelikle işbirlikli çeşitlemede veri iki ya da daha çok işaretin birlikte değerlendirilmesiyle elde etmektedir. Başka bir deyişle, işbirlikli çeşitleme kablosuz haberleşme ağlarında bulunan her bir düğümdeki antenin dağıtık olarak kullanıldığı bir anten çeşitleme tekniğidir. Hareketli düğümlerin (mobile nodes) güç, bant genişliği ve boyut gibi kısıtları sebebiyle diğer çeşitleme tekniklerinin kanal sönümlemesine karşı kullanılamadığı kablosuz tasarsız (ad hoc) algılayıcı ağları için işbirlikli çeşitleme özellikle faydalı olmaktadır. Bütün senaryolar için, hareketli kullanıcılar arasında işbirliği olan kablosuz sistemler bu işbirliğinin olmadığı diğer sistemlere göre daha yüksek bir sığa potansiyeline sahiptir.

Fakat, işbirlikli haberleşme ile hata performansında elde edilen iyileşme çoğu durumda kablosuz ağdaki iletim hızından feragat ile mümkündür. Bu gibi durumlarda, ağ kodlama tekniği sayesinde röle düğümlere gönderilmiş olan veri paketlerinin akıllı bir şekilde birleştirilmesi ile işbirlikli kablosuz ağlardaki veri hızında ciddi bir iyileştirme sağlanabilmektedir. Ağ kodlama esasen kayıpsız haberleşme sistemlerinde yönlendirme ağlarının verimini artırmak için geliştirilmiştir. Fakat, ağ kodlama ile işbirlikli kablosuz ağların tümleştirilmesi (entegrasyonu) sönümlemenin bulunduğu ortamlarda kaynakların daha verimli bir şekilde kullanılması ve hata performansının iyileştirilmesi yönünde ciddi bir potansiyele sahiptir. Ağ kodlama, 5G standartlarının ötesindeki kablosuz ağlarda sürekli artan kullanıcı ve cihazların taleplerini karşılayabilecek kabiliyete sahiptir. Kablosuz sistemlerin yayın doğası işbirlikli haberleşme ve ağ kodlamanın beraber uygulanmasını ve bu iki tekniğin faydalarından yararlanmayı mümkün kılmaktadır.

Bu bağlamda, son yıllarda mevcut literatürde çeşitli ağ kodlama teknikleri değerlendirilmekte fakat her yöntem röle düğümlerdeki veri paketleri işlevlerinin birleştirilmesi ve iletilmesini kapsamaktadır. Bu tezde, rastgele doğrusal ağ kodlama, karmaşık alan ağ kodlama ve XOR ağ kodlama tekniklerinin benzetimleri yapılmış ve çeşitli bakış açıları ile analiz edilmiştir.

Tezin ilk bölümünde, Rayleigh ve Rician sönümleme kanalları için varış düğümlerindeki kod çözme hata olasılığı üzerinden rastgele doğrusal ağ kodlama sistemlerinin performansı incelenmektedir. Doğrusal ağ kodlama sistemlerinde, ara düğümlerdeki veri bitleri paket vektörler olarak alınmakta ve ara düğümler belirli bir boyutta ve eşit olasılıklı Galois kümesinden çıkarılan katsayılar ile alınan paketleri doğrusal olarak birleştirerek veriyi çözmektedir. Bu bölümdeki benzetim ortamı birden çok kaynak ile röle ve varış düğümlerinden oluşmakta; kaynak ve varış noktaları arasında ise doğrudan bağlantılar bulunmamaktadır. Belirtilen sistemdeki haberleşme kanalı kesintileri ve dolayısıyla paket kayıpları sönümleme etkisiyle oluşmaktadır. Belirtilen sistem modeli için ortaya çıkan benzetim sonuçları, paket çözümündeki kayıp olasılığının sadece sönümleme ortamı değil röle düğümlerde ağ kodlama için kullanılan katsayılar tarafından da belirlendiğini göstermektedir. Sönümleme kanallarındaki çözümleme kayıp olasılıkları röle düğümlerdeki paketlerin doğrusal olarak birleştirilmesi sırasında kullanılan rastgele katsayıları barındıran Galois kümesinin boyutu artırılarak düşürülebilmektedir.

Tezin ikinci kısmında ise, karmaşık alan ağ kodlamasının bit hat oranı performansı frekans seçmeli Rayleigh sönümleme kanalları için dik frekans bölmeli çoğullama (OFDM) kullanılarak analiz edilmiştir. Daha önceki çalışmalarda, bu analiz düz sönümleme kanalları için yapılmıştır. Performans değerlendirmesinde kullanılan sistem modeli birden çok kaynak düğümü, tekli ya da çoklu röle düğümleri ve tek varış düğümü içermektedir. Hem kuvvetlendir ve aktar hem de çöz ve aktar tipi röleler için hata performansı elde edilmekte ve çoklu röle sistemleri için röle seçimi hem kuvventlendir ve aktar hem de çöz ve aktar seçenekleri için ele alınmaktadır. Katlamalı kanal kodları da opsiyonel olarak mevcut sisteme performansı artırmak için eklenebilmekte ve sert kararlı (hard decision) Viterbi Algoritması kaynak bitleri çözmek için kullanılmaktadır. Buna ek olarak, kaynak ve varış noktalarına farklı uzaklıklardaki röle düğümlerinde asimetrik bağlantı ortamları da değerlendirilmiştir. Daha önce bahsedilen senaryo kapsamında hedef ve/veya röle düğümlerde her bir bitin aynı zamanda elde edilmesi için OFDM ile birlikte çoklu kullanıcı belirleme kuralları uygulanmıştır. Benzetim sonuçları, rölelerdeki analog dalga formunun kaydedilmesini gerektirmesi dolayısıyla uygulama açısından pratik olmasa da her durumda kuvvetlendir ve aktar röle düğümlerinin, çöz ve aktar tipi röle düğümlerinden daha iyi performansa sahip olduğunu göstermektedir. Dahası, sistem modelinde hem kuvvetlendir ve aktar hem de çöz ve aktar tipi röleler ile röle seçimi yapıldığında hata performansında hatırı sayılır bir iyileştirme gözlenmektedir. Son olarak, asimetrik ağlarda, daha iyi bir hata performansı röle düğümlerinin kaynak düğümlerine daha yakın yerleştirilmesi ile elde edilebilmektedir.

Tezin üçüncü kısmında, ele alınan tekniklerin faydalı yönlerini birleştirecek şekilde, OFDM kullanan kanal kodlamalı karmaşık alan ağ kodlama tekniği önerilmekte ve bit hata oranı üzerinden performans değerlendirmesi yapılmaktadır. Buradaki çalışma OFDM kullanan katlamalı kanal kodlamalı karmaşık alan ağ kodlama ve ikinci bölümde bahsedilen sert kararlı (hard decision) Viterbi Algoritmasının genişletilmesidir. Sistem modeli ikinci kısımdaki ile aynı olmakla birlikte yavaş ve frekans seçimli Rayleigh sönümleme kanalı içermektedir. Yine hem kuvvetlendir ve aktar hem de çöz ve aktar türü röleler bu bağlamda değerlendirilmiş ve birden çok röle içeren senaryolarda röle seçimi uygulanmıştır. Fakat, bu bölümde kodlanmış kaynak bitlerinin elde edilmesi için yumuşak kararlı (soft decision) Viterbi Algoritması ve Max-Log-MAP kod çözme teknikleri kullanılmakta ve böylelikle çok kullanıcı belirleme kuralları kodlanmış kaynak bitleri için log likelihood oranlarını sağlamaktadır. Dahası, kafeste farklı kod oranlarına ve durum sayılarına sahip katlamalı kodlar ve asimetrik bağlantı ortamları için performans analizi verilmektedir. Benzetim sonuçlarına göre, hem yumuşak kararlı Viterbi hem de Max-Log-MAP kanal çözümleme tekniklerinin belirtilen sistem modelinde aynı bit hatası performansına sahip olduğu görülmektedir. Kuvventlendir ve aktar yöntemi çöz ve aktar yöntemine göre her durumda daha iyi sonuç vermekte ve röle seçim teknikleri fark edilir bir performans iyileştirmesine sebep olmaktadır. Daha düşük kod oranlı ve daha çok kafes durumuna (trellis state) sahip katlamalı kodlar sistem performansını ciddi bir şekilde artırmakta ve asimetrik bağlantılarda aynı şekilde performansın iyileştirilmesi amacına katkı yapmaktadır.

Tezin son bölümü OFDM ile birleştirilmiş iki yönlü röle ağları için XOR ağ kodlama tekniğinin geliştirilmiş versiyonu ile ilgilidir. İki yönlü röle ağları için geliştirilen geleneksel stratejiler ile karşılaştırıldığında, bu stratejide Galois küme eklemesi veya kaynaklarda çoklu veri paketlerinin bit XOR kodlaması uygulanmaktadır. XOR kodlamalı paket, iki yönlü röle ağının hata performansını artırmak için verici çeşitleme kazancı elde etmek üzere artıklık barındıran veri paketleri ile birlikte röle düğümlerine iletilmektedir. Sistem modeli, iki kaynak ve istenen hata performansının elde edilmesi için farklı sayıda ve katlamalı kanal kodlamalı röle düğümleri içermektedir. Sistemde birden çok röle olduğu durumda röle seçimi de yapılmakta ve bu sayede sadece hata performansı artırılmamakta aynı zamanda verimlilik de artmaktadır. Sonuçlar, iki yönlü röle ağının iletim ucunda sağlanan artıklık ile sistemde bit hatası performansının artırıldığını göstermektedir.

1. INTRODUCTION

Wireless radio systems facilitate communication among several entities through radio or other type of wireless media and have become an integral part of present-day human life. Wireless communication has got numerous applications in different areas of present society, ranging from personal communication and cellular systems to medical and security. Therefore, extensive efforts have been made to conduct research for bringing useful innovations in the field of wireless communication. With the passage of time, wireless communication has evolved from simple voice communication system to complex digital data communication systems. Modern technologies like sensor and ad-hoc networks and device–to-device communication rely on the transmission of huge volumes of data, so, wireless communication systems require further modernization in future as well.

Among all applications of wireless communication, cellular communication is the most essential and primary one. Cellular systems were first introduced to realize voice communication but now have been transformed into complicated systems, communicating every sort of information. The major obstacles in accomplishing error free or lossless communication in cellular systems is fading and noise [1]. Several techniques were suggested and developed in order to combat the degrading effects of fading and noise and the most elementary of such techniques is channel coding. Channel coding is based on the concept of sending extra bits along with the information bits to avoid bit errors. The extra bits are generated using various methods depending upon the type of channel coding employed. Cooperative diversity [2] is another important method to combat erroneous transmission of data, resulting from fading. Cooperative diversity is basically an antenna diversity technique like multiple input multiple output (MIMO) systems [1] but does not contain multiple transmission antennas per terminal. Instead, cooperative communication systems make the use of intermediate relay nodes for transmitting signal from source to destination nodes and relay nodes may serve the purpose of both communication and cooperation. In cooperative networks, source nodes send their signal to both relay and destination nodes whereas relay nodes forward the received signal to the same destination nodes, providing diversity for the reduction of error probability in data transmission. Relay nodes employ amplify and forward (AAF) and decode and forward (DAF) strategies while relaying source signal. Cooperative communication is a favourable choice when installing multiple antennas per terminal for diversity is not convenient.

One drawback of cooperative diversity systems is the reduction of throughput in the overall communication systems. System throughput decreases as the number of nodes increases in cooperative wireless system, making it impractical from the implementation perspective. Network coding (NC) is an effective solution to address this issue. NC was first suggested by Ashwelde *et al.* in [3] for increasing throughput of the lossless routing networks. In this technique, intermediate relay nodes do not forward the signal to destination nodes as received but perform some operation to combine signals coming from different source nodes, before relaying to the destination nodes [4]. NC not only improves the throughput of cooperative wireless networks but also enhances the error performance in fading environments. Therefore, NC can possibly eliminate the liability to send feedback from destination nodes for acknowledging successful transmission of signal. It can be performed at different layers of a communication system and has several types. Random linear network coding (RLNC) is the type of network coding that can be combined with cooperative communication systems, independent of the design of network topology [5]. The use of randomly extracted coding coefficients in RLNC makes it simpler in implementation than classical Galois field network coding (GFNC) [5]. Complex field network coding (CFNC) is another type of network coding which can increase the throughput of cooperative systems to appreciable limits for any number of source and relay nodes [6]. Exclusive-OR (XOR) network coding only requires performing XOR of each source bits at relay nodes but can considerably enhance throughput and error performance of the two-way relay networks.

Practical communication systems may suffer from frequency selective fading and hence, orthogonal frequency division multiplexing (OFDM) was developed to provide communication in frequency selective fading environments [1]. OFDM divides the available bandwidth into orthogonal sub-carriers that carry information symbols such that each individual sub-carrier experiences flat fading. OFDM system can be uncoded or channel coded but is an essential part of modern cellular networks. Coded OFDM systems are discussed in detail in [7]. It is also possible to combine OFDM systems with network coding to acquire the joint benefits of both techniques in wireless communication.

1.1 Purpose of Thesis

This thesis highlights the performance analysis of various types of NC schemes in different scenarios. This research is an extension of the work presented in the related literature. Performance analysis is performed in terms of decoding failure probability and bit error ratio (BER). Decoding failure probabilities, investigated in this thesis, are functions of both fading environments and NC design. The system models assumed in thesis provide performance improvements when NC is combined with OFDM in cooperative relay networks. Channel codes are also optionally included in the system to boost the performance. XOR network coding scheme with some variation is also suggested and evaluated in thesis for two-way relay networks.

1.2 Literature Review

The related research utilized in the first part of thesis includes the computation of exact successful decoding probability in RLNC at the destination node as a function of the field size, packet loss probability and the number of sources and intermediate nodes by Chiasserini *et al.* in [8] but the work assumed the similar packet loss probability for all network links. RLNC offers several advantages over traditional approaches of routing like providing completely distributed operation, adding more redundancy for reliable communication, simplicity of implementation and reducing number of packet retransmits in lossy environments to improve throughput [5]. In [9], Xi *et al.* proposed a novel retransmission approach in wireless broadcasting based on RLNC, which effectively reduces the average number of transmissions and can achieve higher transmission efficiency than XOR based NC, especially in environments having large number of broadcast receivers. In [10], a scheme based on RLNC was proposed which aims to minimize the mean energy spent for transmitting a pre-determined number of packets over channels where time division duplexing is necessary.

The second and third parts of thesis are concerned with the bit error ratio (BER) performance of NC systems and considerable research has been performed in this regard. Compute-and-forward (CPF) NC [11] was proposed for general multi-source cooperative diversity systems and symbol level network coding (SLNC) [12] for wireless mesh networks. As mentioned before, CFNC [6] is another important technique which offers a good option to realize the high throughput in relay based cooperative wireless networks. An enhanced CFNC scheme with error control coding and selective decode and forward (SDAF) was suggested by Cai *et al.* in [13] to improve the accuracy of a cooperative communication systems. A CFNC scheme based on repetition was proposed in [14], for typical asymmetric link scenario with higher data traffic in downlink such as orthogonal frequency division multiple access (OFDMA) systems, in order to enhance the decision accuracy of maximum likelihood (ML) decision rule for achieving better results. But the existing literature does not include channel coded CFNC systems with OFDM in cooperation based networks.

Two-way relay networks are also an example of cooperative communication systems but the cooperation is used for information exchange between two sources through single or multiple relay nodes. A great deal of research has been contributed to study two-way relay networks and evaluate their performance in various terms. The utilization of NC for message exchange in two-way relay networks reduces the number of time slots and this is accomplished by using the broadcast capability of intermediate relay nodes [15]. Physical layer network coding (PLNC), a technique using the additive nature of electromagnetic (EM) waves for coding purpose, was proposed in [16] for information exchange in two-way relay networks. However, the existing literature does not contain XOR network coded redundancy schemes at the transmission end in OFDM based two-way relay networks.

2. RANDOM NETWORK CODING SYSTEMS IN FADING CHANNELS

NC was introduced by Ahlswede *et al.* in [3] to obtain the max-flow rate for single source multicast that could be impossible to achieve by simply routing the data. NC is based on the notion of computing and transmitting functions of packets at the intermediate nodes, rather than simply routing packets [4]. Traditional ways to operate a network, like routing, try to avoid collisions of data streams as much as possible but allowing intermediate nodes to process the information can increase the achievable rate in unicasting scenarios as compared to simple routing [17]. A further enhanced concept, in which a block of data is taken as a vector over a certain base field and every intermediate node applies a linear transformation to all such incoming vectors, thus making encoding and decoding convenient in practice, is called linear NC [18]. In other words, the information bits at the intermediate nodes are received as packet vectors and the intermediate nodes encode the information data by linearly combining the received vectors (packets), with coefficients selected from a certain field of operation. Another variation of linear NC is RLNC in which the coefficients to encode the packets at the intermediate relay nodes are randomly extracted from a Galois field of size q with equal probability [5] which is suitable for networks with unknown or varying topologies. In algebra, Galois field is a finite field that contains finite number of elements, called its size or order. Galois field of size q would contain q elements and $q = p^n$, where p is a prime number and n is a positive integer. In coding theory, many codes are constructed as subspaces of vector spaces over finite fields [19].

However, in practical scenarios, the wireless communication link may fail and the intermediate nodes may not receive all packets to be encoded. The primary reason for packet loss in wireless communication links is fading. Chiasserini *et al.* in [8] computed the exact probability of successful decoding in RLNC at the destination node as a function of the field size q, the packet loss probability and the number of sources and intermediate nodes. But the work assumed the same packet loss probability for all the links between sources and intermediate nodes and a single failed link for each intermediate node. In this part of the thesis, by extending the work, the decoding failure probabilities in RLNC are analyzed, when the link failure and hence the packet loss occurs due to Rayleigh and Rician types of fading [1].

2.1 System Model

Let assume that a set of N independent sources broadcasts messages to N destinations via M relays, with $M \geq N$. The primary focus is on a two-hop relay network without direct links between source and destination nodes, as shown in Figure 2.1. So, the number of intermediate relay nodes is supposed to be greater than or equal to the number of source nodes to ensure communication between sources and destinations. However, the relay nodes can be smaller in number than source nodes, when direct links between sources and destinations are present for communication, to provide cooperation. Intermediate nodes serving as relays, encode the incoming packets using RLNC but the incoming links may fail due to fading and the packets may not be received correctly at the relays.

All of the N sources generate N packets with length L_b bits, which are transmitted to all of the M relays in total N time slots in a time division multiplexing manner. Then all of the M relays encode the received packets using RLNC, and send the resulting M packets towards the destination nodes in total M time slots again in a time division multiplexing manner, as shown in Figure 2.2.

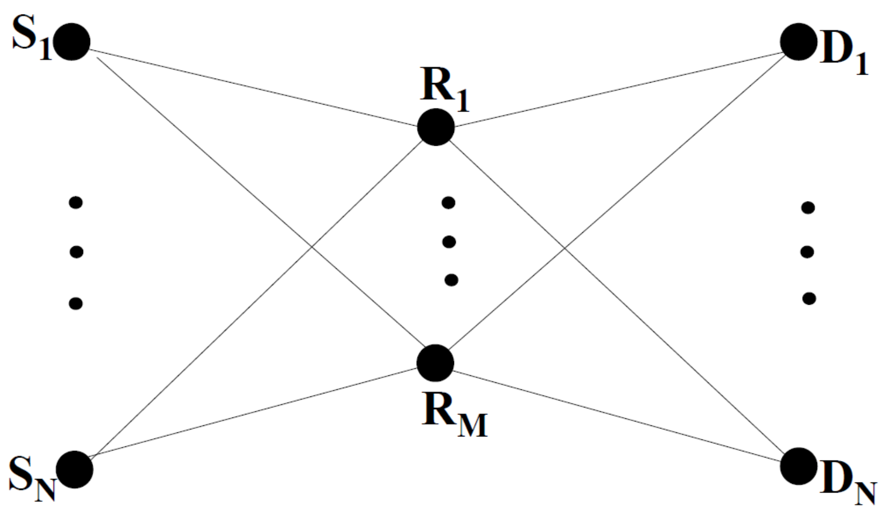

Figure 2.1 : System model, N sources and destinations and M relay nodes.

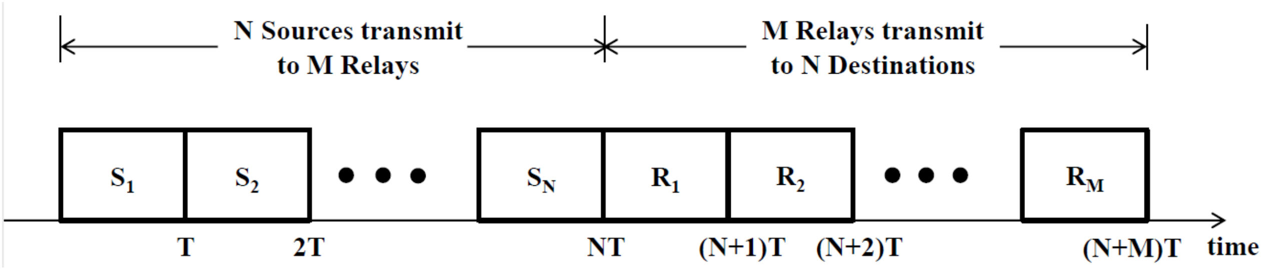

Figure 2.2 : Packet transmission from sources to relay nodes in N time slots and from relay nodes to destinations in M time slots, with T being the length of each time slot.

If s_i for $i = 1, \dots, N$ denotes the ith packet leaving the source S_i, then encoding operation performed at the relay nodes and the packets leaving the relay nodes $(r_1, r_2, \dots, r_M)$ are given by

$$\begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_M \end{bmatrix} = \begin{bmatrix} \alpha_{1,1} & \alpha_{1,2} & \cdots & \alpha_{1,N} \\ \alpha_{2,1} & \alpha_{2,2} & & \alpha_{2,N} \\ \vdots & & \ddots & \vdots \\ \alpha_{M,1} & \alpha_{M,2} & \cdots & \alpha_{M,N} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_N \end{bmatrix}. \tag{2.1}$$

The coefficients used for encoding at the relay nodes $(\alpha_{i,l})$ are randomly extracted from a Galois field of size q, with equal probability. All the nodes are assumed to be equipped with half duplex (i.e. cannot transmit and receive at the same time) single-antennas. The channel between sources and intermediate relay nodes is assumed to be frequency flat fading, in particular Rayleigh and Rician fading. No erroneous transmissions are assumed from relay nodes to the destination nodes, so, the associated results represent the performance limit in case of ideal relay-destination links. Let $h_{i,l}$ denote the instantaneous channel realization between the source S_i and relay node R_l and the channel coefficient $h_{i,l}$ remains constant during the transmission time of the packet.

A total of NL_b bits are transmitted by all sources in $(N + M)$ channel uses, therefore the system rate is $R = \frac{NL}{(N+M)T}$ bits per channel use (BPCU). Here, T is the length of each channel use or time slot. The transmission rate R_0 for each packet transmission is identical, equal to $R_0 = \frac{L_b}{T} = \frac{R(N+M)}{N}$ BPCU. Using the criteria given in [20] for instantaneous mutual information transferred, as a function of channel coefficient $h_{i,l}$ and average signal to noise ratio (SNR) at the receiving end, ρ, the threshold level for the channel to go in outage can be defined as

$$\tau = \frac{2^{\frac{R(M+N)}{N}} - 1}{\rho} \ . \qquad (2.2)$$

Therefore, the outage probability for the channel is given by

$$P_0 = P_r(\left|h_{i,l}\right|^2 \leq \tau) \ . \qquad (2.3)$$

When $\left|h_{i,l}\right|^2 \leq \tau$, the channel with coefficient $h_{i,l}$ is in outage and $\alpha_{i,l}$ will be replaced by a 0 in the coding matrix in (2.1). Otherwise, the channel with coefficient $h_{i,l}$ is operational and hence $\alpha_{i,l}$ remains unchanged. Additionally, when the coding matrix is not full rank, the source packets cannot be decoded. Thus, the failure in decoding of the packets at the destination may occur due to linearly dependent coefficients $\alpha_{i,l}$ as well as due to channel in outage that is an outcome of fading.

2.2 Decoding Failure Probability of Random Linear Network Coding

The probability for the successful decoding in RLNC systems under ideal conditions is the probability that the coefficients extracted at the intermediate nodes for coding operation, constitute a full rank matrix because for decoding, a destination node has to collect as many linearly independent vectors as the number of packets that were originally mixed in. The packet decoding is performed by solving the system of linear equations, received as packet vectors, as shown in Figure 2.3. Only in case of a full rank encoding coefficients matrix, all source packets can be decoded. The decoding probability thus depends on the coding design and selected coefficients [8].

A large field size q ensures the selection of linearly independent encoding coefficients in RLNC. Therefore, when the field size q is sufficiently large, say of the order of 2^{20}, any received packet will be independent from those previously obtained, with high probability and hence linearly independent packet vectors will ensure the successful decoding of all the packets at the destination node [21]. On the other hand, the decoding failure probability of RLNC under ideal conditions can be defined as the probability that the matrix coefficients extracted at the encoding nodes do not make a full rank matrix [4].

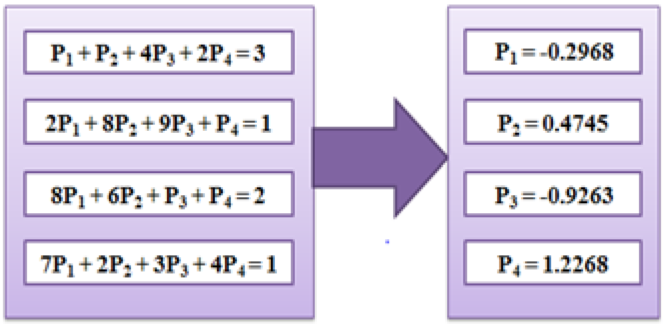

Figure 2.3 : Packet decoding using linear packet vectors.

The presented system model and its functioning are incredibly simple, since the functioning only comprises of the selection of random encoding coefficients from the field of operation, comparison of each soure-relay pair channel coefficient with the threshold level and the possible replacement of encoding coefficient if the channel is in outage. However, the system complexity increases with the field size q for encoding coefficient selection, number of sources N and relays M.

2.4 Simulation Results

In this part of thesis, the channel coefficients $h_{i,l}$ between the sources and relay nodes are generated using Rayleigh and Rician fading channel models. The K-parameter k_R i.e., the ratio between the power in the direct path and the power in the other scattered paths, in Rician fading channel is set to be equal to 3. Monte Carlo simulations are performed for a large number of encoding matrices, having coefficients $\alpha_{i,l}$ for each source-relay pair. The encoding matrix coefficients are forced to zero entry as the channel goes in outage, according to (2.3). The simulations are performed to find the decoding failure probability for different SNR values, system rates R, field size q and number of relay nodes M.

The decoding failure probabilities with respect to SNR for both Rayleigh and Rician fading channels are depicted in Figure 2.4 and Figure 2.5, respectively. The simulations are made for different values of system rate R and field size q. It is easily observable that as SNR increases, decoding failure probability decreases for both fading types. Another important observation from the results is that the higher system rates lead to higher decoding failure probabilities for the same values of SNR and field size q. However, the decoding failure probabilities can be decreased for a specific system rate R or SNR by increasing field size q as it is obvious from the simulation results.

In addition to this, Rayleigh fading has higher decoding failure probabilities as compared to Rician fading channel for the same values of SNR, system rate R, relay node number M and Galois field size q. For example at an SNR of 10 dB and system rate of 1 BPCU, the decoding failure probabilities of Rayleigh fading channel are 0.2194, 0.0373 and 0.0185 at field sizes of 4, 16 and 64 respectively. Whereas for the same SNR and system rates, the corresponding decoding failure probabilities of Rician fading channel are 0.1145, 0.0072 and 0.001 respectively. It can also be observed in both Figure 2.4 and Figure 2.5 that after reaching a certain high SNR value, both system rates give nearly same failure probability results for each field size q. The reason for this is that the decoding failure probabilities, at higher SNR values, no longer depend on fading but are more affected by field size. In other words, the probability of the fading channel going in outage is always small at high SNR for every system rate.

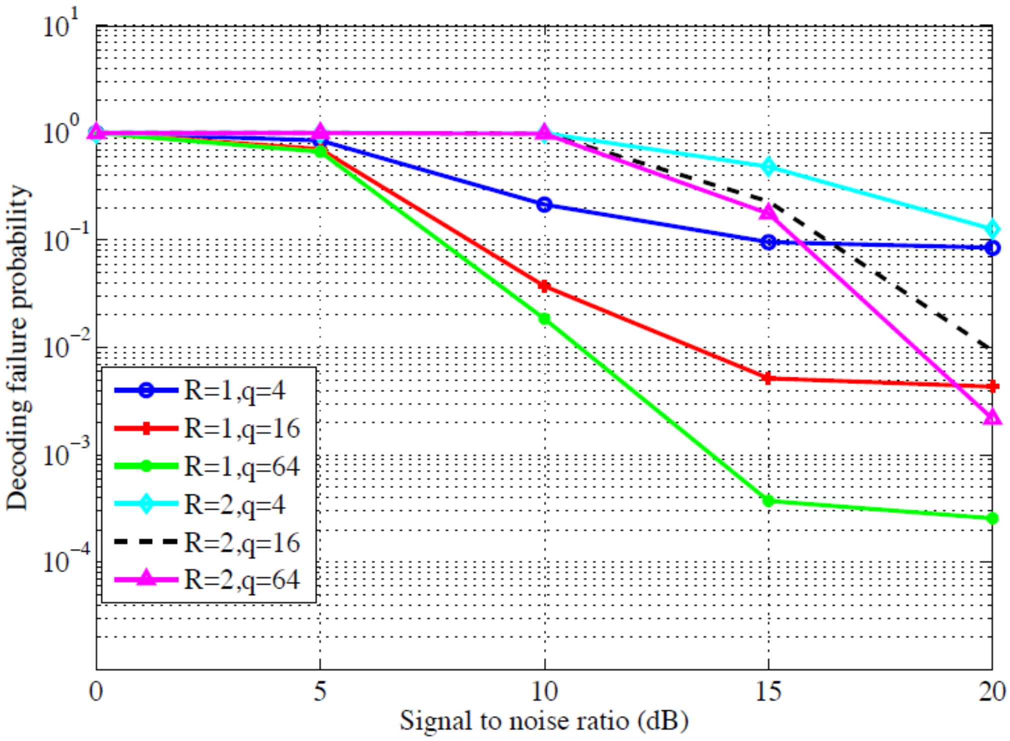

Figure 2.3 : Decoding failure probability in RLNC under Rayleigh fading channel, SNR for traffic sources N = 4, relay nodes M = 5, field size q = 4, 16, 64 and R = 1, 2.

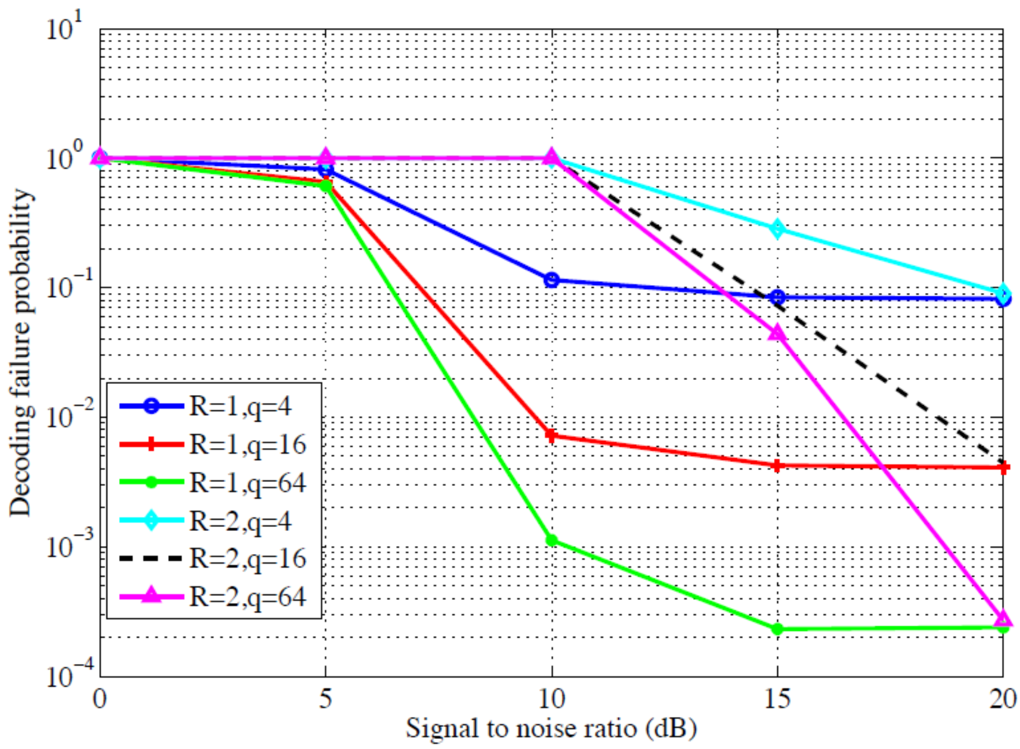

Figure 2.5 : Decoding failure probability in RLNC under Rician fading channel (k_R = 3), SNR for traffic sources N = 4, relay nodes M = 5, field size q = 4, 16, 64 and R = 1, 2.

The decoding failure probabilities with respect to varying field size q for Rayleigh and Rician fading channels are indicated in Figure 2.6 and Figure 2.7, respectively. The results are collected for two different system rates R and number of intermediate relay nodes M. The observations clearly show that an increase in field size q leads to a decrease in decoding failure probabilities in both fading environments, due to the linear independence of selected coefficients used in coding operation in RLNC. In other words, a larger field size q improves successful decoding probability. The increased system rates again have higher decoding failure probabilities for the same field size q and number of relay nodes M. But by increasing number of relay nodes M, the decoding failure probability can be decreased in both fading types. Additionally, Rayleigh fading again seems to have higher decoding failure probabilities as compared to Rician fading channel. Like at field size of 16 and system rate of 2BPCU, Rayleigh fading channel has decoding failure probabilities of 0.2294 and 0.1317 for 5 and 6 relay nodes respectively. While, at the same parameters, the corresponding decoding failure probabilities of Rician fading channel are 0.0726 and 0.06 respectively.

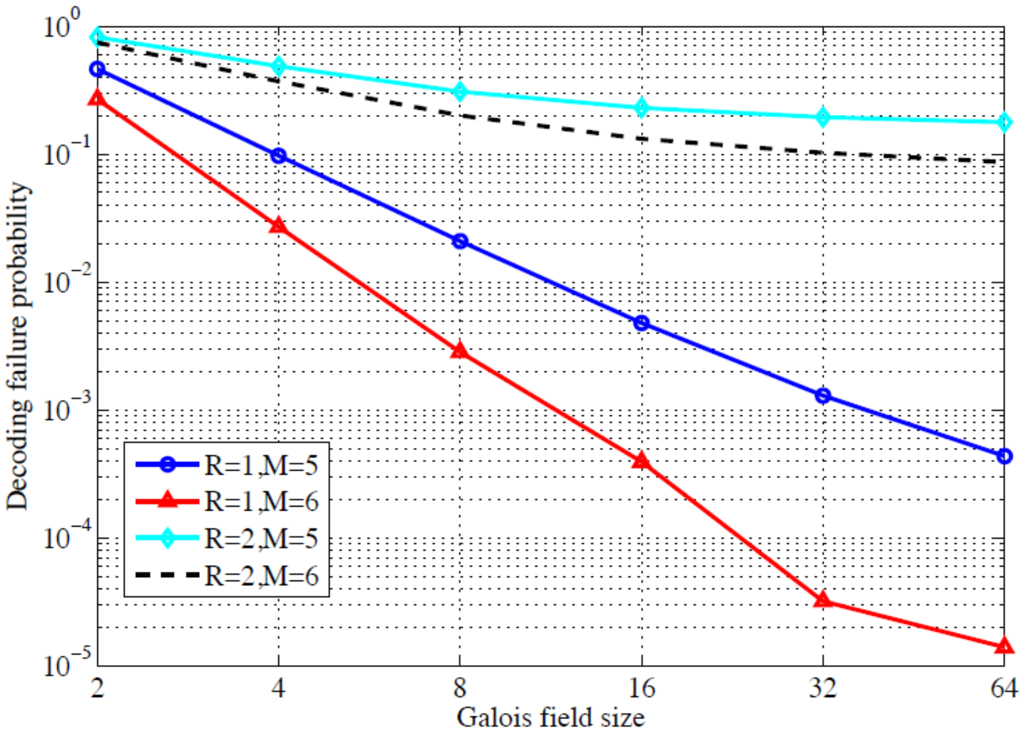

Figure 2.6 : Decoding failure probability in RLNC under Rayleigh fading channel, field size q for traffic sources N = 4, relay nodes M = 5, 6, SNR = 15 dB and R = 1, 2.

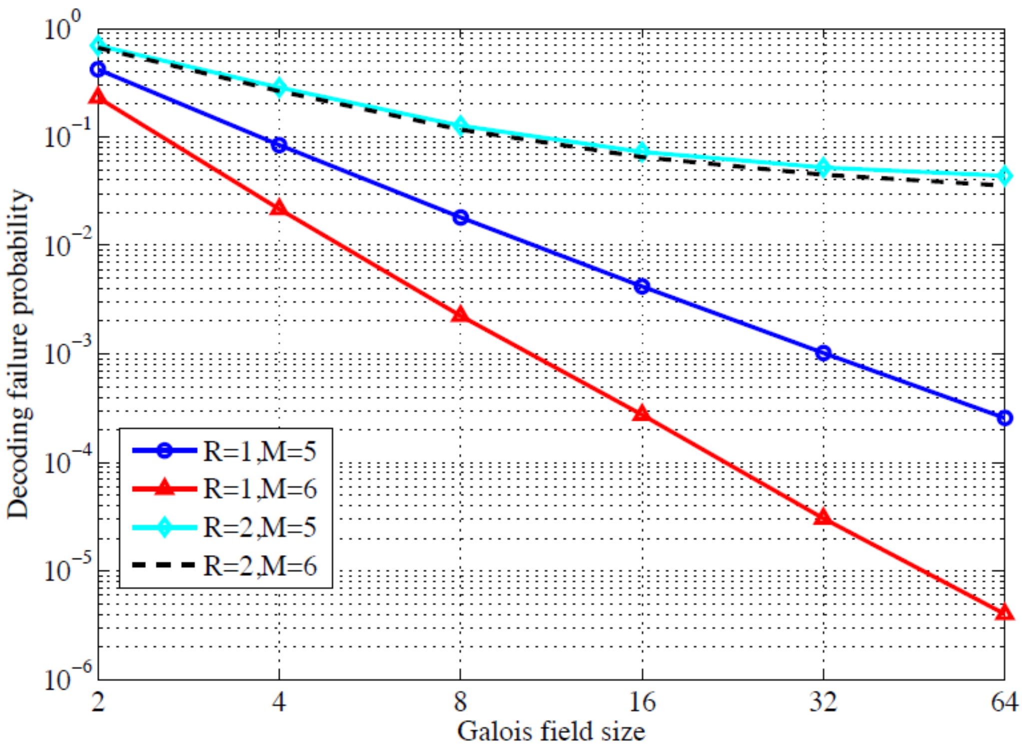

Figure 2.7 : Decoding failure probability in RLNC under Rician fading channel (k_R = 3), field size q for traffic sources N = 4, relay nodes M = 5, 6, SNR = 15 dB and R = 1, 2.

3. COMPLEX FIELD NETWORK CODING WITH OFDM IN WIRELESS NETWORKS

With cooperative communication, spatial diversity gains can be achieved by using relay nodes to forward signal from sources to destinations, and therefore it can be potentially implemented in cellular, ad-hoc, sensor and other types of networks [2]. However, the increase in network size may lead to throughput loss and bandwidth inefficiency. To address these issues, NC is considered for wireless relay networks [22]. Several research efforts have been made to utilize the notion of NC with cooperative networks, in different perspectives. This part of thesis considers CFNC with OFDM in relay based cooperative wireless networks with single or multiple sources [6].

CFNC was originally proposed by Giannakis [23] for linear constellation precoding of symbols in MIMO systems in order to achieve coding gains. In contrast to other types of network coding schemes, CFNC is quite simple and straightforward and can facilitate the transmission of $\frac{1}{2}$ symbol per source per channel use while providing maximum possible diversity gain with multiuser detection. Furthermore, symbol level synchronization of CFNC is more convenient to attain than bit level synchronization [6].

3.1 System Model

The system under consideration consists of N source nodes, represented by $S_i, i \in \{1, \dots, N\}$, M relay nodes, denoted as $R_l, l \in \{1, \dots, M\}$, one destination D and K available sub-carriers (SCs). The generalized system is classified into single-relay and multi-relay systems for the purpose of explicit explanation, as shown in Figure 3.1 and Figure 3.2, respectively. Both types of systems comprise of two phases. The process in Phase I that is OFDM operation with CFNC at the sources is illustrated in Figure 3.3. Each source S_i generates bits to be sent and all the bits are optionally encoded using some channel encoding technique. The bits are modulated and multiplied with the complex coefficient θ_i. For multiple of two N value, the values of $\boldsymbol{\theta} = [\theta_1, \dots, \theta_N]^T$ are calculated as $\theta_i = e^{j\pi(4n-1)(i-1)/(2N)}$ and for a multiple of three N value, as $\theta_i = e^{j\pi(6n-1)(i-1)/(3N)}$ for any $n = 1, \dots, N$ [6], [23].

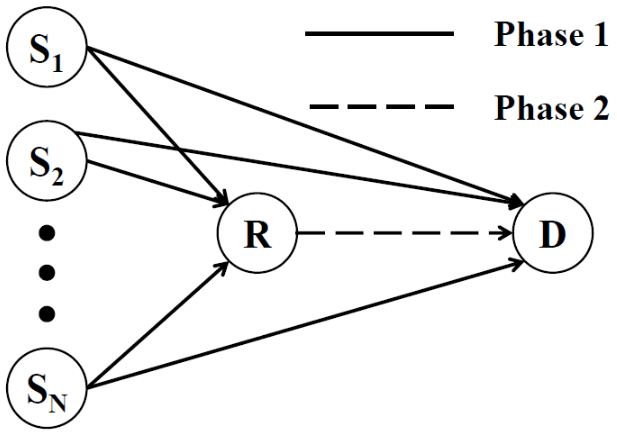

Figure 3.1 : System model for CFNC with N sources and single relay, relay scheduling.

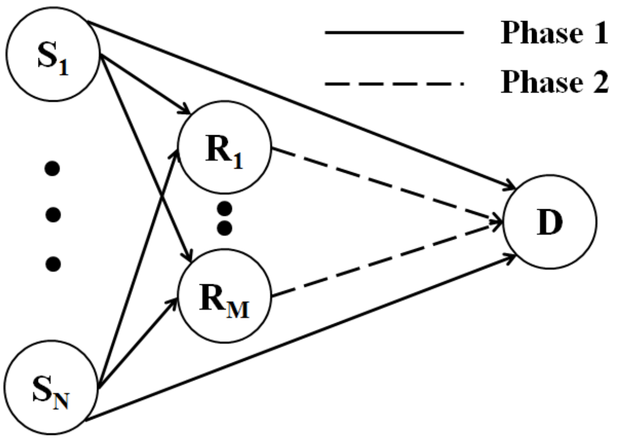

Figure 3.2 : System model for CFNC with N sources and M relays, relay scheduling.

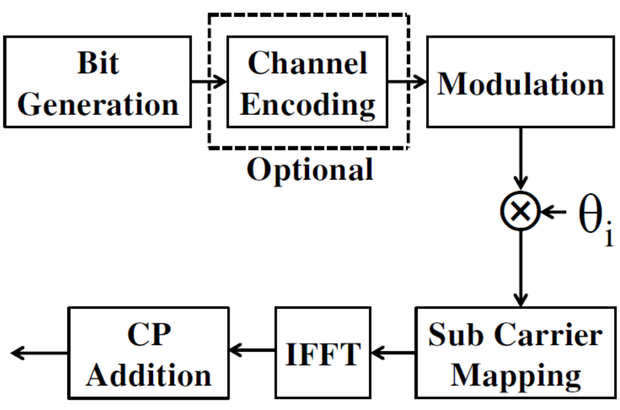

Figure 3.3 : OFDM operation with CFNC at sources.

All sources then map their symbols to all the available K sub-carriers because the multiplication of complex coefficients rotates the actual constellation of modulated symbols and hence allows the joint detection of symbols from multiple sources, even if the symbols are transmitted over the same sub-carriers. Subsequently, inverse fast Fourier transform (IFFT) is taken at each source and cyclic prefix (CP) is appended to prevent interference between sub-carriers. As the transmitted symbols are received by each relay R_l, CP is removed and the symbols are transformed to frequency domain through fast Fourier transform (FFT), as depicted in Figure 3.4. Symbols from each source S_i are retrieved at each relay R_l from their sub-carriers and the further steps of amplification or decoding are performed depending upon the relaying scheme at R_l. In Phase II, all the relays resend source symbols over the same given sub-carriers employing the same conventional OFDM, as shown in Figure 3.4.

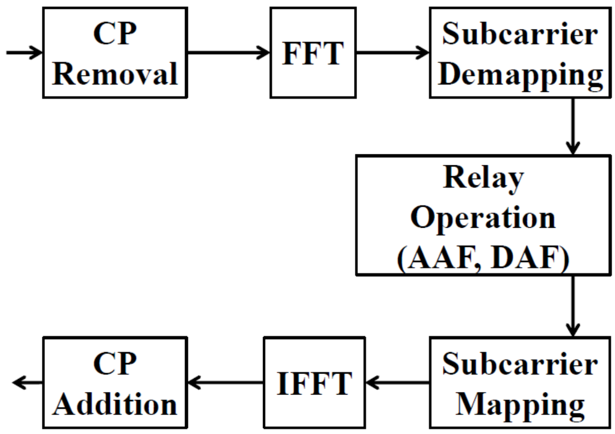

Figure 3.4 : OFDM operation with CFNC at relays.

3.2 Maximum Likelihood Detection Rules for Networks with Single Relay

This section discusses the network model with a single relay, as depicted in Figure 3.1. Defining $\mathbf{x}[k] = \left[x_1[k], \ldots, x_N[k]\right]^T$ as source symbols transmitted on subcarrier k, $k = 1, \ldots, K$, $\boldsymbol{\theta}^T = [\theta_1, \ldots, \theta_N]$ as the complex coefficient entries and P as the average transmit power of each node, on sub-carrier k, the received signals at R and D in phase I on sub-carrier k becomes

$$y_{SR}[k] = \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SR}[k]\mathbf{x}[k] + n_{SR}[k], \tag{3.1}$$

$$y_{SD}[k] = \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SD}[k]\mathbf{x}[k] + n_{SD}[k], \tag{3.2}$$

where $\mathbf{H}_{SR}[k]$ and $\mathbf{H}_{SD}[k]$ are $S_i \rightarrow R$ and $S_i \rightarrow D$ channel gain matrices respectively, on sub-carrier k and $n_{SR}[k]$, $n_{SD}[k]$ represent additive Gaussian noise, with variances σ_{SR}^2 and σ_{SD}^2 respectively. The possible relay operations after source transmission are concisely described as follows.

3.2.1 Amplify and forward for networks with single relay

In AAF or non-regenerative scheme, the signal received at the relay is amplified with square root of the factor $\beta = \frac{1}{2P+1}$ if all channel and noise variances are taken unity. The amplified signal received at the destination node in Phase II is

$$y_{RD}[k] = h_{RD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR}[k]\mathbf{x}[\mathrm{k}] + h_{RD}[k]\sqrt{P\beta}n_{SR}[k] + n_{RD}[k], \quad (3.3)$$

where $h_{RD}[k]$ is relay to destination channel gain on subcarrier k and n_{RD} is additive Gaussian noise with variance σ_{RD}^2. The ML detector at D uses information from both phases and detects source symbols as shown

$$\hat{\mathbf{x}}_D[k] = \underset{\mathbf{x}\in\chi}{argmin}\{\left\|y_{SD}[k] - \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SD}[k]\mathbf{x}[k]\right\|^2$$

$$+\left\|y_{RD}[k] - h_{RD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR}[k]\mathbf{x}[k]\right\|^2\}, \quad (3.4)$$

where $\hat{\mathbf{x}}_D[k] \coloneqq \left[\hat{\mathbf{x}}_1[k], \dots, \hat{\mathbf{x}}_N[k]\right]^T$ are the estimated symbols at D for each S_i and χ is the set of symbols in the modulation scheme considered at S_i.

3.2.2 Decode and forward for networks with single relay

In decode and forward (DAF) or regenerative technique, source symbols at R are decoded and then re-transmitted, following the same series of steps as shown in Figure 3.3 and Figure 3.4. Therefore, the ML process at R is

$$\hat{\mathbf{x}}_R[k] = \underset{\mathbf{x}\in\chi}{argmin}\{\left\|y_{SR}[k] - \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SR}[k]\mathbf{x}[k]\right\|^2\}. \quad (3.5)$$

Here, $\hat{\mathbf{x}}_R[k]$ is the $N \times 1$ symbol vector. Applying the link adaptive regenerative (LAR) relaying scheme as described in [6], with scaled relay signals, the signal received at D in Phase II is

$$y_{RD}[k] = h_{RD}[k]\sqrt{P\alpha[k]}\boldsymbol{\theta}^T\hat{\mathbf{x}}_R[k] + n_{RD}[k]. \quad (3.6)$$

Here, $\alpha[k]$ represents the link-adaptive scalar at sub-carrier k and $\alpha[k] = \frac{\min\{\tilde{\gamma}_{SR}[k], \bar{\gamma}_{RD}[k]\}}{\bar{\gamma}_{RD}[k]}$, where $\tilde{\gamma}_{SR[k]}$ is the instantaneous signal-to-noise ratio (SNR) on $S_i \rightarrow R$ link and $\bar{\gamma}_{RD}[k]$ is the average SNR on $R \rightarrow D$ link over sub-carrier k. Finally, the ML detector for the transmissions with regenerative relay is

$$\hat{\mathbf{x}}_D[k] = \underset{\mathbf{x}\in\chi}{argmin}\{\left\|y_{SD}[k] - \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SD}[k]\mathbf{x}[k]\right\|^2 + \left\|y_{RD}[k] - h_{RD}[k]\sqrt{P\alpha[k]}\,\boldsymbol{\theta}^T\mathbf{x}[k]\right\|^2\}. \quad (3.7)$$

3.3 Maximum Likelihood Detection Rules for Networks with Multiple Relays

The network model in this section comprises of multiple relays, as illustrated in Figure 3.2. The channel states on all the $S_i \rightarrow R_l$, $S_i \rightarrow D$ and $R_l \rightarrow D$ links are assumed to remain invariant throughout the transmission, so, $\mathbf{H}_{SR_l}[k] \coloneqq diag(h_{S_1R_l}[k], \ldots, h_{S_NR_l}[k])$ and $\mathbf{H}_{SD}[k] \coloneqq diag(h_{S_1D}[k], \ldots, h_{S_ND}[k])$ again respectively define $S_i \rightarrow R_l$ and $S_i \rightarrow D$ channel gain matrices over k-th subcarrier. This subsection again highlights two possible relaying strategies as explained below.

3.3.1 Amplify and forward for networks with multiple relays

Similar to the AAF scheme in Section 3.2.1, each source S_i transmits its symbols to each relay R_l, $l = 1, \ldots, M$ and destination D, using CFNC with OFDM and the received signals at R_l and D during phase I are modeled by $y_{SR_l}[k] = \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k] + n_{SR_l}[k]$ and $y_{SD}[k] = \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SD}[k]\mathbf{x}[k] + n_{SD}[k]$ respectively. The signals at each R_l are amplified in the similar way and are relayed to D during Phase II. The received signal at D during Phase II is shown as

$$y_{RD}[k] = \sum_{l=1}^{M}\{\, h_{R_lD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k] + \, h_{R_lD}[k]\sqrt{P\beta}n_{SR_l}[k]\} + n_{RD}[k]. \quad (3.8)$$

Subsequently, the ML detector for detecting source symbols, utilizing the information from both phases becomes

$$\hat{\mathbf{x}}_D[k] = \underset{\mathbf{x}\in\chi}{argmin}\{\left\|y_{SD}[k] - \sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SD}[k]\mathbf{x}[k]\right\|^2 + \left\|y_{RD}[k] - \sum_{l=1}^{M} h_{R_lD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k]\right\|^2\}. \quad (3.9)$$

3.3.2 Decode and forward for networks with multiple relays

In DAF model with multiple relays, each phase consists of M channel uses (CUs), so, during Phase I, all N sources transmit their symbols to M relays and destination in first M CUs as mentioned in [6], using CFNC with OFDM. Different symbols $\mathbf{x}[t,k] := [x_1[t,k],\ldots,x_N[t,k]]^T$ are sent by all source nodes to all relay nodes and destination at each CU t, $t = 1,\ldots,M$, over sub-carrier k. Therefore, the received signals at $R_l \rightarrow D$ during CU t, over sub-carrier k can be written as

$$y_{SR_l}[t,k] = \sqrt{P}\boldsymbol{\theta}_S^T\mathbf{H}_{SR_l}[k]\mathbf{x}[t,k] + n_{SR_l}[t,k], \quad (3.10)$$

$$y_{SD}[t,k] = \sqrt{P}\boldsymbol{\theta}_S^T\mathbf{H}_{SD}[k]\mathbf{x}[t,k] + n_{SD}[t,k], \quad (3.11)$$

where $\boldsymbol{\theta}_S$ is an $N \times 1$ vector of source complex coefficients. After M CUs, relay R_l uses ML detector for the source symbols sent at CU t and sub-carrier k, as shown

$$\hat{\mathbf{x}}_{R_l}[t,k] = \underset{\mathbf{x}\in\chi}{argmin}\left\|y_{SR_l}[t,k] - \sqrt{P}\boldsymbol{\theta}_S^T\ \mathbf{H}_{SR_l}[k]\mathbf{x}[t,k]\right\|^2. \quad (3.12)$$

R_l forwards the detected symbols with scaling coefficient $\alpha_l[k]$ in CU $M + l$ [10] at sub-carrier k and Phase II reception at D can be modeled as

$$y_{R_lD}[k] = h_{R_lD}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}_R^T\hat{\mathbf{x}}_{R_l}[k] + n_{R_lD}[k], \quad (3.13)$$

where $\boldsymbol{\theta}_R$ is an $NM \times 1$ vector. Finally, after transmission of M symbols by each S_i over $2M$ CUs, the ML detector at D yields

$$\hat{\mathbf{x}}_D[k] = \underset{\mathbf{x},\mathbf{x}'\in\chi}{argmin}\{\sum_{t=1}^{M}\left\|y_{SD}[t,k] - \sqrt{P}\boldsymbol{\theta}_S^T\mathbf{H}_{SD}[k]\mathbf{x}[t,k]\right\|^2 + \sum_{l=1}^{M}\left\|y_{R_lD}[k] - h_{R_lD}[k]\sqrt{P\alpha_l[k]}\ \boldsymbol{\theta}_R^T\mathbf{x}'[k]\right\|^2\}. \quad (3.14)$$

3.4 Maximum Likelihood Detection Rules for Networks with Relay Selection

In relay selection (RS) technique, D chooses one out of M relays to serve as transmission agent during Phase II. RS can be implemented with both AAF and DAF.

3.4.1 Amplify and forward for networks with relay selection

In RS with AAF scheme, D uses the products $h_{R_l D}[k]\sqrt{\beta}$ as the criteria to choose the best relay as $R_l[k] = \underset{l=1,\dots,M}{argmax}\left|h_{R_l D}[k]\sqrt{\beta}\right|$. So, the chosen R_l amplifies the received signal and performs transmission during Phase II, as follows

$$y_{R_l D}[t] = h_{R_l D}[k]P\sqrt{\beta}\boldsymbol{\theta}^T \mathbf{H}_{SR_l}[k]\mathbf{x}[k] + h_{R_l D}[k]\sqrt{P\beta}n_{SR_l}[k] + n_{RD}[k]. \quad (3.15)$$

Subsequently, the ML detector for the recovery of source symbols can be written as

$$\hat{\mathbf{x}}_D[k] = \underset{\mathbf{x}\in\chi}{argmin}\{\left\|y_{SD}[k] - \sqrt{P}\boldsymbol{\theta}^T \mathbf{H}_{SD}[k]\mathbf{x}[k]\right\|^2 + \left\|y_{R_l D}[k] - h_{R_l D}[k]P\sqrt{\beta}\boldsymbol{\theta}^T \mathbf{H}_{SR_l}[k]\mathbf{x}[k]\right\|^2\}. \quad (3.16)$$

3.4.2 Decode and forward for networks with relay selection

In RS with DAF protocol, D has got available products $h_{R_l D}[k]\sqrt{\alpha_l[k]}$ for each R_l and selects the best among them as $R_l[k] = \underset{l=1,\dots,M}{argmax}\left|h_{R_l D}[k]\sqrt{\alpha_l[k]}\right|$ as stated in [6]. Therefore, the selected R_l performs transmission in $M + l$ CUs and the corresponding signal at D, over CU $t = M + l$ can be shown as

$$y_{R_l D}[t,k] = h_{R_l D}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}^T \hat{\mathbf{x}}_{R_l}[t,k] + n_{R_l D}[t,k]. \quad (3.17)$$

At last, after $2M$ CUs, the ML detector to recover source symbols at $t = 1, \dots, M$ CU is given below

$$\hat{\mathbf{x}}_D[t,k] = \underset{\mathbf{x}\in\chi}{argmin}\{\left\|y_{SD}[t,k] - \sqrt{P}\boldsymbol{\theta}^T \mathbf{H}_{SD}[k]\mathbf{x}[t,k]\right\|^2 + \left\|y_{R_l D}[t_1,k] - h_{R_l D}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}^T \mathbf{x}[t,k]\right\|^2\}, \quad (3.18)$$

where $t_1 = M, \dots, 2M$.

The system functioning at the transmission end just involves the multiplication of complex coefficients with the modulated symbols and simultaneaous transmission to relay and destination nodes. But the system complexity at the receiving end increases exponentially with the number of sources N and the order of modulation, since ML detection is involved for detecting different source bits. Moreover, for DAF systems with multiple relays, increase in the number of relays M also results in higher system complexity.

3.6 Numerical Results

In this section, various numerical results using Monte Carlo simulations for the above mentioned network models are presented. Throughout the simulations, binary phase shift keying (BPSK) modulation and frequency selective and slow fading Rayleigh channel of unity power are assumed. BPSK modulation is used due to its ease of implementation for a better system analysis and the higher order modulation schemes can also be generalized in the similar way. An FFT size of 64 is used and CP length is one-fourth times of the total FFT size. CP length is always taken greater than the channel taps. Simulations are performed to generate BER versus SNR curves in different scenarios.

In Figure 3.5, different numbers of source nodes are taken in distributed network with a single relay and both non-regenerative (AAF) as well as regenerative (DAF) relay types are considered. AAF seems to outperform DAF for any number of sources and increase in the number of sources increases the margin of difference in performance of AAF and DAF protocols. Therefore, less complex AAF gives better BER results with greater number of sources but on the other hand it requires the storage of analog waveform at the relays. It should be noted that the results for DAF scheme are same as that in [6] even after OFDM is included in the system model.

Figure 3.6 summarizes the results of more generalized multi-relay distributed network topology. Two sources are considered for both AAF and DAF relaying protocols and RS technique is also investigated with AAF as well as DAF schemes to enhance error performance.

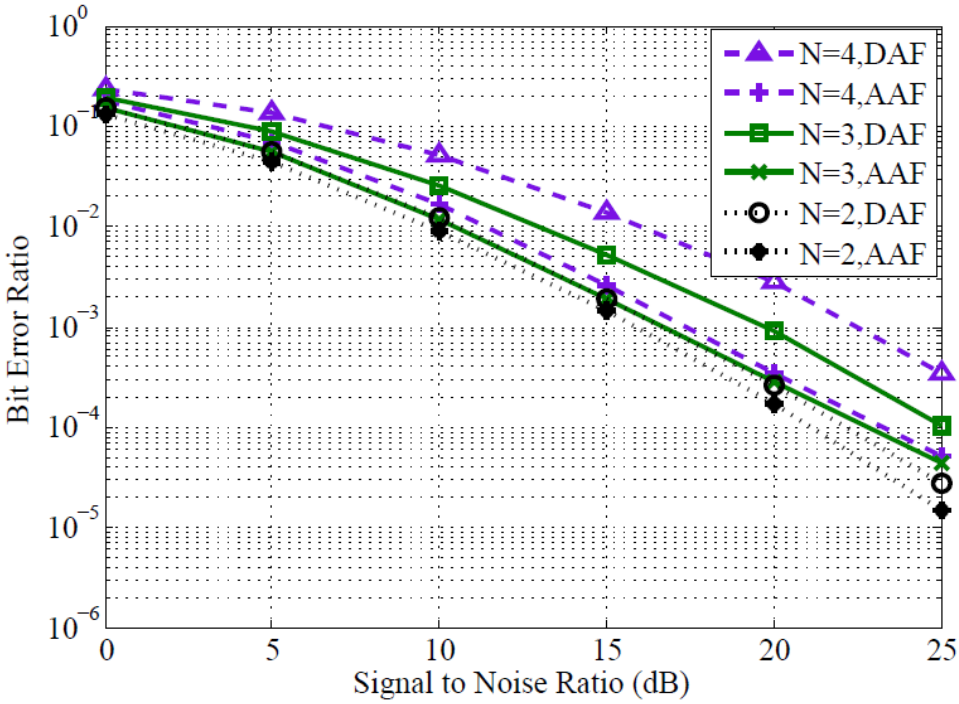

Figure 3.5 : BER versus SNR curves for CFNC with OFDM over unity variance Rayleigh fading channel, $M = 1$, $N = 2,3,4$, AAF and DAF relaying protocols, BPSK modulation.

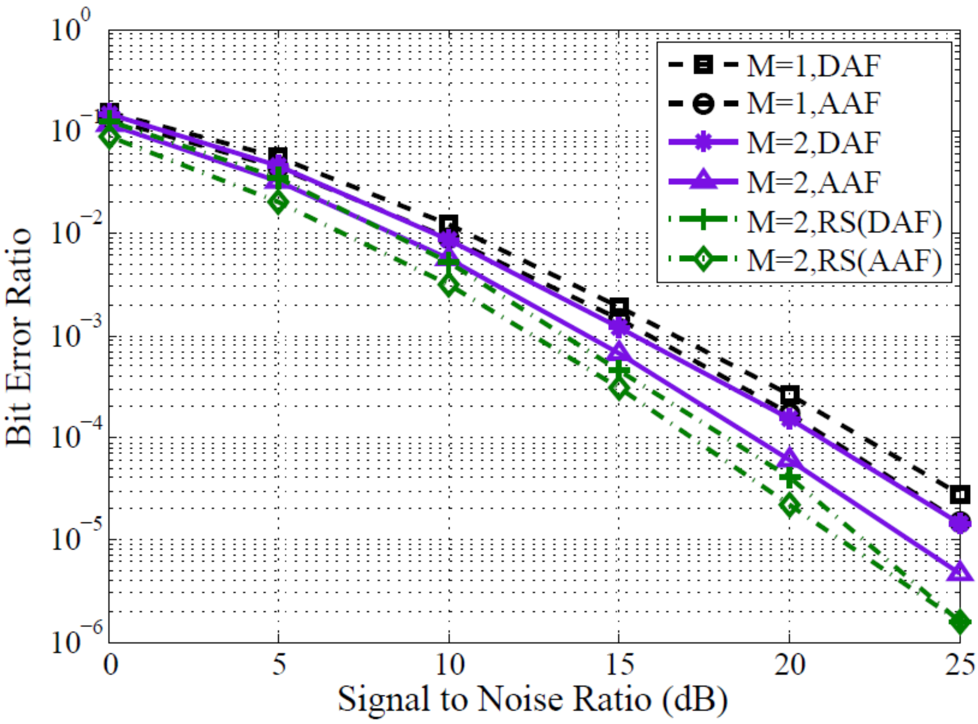

Figure 3.6 : BER versus SNR curves for CFNC with OFDM over unity variance Rayleigh fading channel, $M = 1,2$, $N = 2$, AAF and DAF and RS (AAF and DAF) relaying protocols, BPSK modulation.

However, RS implementation with both AAF and DAF requires the feedback from D to send information about the best relay which makes it a bit more complex in implementation than conventional DAF and AAF. Again the results for DAF protocol (with and without RS) are similar to that in [6] after the addition of OFDM in the network model for frequency selective fading channels.

Figure 3.7 depicts the performance study of two sources and single relay paradigm in asymmetric link environment, when either of the sources or the destination are close to R, for both AAF and DAF protocols. The average SNRs of the links with nodes at smaller distances are 10 dB higher than the average SNRs of the other links. It can be observed that with $\bar{\gamma}_{SR}$ (source to relay average SNR) 10 dB higher than $\bar{\gamma}_{SD}$ (source to destination average SNR) and $\bar{\gamma}_{RD}$ (relay to destination average SNR), the average BER performance improves approximately by 3 dB and 5 dB for DAF and AAF protocols respectively, in comparison to the symmetric link scenario. However, the difference in BER realizations is small when $\bar{\gamma}_{RD}$ is 10 dB higher than others. In AAF, this improvement in BER performance is more obvious with greater $\bar{\gamma}_{SR}$ and $\bar{\gamma}_{RD}$. The results for DAF with asymmetric links and OFDM once again resemble those in [6] since slow fading Rayleigh channel is assumed.

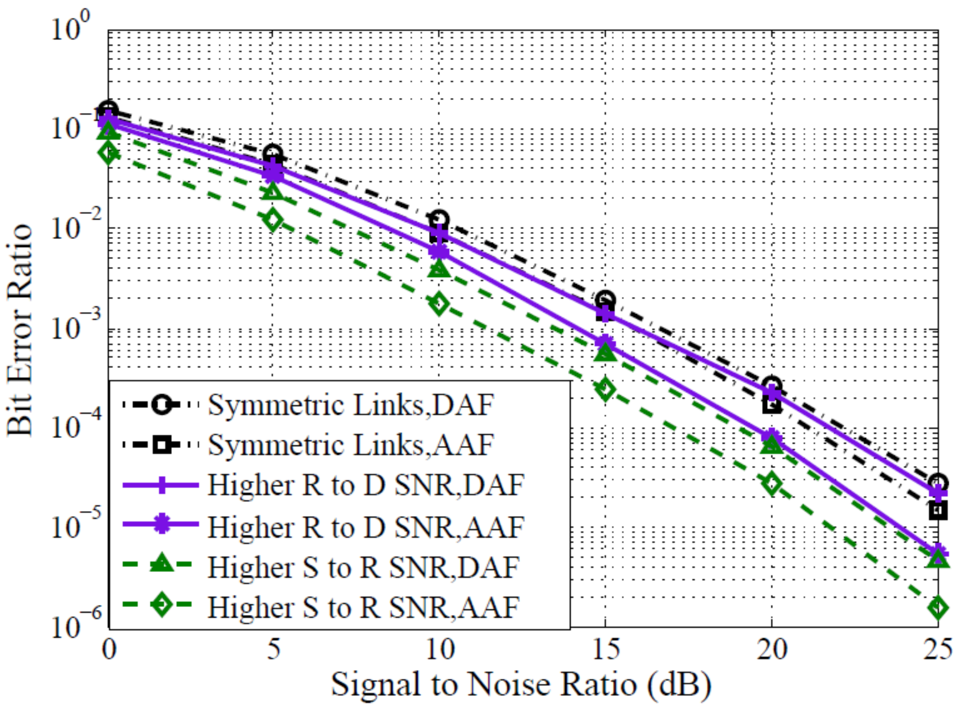

Figure 3.7 : BER versus SNR curves for CFNC with OFDM over unity variance Rayleigh fading channel, $M = 1$, $N = 2$, AAF and DAF relaying protocols with Asymmetric links between nodes, BPSK modulation.

At last, in Figure 3.8, convolutional channel codes are integrated in system model as shown in Figure 3.3 and the performance gain is observed as compared to the uncoded schemes. Three different codes with code rates $\frac{1}{2}$, $\frac{1}{3}$ and $\frac{1}{4}$ are employed in two sources and single relay network topology and BER performances are observed. The octets for rates $\frac{1}{2}$, $\frac{1}{3}$ and $\frac{1}{4}$ codes are [117 155], [123 135 157] and [117 127 155 171] respectively, with optimum distance properties to give a better coding gain [24]. Hard decision Viterbi decoding is used at R_l and D to get source bits and same type of code is utilized at all nodes in the network. Simulation results show that rate $\frac{1}{2}$ code gives a performance gain of about 3 dB at a BER of around 10^{-2} for both AAF and DAF schemes. This gain in performance is approximately 6 dB for rate $\frac{1}{3}$ code and nearly 7.5 dB for rate $\frac{1}{4}$ code. Hence CFNC with OFDM seems to give observable attainment in performance with even rate $\frac{1}{2}$ code.

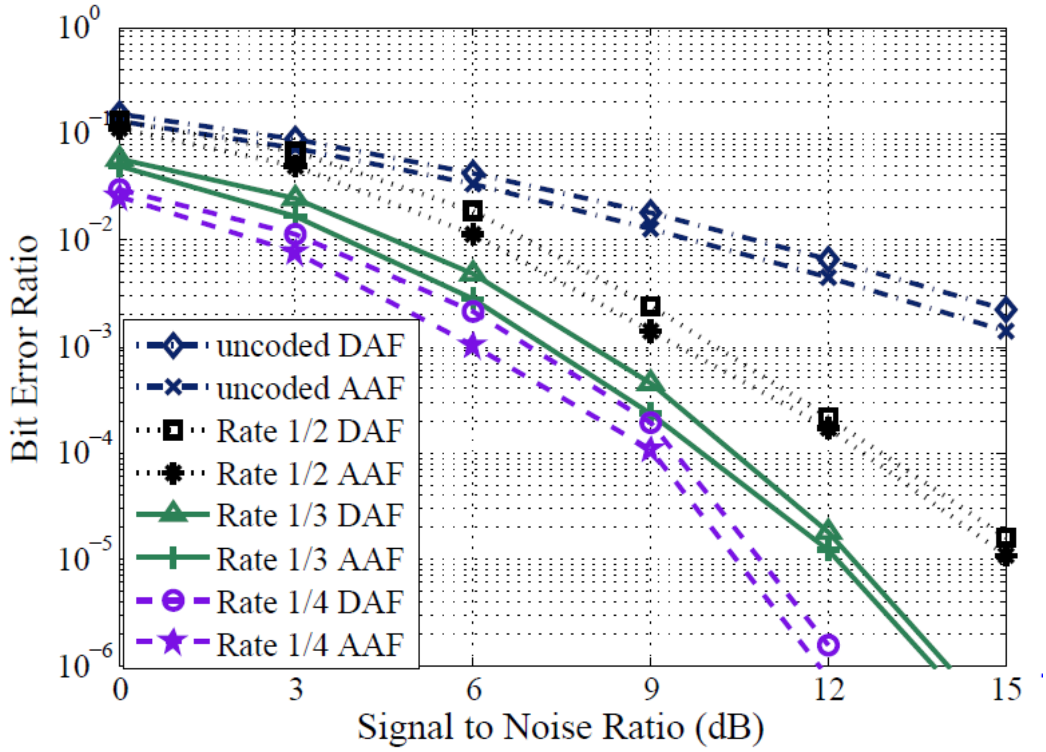

Figure 3.8 : BER versus SNR curves for CFNC with OFDM over unity variance Rayleigh fading channel, $M = 1$, $N = 2$, AAF and DAF relaying protocols, BPSK modulation and convolutional codes of rate $\frac{1}{2}$, $\frac{1}{3}$ and $\frac{1}{4}$.

In this system, AAF always outperforms DAF because of the linear constellation rotation properties of CFNC and the implementation of ML detection at both relay and destination nodes with the information of channel states

4. CHANNEL CODED COMPLEX FIELD NETWORK CODING WITH OFDM IN WIRELESS NETWORKS

As mentioned in Chapter 3 of the thesis, CFNC is quite simple and straightforward and offers a throughput as high as $\frac{1}{2}$ symbol per source per channel use while providing the maximum possible diversity gain with multiuser detection. In contrast to other types of NC techniques, CFNC requires symbol-level synchronization that is easier to attain than bit-level synchronization, as required by GFNC [6].

Cai *et al.* in [13] proposed an enhanced CFNC scheme with error control coding and SDAF to improve error efficiency in adverse cooperative communication environment. A repetition based CFNC scheme was suggested in [14] for typical asymmetric link scenario, with higher data traffic in downlink such as OFDMA systems, to improve the decision accuracy of ML decision rule. In this chapter of thesis, channel coded CFNC with OFDM in multi-source single-destination wireless relay networks is investigated to increase the error performance and overcome the frequency selective fading nature of wideband wireless channels, for slow and frequency selective Rayleigh fading channels. Both non-regenerative (AAF) and regenerative (DAF) types of relays are assumed to obtain error performance results. For multi-relay systems, RS technique is also considered with both AAF and DAF protocols at the relay nodes for better performance. In addition to this, convolutional codes having different code rates and constraint lengths are integrated with the system model, as error control codes to accommodate the degrading effects of wireless channel and different channel decoding techniques are employed. Finally, asymmetric link environments, with relay nodes at different distances from sources and destination, are also taken into account.

4.1 System Model

The system model is made of N source nodes, denoted as $S_i, i \in \{1, \ldots, N\}$, M relay nodes, represented by $R_l, l \in \{1, \ldots, M\}$, one destination D and K available SCs, as mentioned in Chapter 3. In generalized system, information bits from source nodes are sent and relayed to destination node in two phases, as shown in Figure 4.1. The process in Phase I, that is OFDM operation with coded CFNC at sources is illustrated in Figure 4.2.

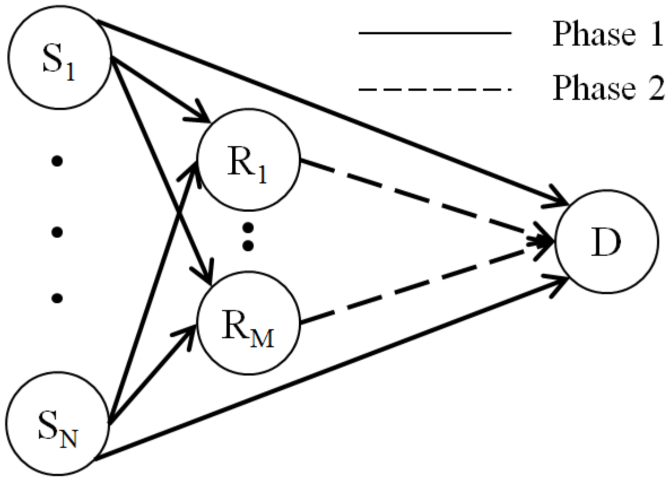

Figure 4.1 : Generalized system model for coded CFNC with *N* sources and *M* relays, relay scheduling.

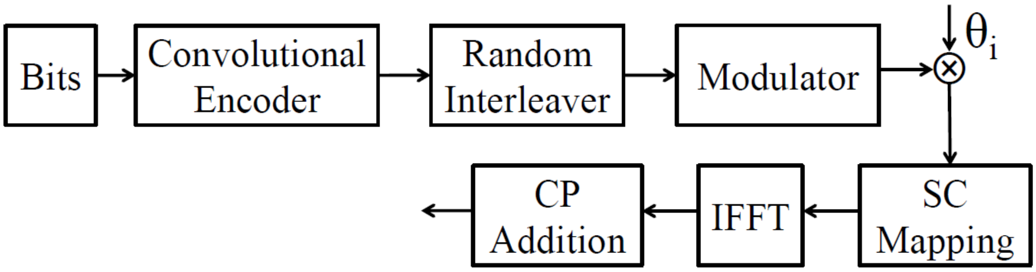

Figure 4.2 : OFDM operation with coded CFNC at sources.

Each source S_i generates bits to be sent that are encoded and interleaved. In contrast to single-carrier systems, codewords in OFDM systems can be arranged, and interleaving is done in frequency as well as in time to fully exploit frequency and time diversities. Therefore, coded OFDM systems usually contain inner and outer levels of channel coding, known as concatenated coding [7]. Typically, the inner code in coded OFDM systems is a rate-half convolutional code with convolutional interleaving and is useful in improving SNR performance. Decoding proceeds through the OFDM SCs as if they all had been transmitted over the same channel. The outer code is a powerful block code like Reed Solomon code with block interleaving and provides robustness to the coded OFDM system in frequency selective fading environments [7]. However, in the given system, only convolutional encoding with random interleaving is considered for the sake of simplicity. The bits are then modulated and multiplied with the complex coefficient θ_i, as described in

Chapter 3. All the sources then map their modulated symbols to all the available K SCs because the multiplication of complex coefficients rotates the actual constellation of modulated symbols and hence allows the multiuser detection of symbols, even if the symbols are transmitted over the same SCs. Subsequently, K-point IFFT is taken at each source and CP is appended to avoid interference between sub-carriers.

As the transmitted signal from sources, y_{SR_l} is received at each relay R_l, its CP is removed and K-point FFT is taken, as depicted in Figure 4.3 and Figure 4.4 for AAF and DAF respectively.

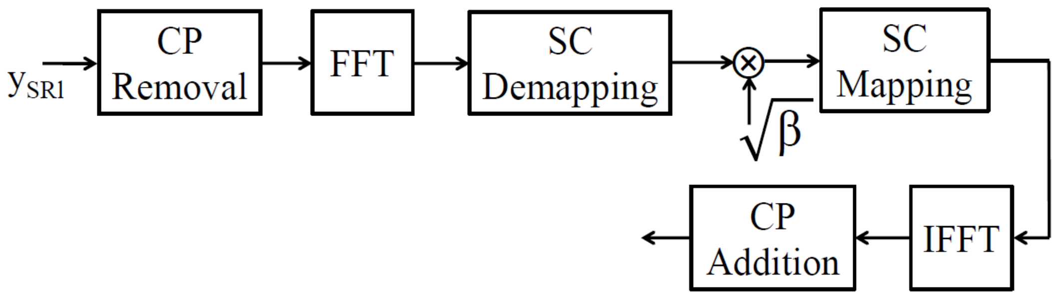

Figure 4.3 : OFDM operation with coded CFNC at relays for AAF.

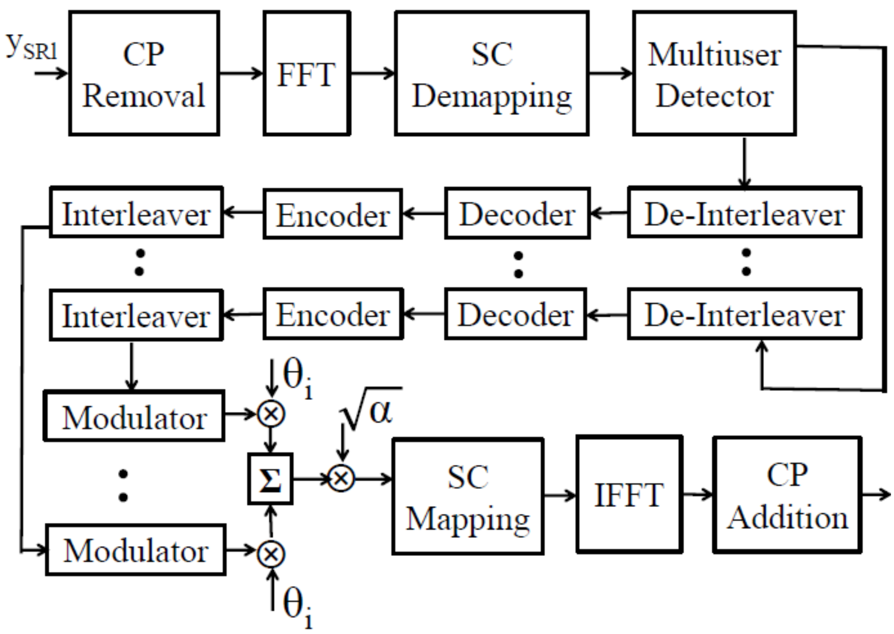

Figure 4.4 : OFDM operation with coded CFNC at relays for DAF.

Symbols from each source S_i are retrieved at each relay R_l from their SCs and the further steps of amplification or decoding are taken depending upon the relaying scheme at R_l. AAF just involves the amplification at relays with the square root of a predefined amplification factor β, as can be seen in Figure 4.3. Whereas in DAF, all source bits are first recovered at relays and then regenerated following the series of steps, as indicated in Figure 4.4. Multiuser detection is made for $S \rightarrow R$ link signal and soft decisions for all coded source bits are parallely deinterleaved. Coded source bits are parallely decoded, re-encoded using the same convolutional encoder as S_i and randomly interleaved. After that, the bits are modulated with the same modulation scheme as in S_i and modulated symbols are multiplied with the complex coefficient θ_i. The regenerated symbols are then added and scaled with the square root of the link-adaptive scalar α for diversity and power efficiency [6], as shown in Figure 4.4. In Phase II, all the relays transmit source symbols over the same available K SCs employing the same conventional OFDM, as depicted in Figure 4.3 and Figure 4.4. As the signals y_{SD} and y_{RD}, from source and relay nodes respectively, arrive at D, CP is removed and K-point FFT of the received signals is taken.

Afterwards, multiuser detection takes place for both $S \rightarrow D$ and $R \rightarrow D$ link signals and corresponding soft decisions for coded bits are added for each S_i, as shown in Figure 4.5. Then deinterleaving of symbols occurs according to the soft decisions, following the decoding of source bits at D.

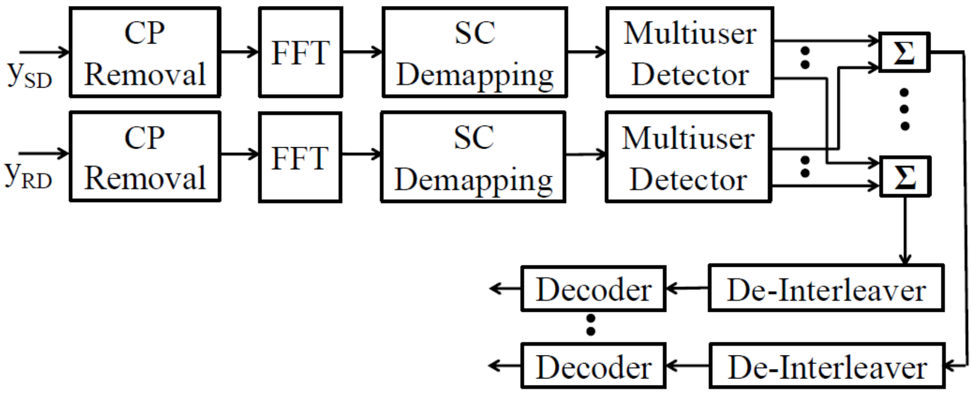

Figure 4.5 : Detection and decoding at D.

4.2 Multiuser Detection Rules for Networks with Multiple Relays

This sub-section discusses the multiuser detection rules applied at the relay nodes and destination. For that purpose, cooperative networks are classified into single or multiple parallel relays and relay selection categories. The network model in this section comprises of any number of relays, as shown in Figure 4.1. The channel states on all the $S \rightarrow R$, $S \rightarrow D$ and $R \rightarrow D$ links are assumed to remain invariant throughout the transmission, so, $\mathbf{H}_{SR_l}[k] \coloneqq diag(h_{S_1R_l}[k], \dots, h_{S_NR_l}[k])$ and $\mathbf{H}_{SD}[k] \coloneqq diag(h_{S_1D}[k], \dots, h_{S_ND}[k])$ respectively define $S \rightarrow R_l$ and $S \rightarrow D$ channel gain matrices over kth SC. This section highlights two possible relaying strategies as explained below.

4.2.1 Amplify and forward for networks with multiple relays

During Phase I in the AAF or non-regenerative scheme, each source S_i transmits its coded symbols to each relay R_l, $l = 1, \dots, M$, and destination D, using CFNC with OFDM. Defining $\mathbf{x}[k] \coloneqq [x_1[k], \dots, x_N[k]]^T$ as source symbols transmitted on SC k, $k = 1, \dots, K$, $\boldsymbol{\theta}^T \coloneqq [\theta_1, \dots, \theta_N]$ as the complex coefficient entries and P as the average transmit power of each node, on SC k, the received signals at R_l and D in Phase I on SC k can be modeled as

$$y_{SR_l}[k] = \sqrt{P}\boldsymbol{\theta}^T \mathbf{H}_{SR_l}[k]\mathbf{x}[k] + n_{SR_l}[k], \tag{4.1}$$

$$y_{SD}[k] = \sqrt{P}\boldsymbol{\theta}^T \mathbf{H}_{SD}[k]\mathbf{x}[k] + n_{SD}[k], \tag{4.2}$$

where $n_{SR_l}[k]$, $n_{SD}[k]$ represent zero mean additive Gaussian noise, with variances $\sigma^2_{SR_l}$ and σ^2_{SD} respectively. The signal received at R_l is amplified with square root of the factor $\beta = \frac{1}{2P+1}$ if all channel and noise variances are taken unity and is relayed to D during Phase II. The received signal at D during Phase II is shown as

$$y_{RD}[k] = \sum_{l=1}^{M} \{ h_{R_lD}[k] P\sqrt{\beta}\boldsymbol{\theta}^T \mathbf{H}_{SR_l}[k]\mathbf{x}[k] + h_{R_lD}[k]\sqrt{P\beta} n_{SR_l}[k]\} + n_{RD}[k], \tag{4.3}$$

where, $h_{R_lD}[k]$ is $R \rightarrow D$ channel gain on SC k and $n_{RD}[k]$ is zero mean additive Gaussian noise with variance σ^2_{RD}. The multiuser detector rules used in this paper are similar in logic to the iterative multiuser decoder suggested in [13] and provide log-likelihood ratios (LLRs) for the coded bits from each S_i. Utilizing the information from both phases, the LLRs corresponding to the $S \rightarrow D$ and $R \rightarrow D$ links on SC k respectively become

$$\lambda_{SD}[k] = \min_{\mathbf{x} \in \chi^+} \left| y_{SD}[k] - \sqrt{P}\boldsymbol{\theta}^T \mathbf{H}_{SD}[k]\mathbf{x}[k] \right|^2$$

$$-\min_{\mathbf{x}\in\chi^-}\left|y_{SD}[k]-\sqrt{P}\boldsymbol{\theta}^T\mathbf{H}_{SD}[k]\mathbf{x}[k]\right|^2, \quad (4.4)$$

$$\lambda_{RD}[k]=\min_{\mathbf{x}\in\chi^+}\left|y_{RD}[k]-\sum_{l=1}^{M}h_{R_lD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k]\right|^2$$
$$-\min_{\mathbf{x}\in\chi^-}\left|y_{RD}[k]-\sum_{l=1}^{M}h_{R_lD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k]\right|^2, \quad (4.5)$$

where χ^+ and χ^- are the set of modulated symbols with a coded "0" or "1" bit respectively at S_i. These LLRs are then added and later fed to decoder to obtain the source bits.

4.2.2 Decode and forward for networks with multiple relays

In the DAF or regenerative relaying model with single or multiple parallel relays, each phase consists of M CUs, so, during Phase I, all N sources transmit their coded symbols to M relays and destination in the first M CUs as mentioned in [10], using CFNC with OFDM. Different symbols $\mathbf{x}[t,k]:=\left[x_1[t,k],\ldots,x_N[t,k]\right]^T$ are sent by all source nodes to all relay nodes and destination at each CU t, $t=1,\ldots,M$, over SC k. Therefore, the received signals at R_l and D during CU t, over SC k can be written as

$$y_{SR_l}[t,k]=\sqrt{P}\boldsymbol{\theta}_S^T\mathbf{H}_{SR_l}[k]\mathbf{x}[t,k]+n_{SR_l}[t,k], \quad (4.6)$$

$$y_{SD}[t,k]=\sqrt{P}\boldsymbol{\theta}_S^T\mathbf{H}_{SD}[k]\mathbf{x}[t,k]+n_{SD}[t,k], \quad (4.7)$$

where θ_S is an $N\times 1$ vector, as defined in Chapter 3. After M CUs, relay R_l uses multiuser detection to generate LLRs for coded source bits at CU t and SC k, as shown

$$\lambda_{SR_l}[t,k]=\min_{\mathbf{x}\in\chi^+}\left|y_{SR_l}[t,k]-\sqrt{P}\boldsymbol{\theta}_S^T\,\mathbf{H}_{SR_l}[k]\mathbf{x}[t,k]\right|^2$$
$$-\min_{\mathbf{x}\in\chi^-}\left|y_{SR_l}[t,k]-\sqrt{P}\boldsymbol{\theta}_S^T\,\mathbf{H}_{SR_l}[k]\mathbf{x}[t,k]\right|^2. \quad (4.8)$$

Subsequently, each R_l regenerates source symbol vector $\hat{\mathbf{x}}_l[k]$ using the detected bits, as illustrated in Figure 4.4. Applying the LAR relaying scheme as described in

[10], in which relayed symbols are scaled before being forwarded to destination, the signal received at D in Phase II becomes

$$y_{R_lD}[k] = h_{R_lD}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}_R^T\hat{\mathbf{x}}_{R_l}[k] + n_{R_lD}[k], \tag{4.9}$$

where $\boldsymbol{\theta}_R$ is an $NM \times 1$ vector. Here, $\alpha_l[k]$ represents the link-adaptive scalar at R_l over SC k and $\alpha_l[k] = \frac{\min\{\tilde{\gamma}_{SR_l}[k], \bar{\gamma}_{R_lD}[k]\}}{\bar{\gamma}_{R_lD}[k]}$, where $\tilde{\gamma}_{SR_l}[k]$ is the instantaneous signal-to-noise ratio (SNR) on $S \rightarrow R_l$ link and $\bar{\gamma}_{R_lD}[k]$ is the average SNR on $R \rightarrow D$ link [25] over SC k. Finally, after transmission of M symbols by each S_i over $2M$ CUs, the multiuser detection to yield LLRs at D from both phases can be written as

$$\lambda_{SD}[k] = \min_{\mathbf{x}\in\chi^+}\sum_{t=1}^{M}\left|y_{SD}[t,k] - \sqrt{P}\boldsymbol{\theta}_S^T\mathbf{H}_{SD}[k]\mathbf{x}[t,k]\right|^2$$
$$-\min_{\mathbf{x}\in\chi^-}\sum_{t=1}^{M}\left|y_{SD}[t,k] - \sqrt{P}\boldsymbol{\theta}_S^T\mathbf{H}_{SD}[k]\mathbf{x}[t,k]\right|^2, \tag{4.10}$$

$$\lambda_{RD}[k] = \min_{\mathbf{x}'\in\chi^+}\sum_{l=1}^{M}\left|y_{R_lD}[k] - h_{R_lD}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}_R^T\mathbf{x}'[k]\right|^2$$
$$-\min_{\mathbf{x}'\in\chi^-}\sum_{l=1}^{M}\left|y_{R_lD}[k] - h_{R_lD}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}_R^T\mathbf{x}'[k]\right|^2. \tag{4.11}$$

4.3 Multiuser Detection Rules for Networks with Relay Selection

In the RS technique, D chooses one out of M relays to serve as transmission agent during Phase II. This section implements RS with both AAF and DAF.

4.3.1 Amplify and forward for networks with relay selection

In the RS with AAF scheme, D uses $h_{R_lD}[k]$ as the criteria to choose the best relay as $R_l[k] = \underset{l=1,\ldots,M}{argmax}\left|h_{R_lD}[k]\right|$, for β being a constant term. So, the chosen R_l amplifies the received signal and performs transmission during Phase II, as follows

$$y_{R_lD}[t] = h_{R_lD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k] + h_{R_lD}[k]\sqrt{P\beta}n_{SR_l}[k]$$
$$+n_{RD}[k]. \tag{4.12}$$

The multiuser detection rule corresponding to Phase I for RS with AAF is the same as described in subsection 4.2.1 for the AAF case. At last, the multiuser detection to get LLRs for Phase II can be written as

$$\lambda_{RD}[k] = \min_{\mathbf{x}\in\chi^+}\left|y_{RD}[k] - h_{R_lD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k]\right|^2$$
$$-\min_{\mathbf{x}\in\chi^-}\left|y_{RD}[k] - h_{R_lD}[k]P\sqrt{\beta}\boldsymbol{\theta}^T\mathbf{H}_{SR_l}[k]\mathbf{x}[k]\right|^2. \quad (4.13)$$

4.3.2 Decode and forward for networks with relay selection

In the RS with DAF protocol, D has got available products $h_{R_lD}[k]\sqrt{\alpha_l[k]}$ for each R_l and selects the best among them as $R_l[k] = \underset{l=1,\dots,M}{argmax}\left|h_{R_lD}[k]\sqrt{\alpha_l[k]}\right|$ as stated in [6]. Therefore, the selected R_l performs transmission in $M + l$ CUs and the signal at D, on SC k, over CU $t = M + l$ can be shown as

$$y_{R_lD}[t,k] = h_{R_lD}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}^T\hat{\mathbf{x}}_{R_l}[t,k] + n_{R_lD}[t,k]. \quad (4.14)$$

After $2M$ CUs, the multiuser detection related to Phase I to obtain LLRs for coded source bits at $t = 1, \dots, M$ CU is similar to the previously described DAF scenario and for Phase II is given below

$$\lambda_{RD}[k] = \min_{\mathbf{x}'\in\chi^+}\left|y_{R_lD}[t_1,k] - h_{R_lD}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}^T\mathbf{x}\,[t_1,k]\right|^2$$
$$-\min_{\mathbf{x}'\in\chi^-}\left|y_{R_lD}[t_1,k] - h_{R_lD}[k]\sqrt{P\alpha_l[k]}\boldsymbol{\theta}^T\mathbf{x}\,[t_1,k]\right|^2, \quad (4.15)$$

where $t_1 = M, \dots, 2M$.

This system involves channel coding with CFNC and OFDM resulting in a higher system complexity at both transmission and reception ends. While, at the transmission end, the coded and modulated source symbols are multiplied with the complex coefficients, the system complexity gets doubled at the reception as compared to the uncoded system. The complexity level of multiuser detector increases with the number of sources N, number of relays M and the order of modultion. LLR generation for each coded source bit at the reception results in higher system complexity.

4.5 Decoding Strategies

In this work, the multiuser detection rules to provide LLRs are derived by using Max-Log-MAP approximation [26] and follow the same outlook as Max-Log-MAP or soft output Viterbi algorithm (SOVA) [26] for decoding. The reason behind using Max-Log-Map algorithm for obtaining multiuser detection rules is its reduced decoding complexity as compared to the Log-Map algorithm. The Max-Log-MAP Algorithm computes log-likelihoods for the best paths in the trellis, with bit zero as well as bit one and uses their difference as LLRs [26] which allows the usage of Max-Log-MAP as the decoding algorithm. In the similar way, SOVA also takes log-likelihoods of the ML path and the best path with the complementary symbol, at the given instant and returns their difference [26]. The two paths in SOVA are identical to the two paths considered in Max-Log-MAP, therefore, soft Viterbi Algorithm can also be used equivalently as a decoding strategy.

4.6 Numerical Results

In this section, various numerical results using Monte Carlo simulations are presented for the above mentioned network models. Throughout the simulations, BPSK modulation and frequency selective slow fading Rayleigh channel of unity power are assumed. An FFT size of 64 is considered and CP length is one-fourth times of the total FFT size. CP length is always taken greater than the number of channel taps. In all simulations, a 4-state and rate-1/2 convolutional code with [5 7] octets and a random interleaver of length 64 are used, unless stated otherwise and BER versus SNR curves are generated in different scenarios.

In Figure 4.6, BER performance of the systems under consideration is presented. Different numbers of source nodes are taken in cooperative network with a single relay and both AAF as well as DAF relay types are considered. Moreover, both Max-Log-MAP and soft Viterbi Algorithms are used for decoding. AAF appears to outperform DAF for any number of sources and both decoding algorithms seem to give almost the same performance for all scenarios. A difference of approximately 2 dB in performance loss can be observed for both AAF and DAF as the number of sources increases from two to three. Moreover, this performance difference increases with an increase in average SNR values. Both Viterbi and Max-Log-MAP appear to give almost same BER performance for AAF and DAF as well as for different number of source nodes.

Figure 4.7 summarizes the results of more generalized multi-relay cooperative network topology. Two sources are considered for both AAF and DAF relaying protocols and RS technique is also investigated with AAF as well as DAF schemes to enhance error performance. However, RS implementation with both AAF and DAF requires the feedback from D to send information about the best relay which makes it a bit more complex in implementation than conventional AAF and DAF. At a BER of around 10^{-5}, two relays with parallel relay (PR) DAF operation give a performance gain of just 0.5 dB over the single relay DAF network but this gain is improved to 2.5 dB when RS with DAF is employed. The corresponding gain in performance for AAF with PR and RS is almost 1 dB and 2.7 dB respectively. Furthermore, a higher difference in performance can be observed as SNR increases, showing the diversity facilitated by multiple relays.

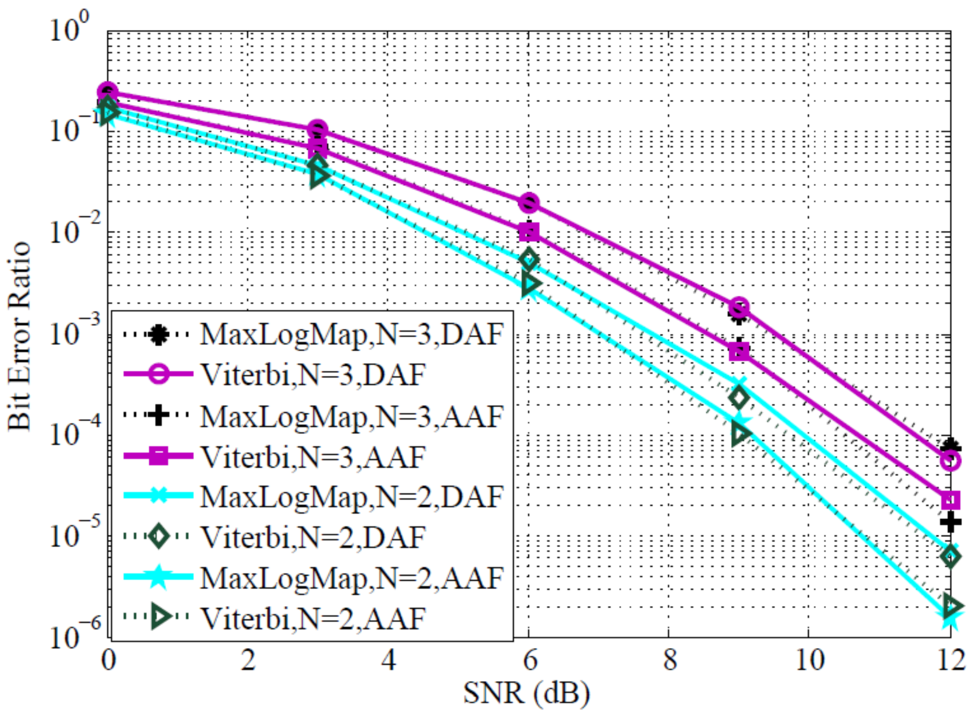

Figure 4.6 : BER versus SNR curves for coded CFNC with OFDM, $M = 1$, $N2,3$, Max-Log-Map and soft Viterbi decoding, AAF and DAF relaying protocols.

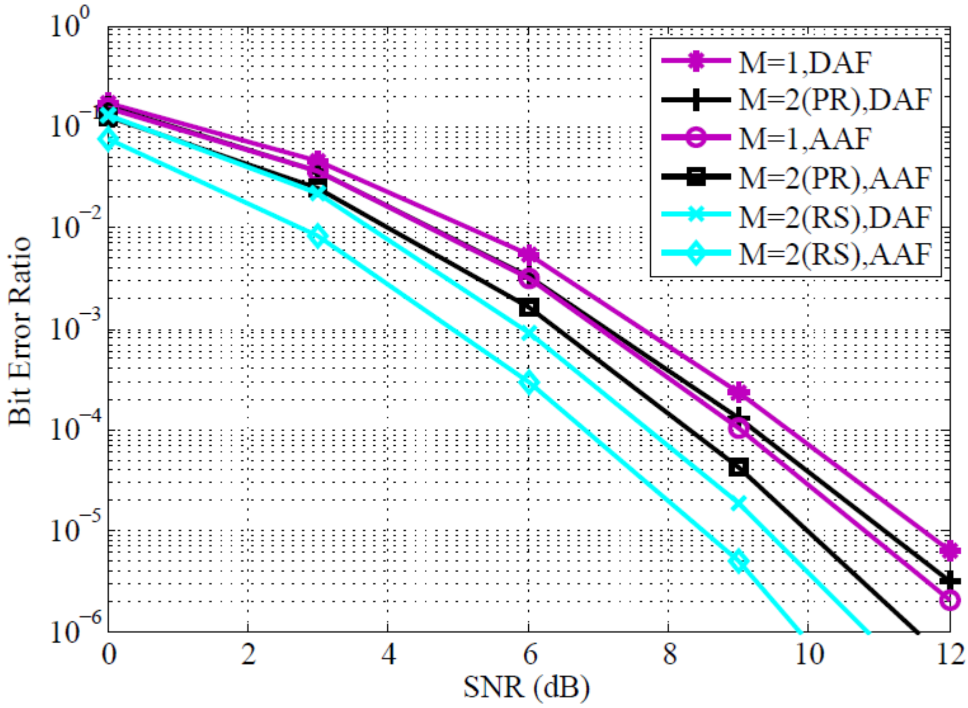

Figure 4.7 : BER versus SNR curves for coded CFNC with OFDM, $M = 1{,}2$, $N = 2$, AAF and DAF relaying protocols.

Figure 4.8 depicts the performance study of two sources and single-relay paradigm in asymmetric link environment, when R is located either close to the sources or close to the destination, for both AAF and DAF protocols. The average SNRs of the links with nodes at smaller distances are 10 dB higher than the average SNRs of the other links. It can be observed that with $\bar{\gamma}_{SR}$ (source to relay average SNR) 10 dB higher than $\bar{\gamma}_{SD}$ (source to destination average SNR) and $\bar{\gamma}_{RD}$ (relay to destination average SNR), the BER performance improves by 3.7 dB and 3.3 dB for DAF and AAF protocols respectively, at a BER of around 10^{-3}, in comparison to the symmetric link scenario. However, the difference in BER realizations is comparatively small when $\bar{\gamma}_{RD}$ is 10 dB higher than others. This improvement in BER performance is more obvious at higher SNRs for both AAF and DAF schemes.

Finally, in Figure 4.9, convolutional channel codes with different code rates and number of states in the code trellis are integrated. Another 128-state code with code rate 2/3 and octets $\begin{bmatrix} 23 & 35 & 0 \\ 0 & 5 & 13 \end{bmatrix}$, is employed in two sources and single- relay network topology and BER performances are observed for both AAF and DAF.

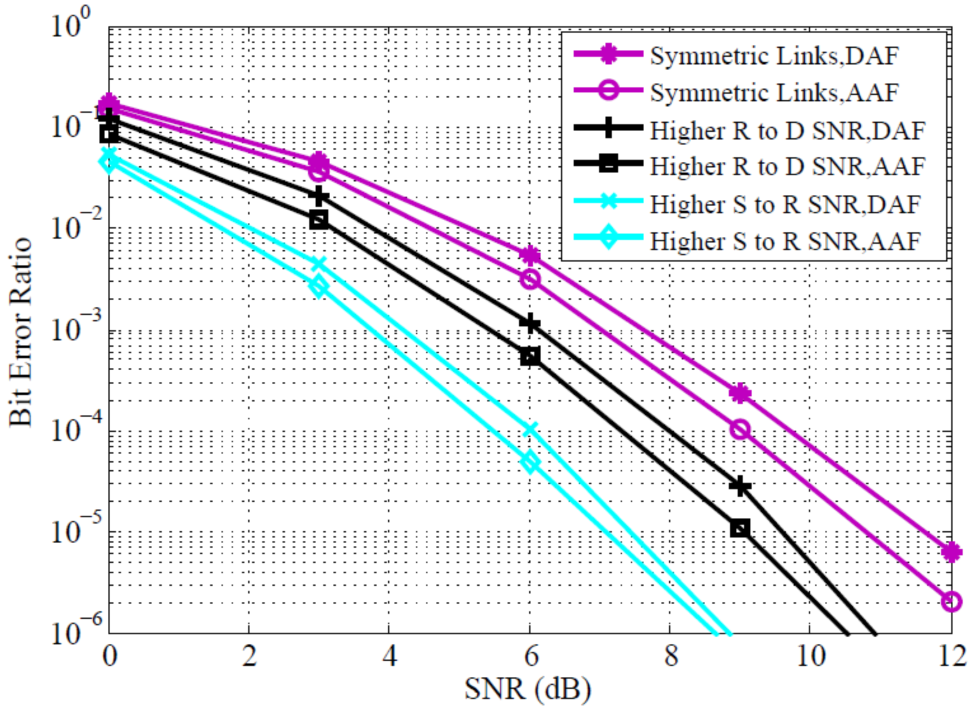

Figure 4.8 : BER versus SNR curves for coded CFNC with OFDM, $M = 1$, $N = 2$, AAF and DAF relaying protocols with asymmetric links between nodes.

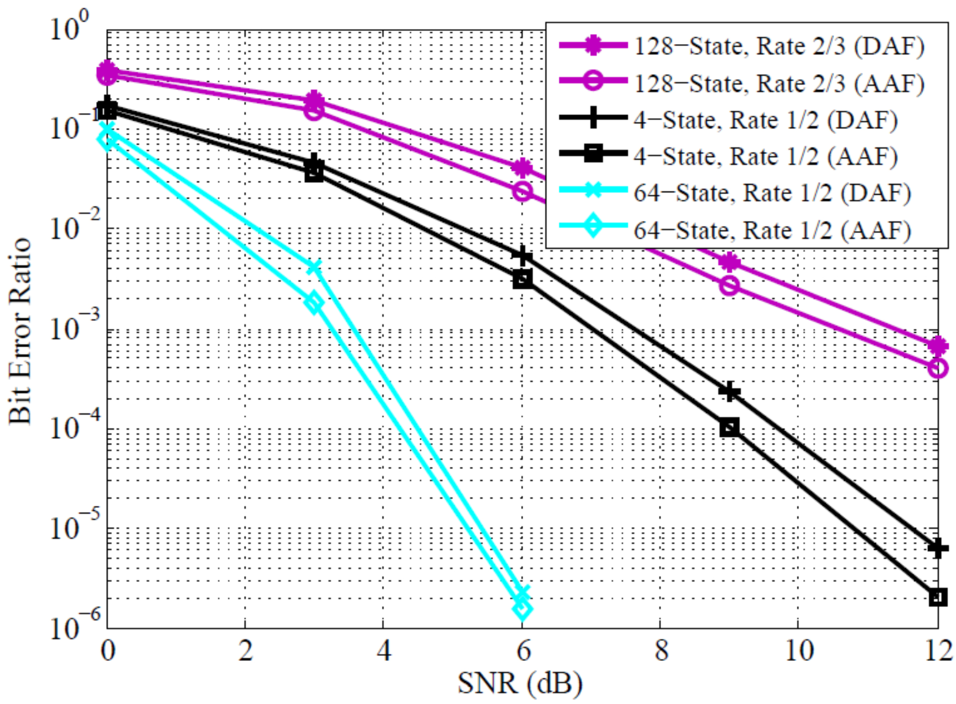

Figure 4.9 : BER versus SNR curves for coded CFNC with OFDM, $M = 1$, $N = 2$, AAF and DAF relaying protocols, 128-State Rate-2/3, 4-State Rate-1/2 and 64-State Rate-1/2 convolutional codes.

It can be observed that 128-state code gives poorer performance than 4-state and 64-state codes because it is a higher rate code while the codes with 4 and 64 states are lower rate codes, leading to their better performance. From the observations, it is clear that even if rate-1/2 code gives better performance than high rate codes, the BER performance of rate-2/3 with our network model is still acceptable for voice applications at 12 dB SNR. At last, a considerable gain in performance can be seen when the number of states in the trellis of rate-1/2 code are increased from 4 states to 64 states with octet values of $[117 \quad 155]$.

5. ENHANCED XOR NETWORK CODING SCHEME WITH OFDM FOR TWO-WAY RELAY NETWORKS

Among all the joint applications of cooperative communication and NC, two-way relay network is one of the most interesting and extensively studied communication scenarios. A classical two-way relay network consists of two nodes exchanging their information using intermediate relay nodes. Wu *et al.* in [15] exploited broadcasting capability at the relay and showed that the utilization of NC reduces the number of transmission slots, required to exchange a message in a two-way relay network. The use of RS was suggested in [27] to boost system performance and throughput in two-way relay networks with multiple relay nodes.

This chapter of thesis presents a flexible NC scheme for information exchange in two-way relay networks. OFDM is included in the system to combat the frequency selective fading nature of wireless networks. Compared to other conventional strategies for two-way relay networks, this strategy performs Galois field addition or bit-wise exclusive-OR (XOR) coding of multiple information packets at sources. The XOR coded packet is transmitted to the relays along with the information packets. This idea was proposed in [28] for one-hop broadcast wireless networks with a cross layer design, using cyclic redundancy check (CRC) for error detection at media access control layer. However, in the given work, a detection rule is defined at relay nodes for correct recovery of source bits. Relay nodes, after the detection of source bits, perform conventional Galois field addition of source bits. The suggested detection rule, as will be seen in the next chapters, is quite simple and straight forward. The XOR coded bits facilitate redundancy to acquire transmit diversity gain, which in turn improves error performance of the two-way relay network. Convolutional channel encoding is also included in the system to obtain desired error performance. Different numbers of relay nodes are assumed for obtaining error performance results and RS is also considered for multi-relay systems.

5.1 System Model

The system comprises of two source nodes, denoted as S_i, $i \in \{1,2\}$, M relay nodes, represented by R_l, $l \in \{1, \dots, M\}$ and K available OFDM SCs. Source nodes exchange their information bits as packets through relay nodes, constituting a two-way relay network, as shown in Figure 5.1. Phase I consists of media access where sources send their information bits to the relay nodes in different time slots (TS), as each S_i uses the same set of K SCs. Phase II is the relaying phase in which relay nodes broadcast the processed packets of information to both sources again in single or multiple TS, over the same K SCs. Each S_i transmits its information bits in separate TS during Phase I followed by each R_l, broadcasting its information in consecutive TS during Phase II.

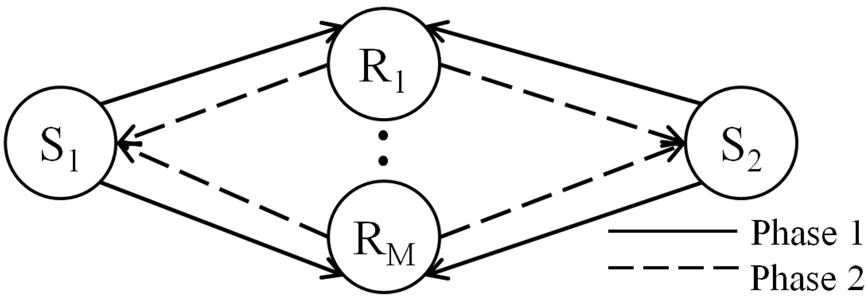

Figure 5.1 : Two-way relay network with two sources and M relays.

Figure 5.2 illustrates the series of steps taken at the source nodes for transmission of information to relay nodes. Each S_i generates its information bits that are convolutionally encoded and then the encoded bits are grouped into packets, represented as $\{X_i(1), X_i(2), \dots\}$ for S_i. Then information packets at S_i are bit-wise XOR coded, such that $X_i(1) \oplus X_i(2) \dots \oplus X_i(L) = X_i(L+1)$, where L is the total number of packets that are XOR coded. The resulting XOR coded packets, along with the information packets, provide redundancy at the transmission level. The bits are modulated and then each S_i maps its modulated symbols to all the available K SCs. Later, K-point IFFT is taken at each S_i and CP is appended to avoid interference between SCs. Finally, both source nodes send their encoded and modulated information to all relay nodes in two consecutive TS, during Phase I.

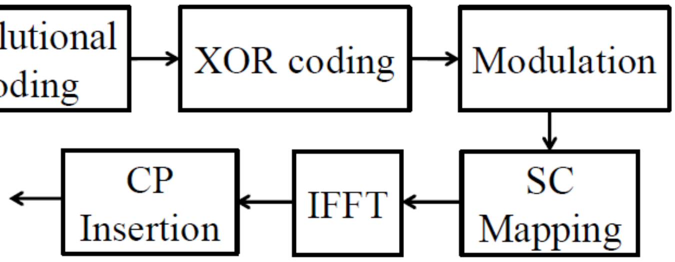

Figure 5.2 : XOR network coding with OFDM at sources.

As the signal transmitted from S_i to each R_l, that is $y_{S_iR_l}$ arrives at R_l, its CP is removed and K-point FFT is taken, as indicated in Figure 5.3.

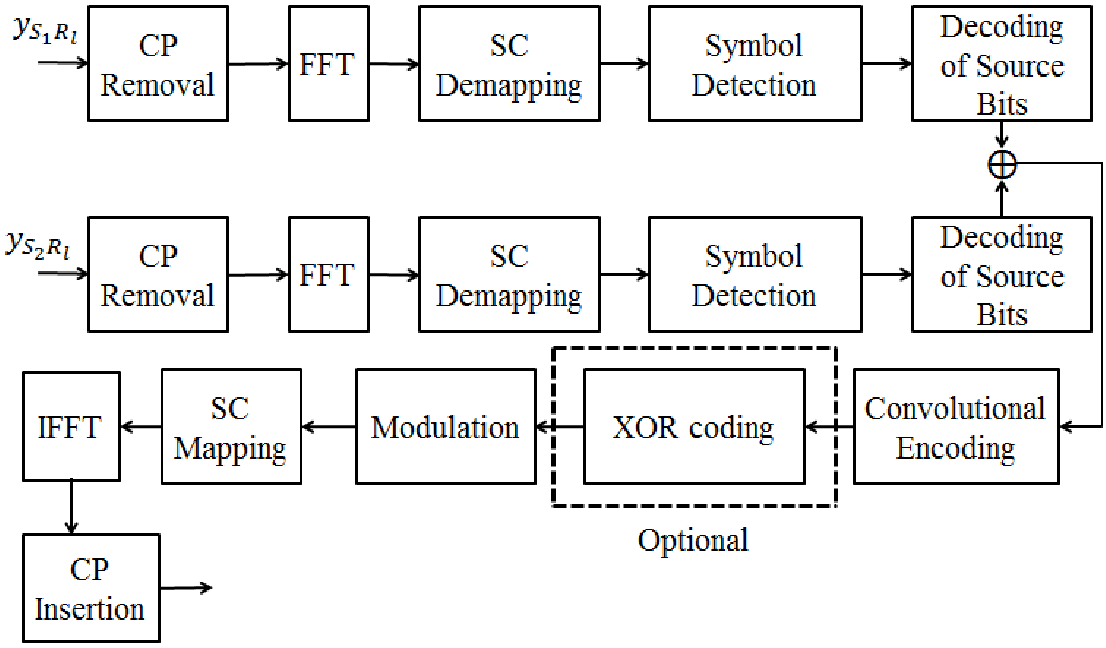

Figure 5.3 : Symbol detection XOR network coding with OFDM at relays.

Symbols from each source S_i are retrieved at each relay R_l from their SCs and then the detection of information packets is made with the help of XOR coded packet. The detection generates soft decisions for all coded source bits, transmitted on $S_i \rightarrow R_l$ link, followed by the decoding of source bits at each R_l. Then each R_l performs the classical network coding (XOR) of the detected bits from both sources. The resulting relay bits are convolutionally encoded, forming packets, given as $\{X_l(1), X_l(2), \ldots\}$ for R_l. These packets at R_l are bit-wise XOR coded optionally, as mentioned above for source nodes, granting transmission redundancy at R_l as well. After that, the coded bits are modulated, forming the symbols of information to be transmitted to both sources in Phase II. Each R_l, then allocates its modulated symbols over the same available K SCs, followed by IFFT and CP insertion, as shown in Figure 5.3. During Phase II, each R_l broadcasts its corresponding information with OFDM over K SCs in subsequent TS.

As the broadcasted signal $y_{R_l S_i}$ from each R_l is received at S_i, CP is removed and K-point FFT of the received signals is taken, as depicted in Figure 5.4. Symbols arriving from each R_l are retrieved from K SCs and information detection is made using all relay signals. If R_l sends redundancy information or XOR coded packet, S_i utilizes it for the detection of information packets to provide soft decisions for all coded relay bits, otherwise, the generation of soft decisions is made in a conventional way. Relay bits are decoded using the soft decisions, made for coded relay bits, transmitted on $R_l \to S_i$ link. Lastly, each source recovers the other source bits by performing the XOR of the decoded relay bits with its own bits, completing information exchange in the two-way relay network.

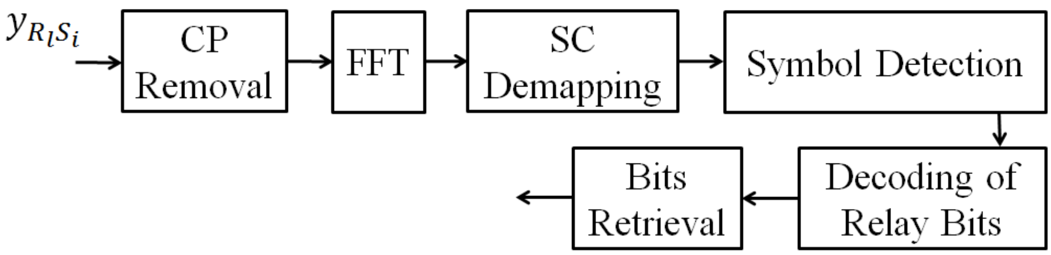

Figure 5.4 : Bit retrieval at sources.

5.2 Detection Rules

This section elaborates the detection rules applied at the relay and source nodes for the retrieval of source and relay bits respectively. The two-way relay network is classified into multiple parallel relay (PR) and RS categories for the purpose of simplicity.

5.2.1 Detection with multiple parallel relays

The network model in this sub-section comprises of any number of relays, as shown in Figure 5.1. The channel states on all the $S_i \to R_l$ and $R_l \to S_i$ links are assumed to remain invariant throughout the transmission of a single phase, so, $h_{S_i R_l}[k]$ and $h_{R_l S_i}[k]$ respectively define $S_i \to R_l$ and $R_l \to S_i$ channel gains over kth SC during the subsequent phases. Taking $x_{S_i}[k]$ as source symbol transmitted by S_i on SC k,

$k = 1, \ldots, K$ and P as the average transmit power of each S_i, on SC k, the received signals at R_l during Phase I on SC k can be modeled as

$$y_{S_iR_l}[k] = \sqrt{P} h_{S_iR_l}[k] x_{S_i}[k] + n_{S_iR_l}[k], \tag{5.1}$$

where $n_{S_iR_l}[k]$ represents zero mean additive Gaussian noise, with variance $\sigma^2_{S_iR_l}$. Quadrature phase shift keying (QPSK) modulation with Gray mapping and frequency selective Rayleigh fading channel of unity power are assumed throughout the simulations so, the components of $h_{S_iR_l}[k]$, $h_{R_lS_i}[k]$ and $x_{S_i}[k]$ are taken accordingly. The detection rule employed follows the same outlook of the multiuser iterative decoder proposed in [11] and gives LLRs for the coded information bits from each S_i. Utilizing both information and XOR coded redundancy bits, the LLRs corresponding to the $S_i \rightarrow R_l$ link on SC k respectively become

$$\begin{aligned} \lambda_{S_iR_l}[k_1] = & \min_{x_{S_i} \in \chi^+} \{ \left| y_{S_iR_l}[k_1] - \sqrt{P} h_{S_iR_l}[k_1] x_{S_i}[k_1] \right|^2 \\ & + \left| y_{S_iR_l}[k_2] - \sqrt{P} h_{S_iR_l}[k_2] v_{S_i}[k_2] \right|^2 \} \\ & - \min_{x_{S_i} \in \chi^-} \{ \left| y_{S_iR_l}[k_1] - \sqrt{P} h_{S_iR_l}[k_1] x_{S_i}[k_1] \right|^2 \\ & + \left| y_{S_iR_l}[k_2] - \sqrt{P} h_{S_iR_l}[k_2] v_{S_i}[k_2] \right|^2 \}, \end{aligned} \tag{5.2}$$

where χ^+ and χ^- are the set of modulated symbols with a coded “0” or “1” bit respectively at S_i and v_{S_i} represents the modulated symbol corresponding to the XOR coded or redundancy bits at S_i [13]. The SCs that carry information bits and XOR coded bits for redundancy are respectively represented by k_1 and k_2. These LLRs, providing soft decisions on coded bits, are then decoded by soft Viterbi algorithm to recover source bits since the detection rule follows the same logic as SOVA. SOVA also takes log-likelihoods of the ML path and the best path with the complementary symbol as inputs, at the given instant and returns their difference [26]. Later, each R_l follows the series of steps discussed in Section 5.1 to generate relay signal, which is broadcasted to both the sources. The signal transmitted on the $R_l \rightarrow S_i$ link during Phase II becomes

$$y_{R_lS_i}[k] = \sqrt{P} h_{R_lS_i}[k] x_{R_l}[k] + n_{R_lS_i}[k], \tag{5.3}$$

where $x_{R_l}[k]$ is the relay symbol with QPSK modulation and $n_{R_l S_i}[k]$ is the zero mean additive Gaussian noise, with variance $\sigma^2_{R_l S_i}$. Finally, after transmission of symbols on $R_l \rightarrow S_i$ link, the detection rule to yield LLRs at S_i can be obtained as

$$\lambda_{R_l S_i}[k_1] = \min_{x_{R_l} \in \chi^+} \{ \left| y_{R_l S_i}[k_1] - \sqrt{P} h_{R_l S_i}[k_1] x_{R_l}[k_1] \right|^2 + \left| y_{R_l S_i}[k_2] - \sqrt{P} h_{R_l S_i}[k_2] v_{R_l}[k_2] \right|^2 \} - \min_{x_{R_l} \in \chi^-} \{ \left| y_{R_l S_i}[k_1] - \sqrt{P} h_{R_l S_i}[k_1] x_{R_l}[k_1] \right|^2 + \left| y_{R_l S_i}[k_2] - \sqrt{P} h_{R_l S_i}[k_2] v_{R_l}[k_2] \right|^2 \}, \quad (5.4)$$

where v_{R_l} is the modulated symbol corresponding to the XOR coded or redundancy bits at R_l. As each S_i receives broadcast signals from all relay nodes and finds LLRs for the coded information bits sent by relays, it adds them as

$$\lambda_{S_i}[k] = \lambda_{R_1 S_i}[k] + \cdots + \lambda_{R_M S_i}[k]. \quad (5.5)$$

It should be noted that this rule is only applicable when R_l also uses redundancy packet otherwise the detection is performed in the typical manner. The given sum of the LLRs is then decoded by soft Viterbi algorithm to obtain relay bits, which are added with the source bits in Galois field to recover the other source bits.

5.2.2 Detection with relay selection

In detection with RS, each S_i is assumed to know all channel states between itself and all relay nodes in the network and selects the best relay node as $R_{l*}[k] = \underset{l=1,\ldots,M}{argmax} \left| h_{R_l S_i}[k] \right|$ for relaying phase, where $l*$ is the index of the selected relay.

This not only reduces the number of TS in Phase II but also improves the performance as will be seen in the next section. The rest of the procedure for decoding and retrieval of exchanged bits is similar to the steps mentioned in subsection 5.2.1.

The transmission involves bit-wise XOR addition of multiple information packets at the sources and/or relays to generate XOR coded packet for redundancy at the transmission level which may lead to higher complexity. But the detection to find

LLRs for coded source bits at the reception is performed using an information and a redundancy symbol at each relay independently. So, the complexity remains same for any number of relay nodes but increases with the order of modulation. The system complexity can be reduced by omitting the transmission redundancy during the relaying phase but it leads to poorer error performance.

5.4 Simulation Results

This section presents various simulation results using Monte Carlo simulations for the above mentioned two-way relay network model with different redundancy schemes. A 4-state and rate-1/2 convolutional code is used for channel encoding and an FFT size of 64 is considered. CP length is one-fourth times of the total FFT size and CP range is always higher than the number of channel taps. SNR is defined as the ratio of bit energy to noise and BER versus SNR realizations are explained in different perspectives.

Figure 5.5 summarizes results for different redundancy protocols employed at both sources and a single relay node. Here $(L+1, L)$ format is used to illustrate information packets with redundancy, where L is the number of information packets. (4, 3) and (3, 2) represent $L=3$ and $L=2$ information packets respectively and the extra packet is used for providing redundancy using XOR coding of information packets. From results shown in Figure 5.5, it can be observed that the error performance can be enhanced by around 3 dB, at a BER of 10^{-2}, by using XOR coded redundancy packet just at the source nodes, during Phase I transmission. However, the inclusion of redundancy at sources as well as relays results in a significant performance gain at higher SNR value. (3, 2) scheme has lower information transfer rate than (4, 3) scheme since the redundancy packet is delivered for just two information packets but appears to give slightly better error performance than (4, 3) scheme in both scenarios. (4, 3) scheme maps three information packets to a single redundancy packet which causes loss in the coding gain as compared to (3, 2) scheme.

Figure 5.6 depicts the performance study when different number of relays is considered in the two-way relay network. (3,2) redundancy scheme is used for this investigation. It can be seen that the increase in the number of relay nodes results in diversity gain but increasing M results in the loss of throughput in PR as each relay broadcasts its packets in different TS, during Phase II. At a BER of around 10^{-3} and $M = 2$, the performance gain is improved by 1 dB when redundancy is provided at both sources and relays, in comparison to the redundancy at sources only. RS not only enhances this performance gain to 1.5 dB but also increases the network throughout because a single relay is chosen to carry information during Phase II. This enhancement in performance with an increase in the number of relays is more obvious at higher SNR values in both cases that is redundancy provided at sources only as well as redundancy provided at sources and relays.

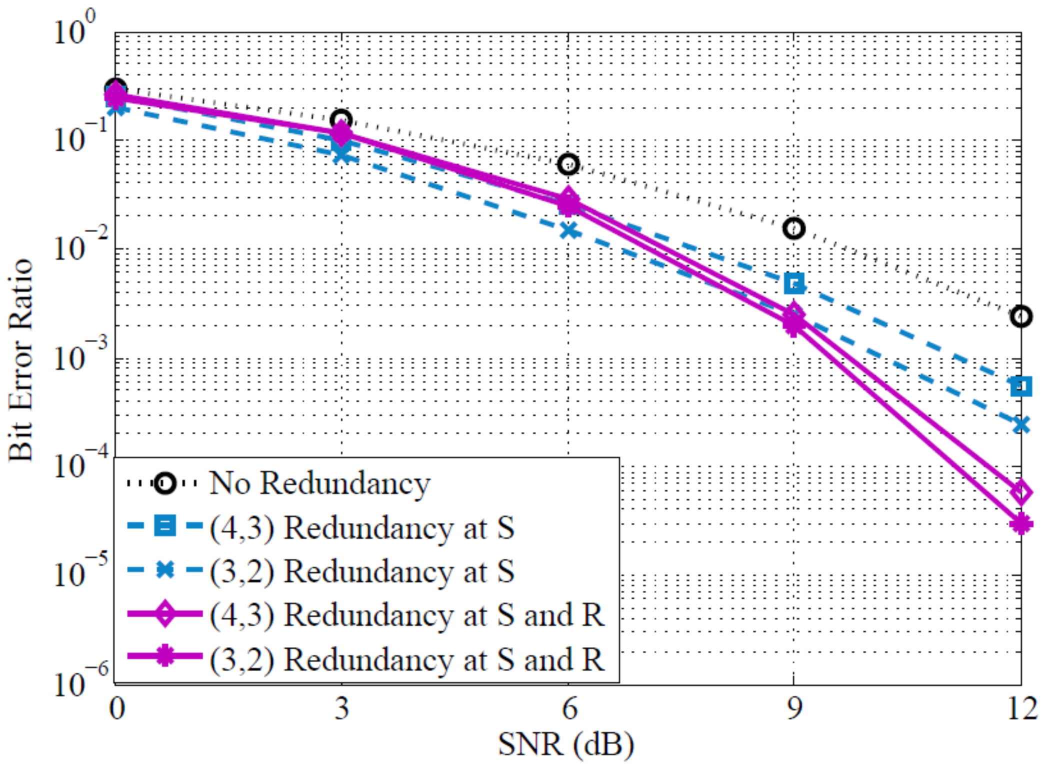

Figure 5.5 : BER versus SNR curves, $N = 2$, $M = 1$, (4, 3) and (3, 2) redundancy schemes, QPSK modulation with Gray mapping.

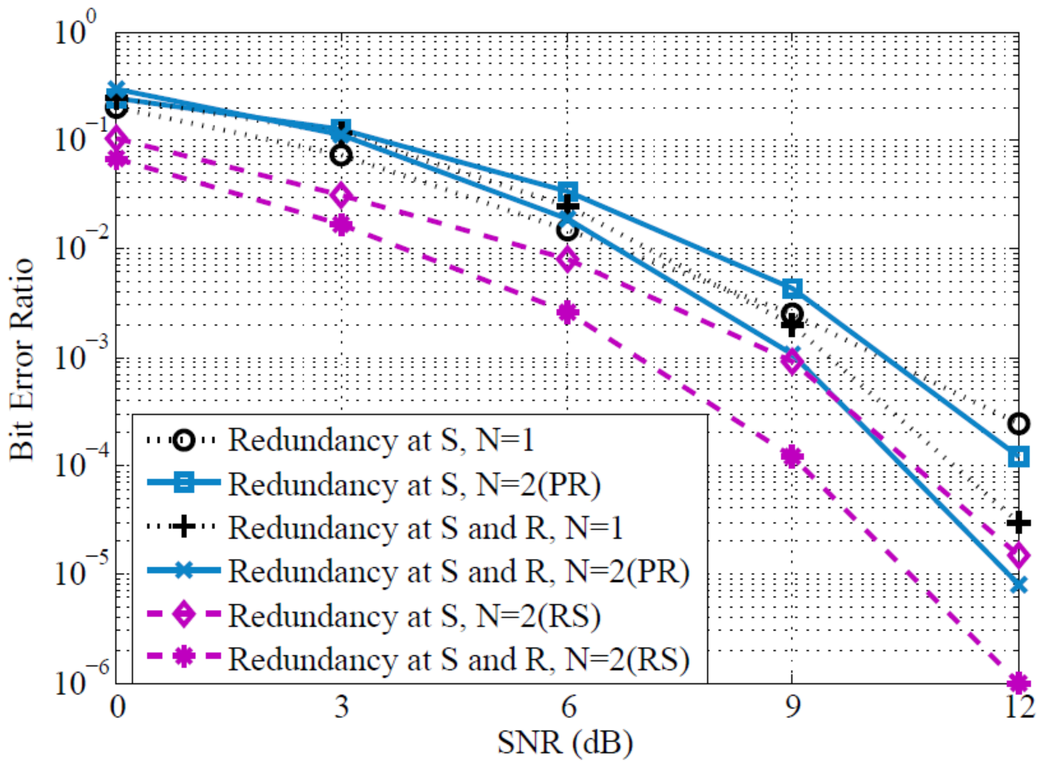

Figure 5.6 : BER versus SNR curves, $N = 2$, $M = 1,2$, multiple PR and RS for the (3, 2) redundancy scheme, QPSK modulation with Gray mapping.

5.5 Comparison of CFNC and Enhanced XOR coded Schemes

CFNC has higher throughput and provides slightly better performance than enhanced XOR network coded scheme for the same parameters but its system complexity at reception increases exponentially with an increase in the number of source and rely nodes. Enhanced XOR network coding scheme, on the other hand, requires separate time slots for each node to send its signal in comparison to CFNC. But enhanced XOR network coding scheme is better than CFNC in terms of simplicity of detector at the receiving end.

6. CONCLUSION AND RECOMMENDATIONS

This thesis is written to investigate the performance analysis of network coded systems in cooperative relay networks. The first part of thesis considers a scenario where various sources are multicasting their packets to destinations using RLNC at the intermediate relay nodes and the links between sources and relay nodes are subjected to Rayleigh and Rician types of fading. Analyzing the simulation results, it can be concluded that Galois field size, SNR at the destination and number of intermediate relay nodes are the crucial parameters to obtain the desired performance in the communication scenarios having Rayleigh or Rician fading when RLNC is employed to send packets to their destinations. Moreover, a low decoding failure probability can be ensured by allowing appropriate values of field size, number of intermediate nodes, SNR at the receiving end and system rate. However, the impact of the fading channels needs to be taken into account in order to determine the decoding failure probability accurately.

In the second part of thesis, CFNC is studied in combination with OFDM for frequency selective Rayleigh fading channel in different scenarios of distributed networks. CFNC, due to its constellation rotation properties, allows different sources and relays to transfer their information on the same set of subcarriers, which leads to better bandwidth efficiency. CFNC offers its own coding gain with the appropriate design of complex coefficients and higher throughput in distributed network models, and therefore, can be utilized in OFDM systems, to attain desired outcomes. The gain in performance becomes more evident when channel codes with hard decision Viterbi decoding are utilized in both non-regenerative (AAF) and regenerative (DAF) schemes for relaying. The detection rules for CFNC are more complex when used in cooperative relay networks but the overall system throughput is significantly increased.

The third part of thesis integrates channels codes in the system model of the second part and uses soft decision Viterbi decoding to obtain better performance. So, coded CFNC is combined with OFDM for frequency selective Rayleigh fading channel in different scenarios of relay networks with AAF as well as DAF. CFNC offers its own coding gain with the appropriate design of complex coefficients and an observable attainment in performance is possible if convolutional codes are also combined with it and soft decision decoding is employed. Max-Log-MAP decoding is also used in contrast with soft Viterbi decoding and it is shown that both decoding algorithms almost give the similar performance results.

An enhanced XOR network coding scheme is analyzed in the fourth part of thesis for two-way relay networks. OFDM and convolutional channel codes with soft Viterbi decoding are also utilized in the system model. The suggested method involves redundancy at the transmission level at sources and an optional redundancy in the relaying phase. The detection rules are simple. LLR calculation involves an information bit and a redundancy bit for any number of XOR coded information packets but provides considerable improvement in error performance. The performance gain can be significantly improved with the use of RS for multiple relays in the network.

Some of the future recommendations to get better performance with the proposed systems are given below

- The gain in performance for both channel coded CFNC and enhanced XOR network coding schemes can be enhanced even further if more powerful channel codes such as turbo or low density parity check (LDPC) codes are invoked in the system model.
- In this thesis, sub-optimum RS scheme is used in both channel coded CFNC and enhanced XOR network coding techniques since it only depends on relay to destination channel states. The system can also be implemented with optimum RS scheme, utilizing both source to relay and relay to destination channel states for increasing system performance.

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CURRICULUM VITAE

Name Surname : Rida KHAN

Place and Date of Birth : 02.10.1990/Pakistan

E-Mail : rida.khanoct@yahoo.com

EDUCATION:

- **B.Sc. :** 2012, Mehran University of Engineering and Technology, Faculty of Electrical and Electronics Engineering, Department of Telecommunication Engineering.

PROFESSIONAL EXPERIENCE AND REWARDS:

- 06.2011-07.2011 Pakistan Telecommunication Company limited (PTCL), Internee Engineer.
- 06.2012-07.2012 Civil Aviation Authority, Internee Engineer.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Rida Khan, Gunes Karabulut Kurt, Ibrahim Altunbas, 2015. Decoding Failure Probability of Random Network coding Systems in Fading Channels, IEEE SIU conference (May 16-19, 2015), Inonu University, Turkey.
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