ENHANCING THE PERFORMANCE OF WIRELESS NETWORKS WITH PACKET LEVEL FORWARD ERROR CORRECTION

by

Roderick Coolen

Submitted in partial fulfilment of the requirements for the degree of

MASTER OF APPLIED SCIENCE

Major Subject: Electrical and Computer Engineering

at

DALHOUSIE UNIVERSITY
Halifax, Nova Scotia
December, 2006

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-27570-2
Our file Notre référence
ISBN: 978-0-494-27570-2

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Table of Contents

List of Figures

List of Symbols and Abbreviations

1-D	One Dimensional
2-D	Two Dimensional
ACK	Positive Acknowledgement
ARQ	Automatic Repeat Request
BER	Bit Error Rate
CRC	Cyclic Redundancy Check
EM	Electromagnetic
FCS	Frame Check Sequence
FEC	Forward Error Control
HARQ	Hybrid FEC/ARQ
IP	Internet Protocol
NACK	Negative Acknowledgement
PLR	Packet Loss Rate
QoS	Quality of Service
RLC	Radio Link Control
RN	Regenerating Node
R-S	Reed-Solomon
SNR	Signal-to-Noise Ratio
SR-ARQ	Selective Repeat ARQ
TCP	Transport Control Protocol
UDP	User Datagram Protocol

Acknowledgements

I am grateful to my supervisor Dr. Jacek Ilow for helping me along the way with the progression of this thesis. Many hours were spent on discussing the theory contained herein, and through his motivation, and support, I was able to keep my research on track, ultimately leading to this moment.

I would also like to express my appreciation to the Faculty of Graduate Studies at Dalhousie University for providing me with a scholarship during my second year of study, and for the Natural Sciences and Engineering Research Council of Canada (NSERC) from whom I received support from Dr.Ilow's operating grant.

I would like to thank Dr.Larry Hughes and Dr.Srinivas Sampalli for their suggestions and help on my research as the supervisory committee members.

Finally, I would like to thank Qihong, and my parents for their love during the completion of this work.

Abstract

Wireless networks experience high packet loss rates due to low quality links. To create reliable connectivity between the source and the destination so that all packets are guaranteed to be delivered, Automatic Repeat Request (ARQ) is a commonly deployed mechanism. However, the ARQ creates a jitter in the packet arrival times that can cause prohibitive delays in real-time communications. To address this problem, this thesis investigates a modification to the ARQ scheme by introducing hybrid ARQ and packet level Forward Error Correction (FEC). While an ARQ scheme alone is sufficient to guarantee successful data transmission, this thesis shows that a hybrid packet level FEC/ARQ system offers enhanced throughput performance with reduced delay effects.

Two implementations for packet loss recovery using packet level FEC to aid ARQ operation are pursued in this thesis: (i) end-to-end, and (ii) hop-by-hop. End-to-end packet loss recovery uses packet level FEC only at the destination node of a network, and is the focus of existing work in the literature. Hop-by-hop packet loss recovery is facilitated throughout the network with the use of regenerating nodes, where forward error recovery is performed at intermediate nodes and the destination. The regenerating nodes reduce the packet loss rate (PLR) between the source and the intermediate nodes by minimizing the accumulated number of lost packets at the destination. The throughput and delay performance tradeoffs for the hybrid FEC/ARQ system are documented in this thesis. The regenerating node concept was originally envisioned to only use packet level FEC, but this work considers the combination of packet level FEC with different ARQ mechanisms to examine the effect of this combination on throughput and packet delivery delay. Specifically, it is found that when a hybrid packet erasure FEC/ARQ mechanism is incorporated into regenerating node functionality, an improved throughput results in comparison to using FEC alone as implemented in the past.

To take advantage of having multiple links to the destination, two dimensional (2-D) Reed-Solomon product codes are introduced for packet level FEC in conjunction with regenerating nodes. It is shown that when these codes are used in a hybrid FEC/ARQ packet erasure recovery scheme, there are improvements in throughput over a standard one dimensional (1-D) coding scheme. This improvement in throughput comes at the cost of an increase in decoding delay when considering an end-to-end 2-D packet erasure mechanism, and when considering hop-by-hop 2-D decoding functionality, the decoding delay is shown to be prohibitive. It is found in this work that a combination of hop-by-hop 1-D packet erasure recovery functionality combined with an end-to-end 2-D packet erasure recovery mechanism, provides a reasonable trade-off between decoding delay and throughput.

The main contribution of this work is in showing that a combination of hybrid packet erasure FEC/ARQ based on positive acknowledgements with 1-D R-S regenerating node functionality, and 2-D R-S end-to-end packet erasure recovery, offers the best compromise for throughput performance and delay in a multi-hop wireless network.

Chapter 1

Introduction

Multi-hop wireless networks are communication networks, where packets are sent across one or more wireless transmission links in traversing from an information source to a destination. In any network using wireless communication systems, signal degradation across the links due to fading and electromagnetic (EM) interference cause the erroneous reception of bits, which in turn implies received packets to be in error. In order to ensure the correct arrival of information at the destination, network protocols are deployed to handle imperfect network conditions. The protocol transmission of information is organized into layers where different layers traditionally are independent of each other to manage the complexity of the delivery mechanism. In general, the network protocol is divided into five layers, where the physical layer deals with transmission of bits, the data link layer relates to the transmission of frames for medium access and the network layer is concerned with the transmission of packets to ensure the delivery at the destination. The upper network layers are the transport layer, and the application layer.

A cyclic redundancy check (CRC) is often performed at the data link layer of the receiving node to determine which frames have had bits corrupted after being sent across a wireless link. Such frames are typically dropped by the receiving node, causing the corresponding packet at the network layer to be lost. In addition, packets can be lost in the network due to the overflow of buffers in the intermediate nodes. If the channel conditions are poor or the network is congested, the frame/packet dropping mechanism may cause the packet loss rate to become prohibitively high for some networking applications. This problem is cumulative when sending packets across multiple links from the source to the destination. To recover from lost packets, at the transport layer the ARQ mechanism is deployed in the Internet Protocol (IP) stack using Transport Control Protocol (TCP). The drawbacks of the TCP are the jitter and limited control over packet delays and this is the reason why in some applications at the transport layer the User Datagram (UDP) protocol is utilized [Khe2004].

Regardless of which layer the actual information loss recovery mechanism is deployed, this thesis assumes that the unit representing lost group of bits is referred to as a packet. Prohibitively high packet loss rates in multi-hop wireless networks with end-to-end ARQ will decrease throughput, and cause significant increases in the delay when sending a packet reliably across a network. This thesis examines the impact of high packet loss rates on the quality of service (QoS) assurances of throughput, reliability, and delay. This investigation will examine what currently is being done to improve these QoS assurances in multi-hop wireless networks, and then propose methods for improvement. In particular, modified hybrid packet level FEC/ARQ packet recovery mechanisms, as well as two dimensional packet erasure recovery using Reed-Solomon erasure codes will be examined in terms of improving the performance of multi-hop networks.

Section 1.1 discusses the QoS assurances of interest in this thesis for multi-hop wireless networks. Section 1.2 discusses the thesis objectives, and Section 1.3 provides the thesis organization.

1.1 Quality of Service Assurances in Multi-hop Wireless Networks

There are many QoS assurances that are discussed in conjunction with multi-hop wireless networks. However, this thesis is focused on the impact of high packet loss rates on reliability, throughput and packet arrival delay.

Section 1.1.1 discusses reliability as a general concept, and the packet loss recovery mechanisms used to ensure reliability. Section 1.1.2 discusses the delay in a network when sending a packet from a source to a destination, and Section 1.1.3 discusses throughput as a QoS assurance.

1.1.1 Reliability

Reliability is the level of delivery guarantee when sending data from a network source to a destination. In a best effort network, not all data is guaranteed to be delivered to the destination, but there is a limited control over the degree of data loss experienced, e.g., by using more reliable links or facilitating better congestion control in the network. In a reliable network, there is a possibility of packets being lost in the “raw” channel, however all lost packets are recovered using packet loss recovery mechanisms such as conventional ARQ or as in the recently proposed hybrid packet level FEC and ARQ [Kos2002].

When packet level FEC is deployed alone to recover from lost packets, the PLR is reduced over the raw channel PLR. In this method, there is no guarantee that all packets will successfully arrive at the destination, and we refer to such a packet loss recovery mechanism as better than best effort. A lost packet in this thesis from the raw channel is referred to alternatively as an erasure, since in some cases we will use erasure recovery codes to reconstruct the lost packets from the lower protocol layers, i.e., raw channel.

Advanced networks with hybrid FEC/ARQ (HARQ) mechanisms can have either a conventional implementation with retransmission until all lost packets are recovered or better than best effort implementation using ARQ with finite number of retransmissions that does not guarantee recovery of all lost packets. The latter case is exemplified in the radio link control (RLC) layer of cellular systems [Leo2000]. These erasure recovery mechanisms will be elaborated further in Chapter 2.

1.1.2 Delay

Delay is characterized by the average amount of time it takes for a packet to be sent from the network source to the destination. This delay is dependant upon the following four factors [Rap1996]:

1. The propagation delay in sending a packet across a link.
2. The transmission time in sending a packet across a link.
3. The queuing delay at the intermediate nodes and at the destination.
4. The processing delay at the intermediate nodes and at the destination.

The propagation delay, P, is given by:

$$P = \frac{d}{c} \tag{1}$$

where:

d = distance between the source node and the destination (or intermediate node) (Units: meters)

c = speed of light = $3(10^8)$ meters/second

The transmission time, T_x, in sending a packet across a single link is given by:

$$T_x = \left(\frac{PL}{R}\right) \tag{2}$$

where:

PL = packet length (bits)

R = channel rate (bits/s)

It is assumed in this work that the channel rate is constant, and the packet length of the packets being transmitted is fixed. Hence, the transmission time in sending a packet across a single link is assumed to be constant. The queuing delay and processing delay at the intermediate nodes and at the destination is not taken into consideration in the analysis of this work.

Therefore, for this analysis, the average delay, $D_{1\text{-PKT}}$, in sending one packet across a single link is given by [Leo2000]:

$$D_{1\text{-PKT}} = \left(\frac{PL}{R} + \frac{d}{c}\right) \tag{3}$$

A more detailed derivation for the delay experienced in multi-hop wireless networks is provided in Chapter 3.

Packet delivery mechanisms across wireless networks with different delay characteristics typically are of two distinct types:

1. *Packet delivery that can not tolerate packet loss, but can tolerate an unbounded delay:*

This type of delivery is typical for a reliable network, where there is a loss-free delivery guarantee, and all data will eventually arrive at the destination correctly. This type of packet delivery always involves some form of ARQ mechanism, where packets that are lost can be retransmitted until they arrive at the destination successfully. Such retransmission schemes require there to be a path of retransmission available. Also, if the channel conditions are poor yielding a high packet loss rate, the average number of packets that need to be retransmitted will be greater. As a result, the average delay in getting a data packet successfully to the destination increases. In such schemes, the packet delivery delay is unbounded, as the number of retransmissions required to successfully transmit a packet across a communication link could in the worst case scenario approach infinity.

2. *Packet delivery that can tolerate a maximum delay and a flexible packet loss rate:*

This type of delivery is typical for a better than best effort network, where data is not guaranteed to be delivered correctly, but there is control over the degree of data loss experienced. An example of this type of packet delivery is for the transmission of multimedia data, such as audio and video streams. Such multimedia networks require a guaranteed maximum end-to-end delay, which is typically the response time of a human being, or about 150ms [Che2004]. For this type of packet delivery, a FEC alone erasure recovery approach is often employed. However, if channel conditions are good, a path of retransmission is stable, and round trip time is significantly small, then an ARQ based approach may be beneficial. This analysis will be looked at in more detail in Chapter 2.

1.1.3 Throughput

Throughput represents the percentage of channel bandwidth that is used for sending useful data between the network source and the network destination. [Gar1996] Typically, there is a trade-off between throughput and delay, where achieving a higher overall throughput comes at the cost of an increased delay. A more detailed consideration of throughput in multi-hop wireless networks is given in Chapter 3. The throughput definition used in this work is on a per packet performance basis. Other definitions of throughput may be related to the number of information bits actually delivered to the destination. However, here this definition of throughput is related to the number of information packets actually delivered to the destination. As a result, the coding rates of the error detecting code, as well as other overhead bits are not taken into account in this definition of throughput.

1.2 Thesis Objectives

This thesis is concerned with protocol design for wireless networks suffering from high packet loss rates. Specifically, packet loss recovery mechanisms building on packet erasure reconstructions with hybrid packet level FEC and ARQ are investigated with the objective of improving the performance of the proposed systems.

Packet level FEC is used in conjunction with ARQ in this work, instead of the more conventional bit level FEC. Conventional bit level FEC when used with ARQ has been examined in the literature in great detail, and such a mechanism improves the probability of a packet being correct at the destination by combating individual packet bits in error. However, the raw packet loss rate (PLR) is a result of two effects: (i) bits in error, and (ii) packets lost due to overflow of buffers in the intermediate nodes in multi-hop networks. Bit Level FEC can not do anything about the latter problem. In contrast, packet level FEC addresses both issues by reducing the packet loss due to the bits in error, and it can recover the lost packets due to buffer overflow, by dealing with packet erasures independently of what is the origin of the problem.

Hybrid packet level FEC/ARQ has been considered recently in the literature as a packet erasure recovery technique, as in [Kos2002] and [Maj2002]. However, in the implementations of hybrid packet level FEC/ARQ examined in the literature the focus of the work primarily is on end-to-end packet erasure recovery, and where the units used for the FEC and ARQ mechanisms are of the same size. In this work, consideration of different size transmission units for the FEC mechanism and the ARQ mechanism in hybrid packet level FEC/ARQ will be examined, as well as intermediate node packet erasure recovery using hybrid packet level FEC/ARQ.

Packet erasures differ from packet errors, in that packet erasures represent packets that have been completely dropped by the network. Packet errors represent packets that have individual bits in error. In general, when considering the performance of wireless links, first erroneous frames are being corrected using bit level FEC, and then the frame check sequence (FCS) in the data link layer performs frame error detection ensuring that the data passed to the next layer are free of bits in error. Considering that the data unit for processing in the proposed algorithm is a packet if a packet is found to have bits in error at the lower layer when it arrives at the destination, then it is dropped by the lower layer resulting in a packet erasure. Packet erasures can also occur when packets are dropped due to buffer overflow caused by excessive queuing delays [Lin2004]. The packets that arrive at the layer of the proposed scheme are therefore error free. Under this assumption, the sub layer in which the proposed mechanisms operate will be above the FCS. Using the terminology of the proposed packet loss recovery layer, we are not limiting the application of the developed schemes to any particular network layer in the IP stack. The packet erasure recovery mechanisms examined in this thesis do not depend explicitly on the packet size or the BER in the channel but only on the general concept of the raw PLR. It is foreseen that the immediate application of the proposed schemes could be done at the network layer as the assumptions of packet received correctly or lost completely is met there and the easy implementation using Berkeley Socket Programming or WinSocket could be pursued using UDP packets. This explains why in this thesis we adopted the name of packet for the underlying data processing unit.

The overall objective of a packet erasure recovery mechanism is to allow a specified reliability QoS criterion to be met, that otherwise may not be guaranteed without an erasure recovery mechanism in place [Wic1995]. Intuitively, it appears that by allowing for the recovery of packet erasures, more information packets overall would be received at the destination, and henceforth throughput would be increased. However, in order to allow for packet erasure recovery, additional bandwidth is required to accommodate: (i) redundancy packets, (ii) retransmitted packets, or (iii) both in (i) packet level FEC, (ii) ARQ and (iii) HARQ schemes, respectively.

This additional bandwidth may be used inefficiently if channel conditions are good, leading to unnecessary throughput reduction. Typically, as channel conditions degrade, and the packet loss rate of the channel increases, additional bandwidth is required for erasure packet recovery to meet a specified QoS reliability criterion. For reliable networks, there is a data delivery guarantee, and either an ARQ alone or a hybrid ARQ/packet level FEC erasure recovery mechanism can be deployed. In such networks, throughput represents how effective the erasure recovery mechanism is in allowing for a guaranteed reliability. For reliable multi-hop wireless networks, the main objective is to improve throughput, while still allowing for a data delivery guarantee [McA1990]. On the other hand, it is also important to consider the effects of the erasure recovery mechanism on the average packet delivery delay. If data is time sensitive, the erasure recovery mechanism should be selected to try to minimize the average packet delivery delay as much as possible.

For better than best effort networks, data is not guaranteed to be delivered necessarily without missing packets, and either an FEC alone or a hybrid ARQ/packet level FEC erasure recovery mechanism can be deployed. In such networks there is no data delivery guarantee, and the throughput represents how effective the erasure recovery mechanism is using channel bandwidth to send data to the destination node. Typically for these networks, there is a trade-off between throughput and delay, where achieving a higher overall throughput comes at the cost of an increased delay.

To summarize, in both reliable networks and better than best effort networks, the two main objectives of the packet erasure recovery mechanism are to improve throughput, and decrease packet delivery delay. Additionally, in reliable networks, the packet erasure recovery mechanism must also allow for a no loss data delivery guarantee while in the better than best effort network there is a flexibility of working with acceptable PLR after packet loss recovery.

Much work has been done in the literature concerning single hop wireless networks, but the focus of this thesis is on packet erasure recovery mechanisms for multi-hop wireless networks. Different mechanisms are examined in this thesis to try to optimize the throughput, and end-to-end packet delivery delay for both reliable and better than best effort multi-hop wireless networks. These goals are worthy as an improved throughput equates to reduced network bandwidth demand, and a decreased end-to-end packet delivery delay allows for better performance in time sensitive network applications, especially if one considers that in time sensitive application packets arriving too late are considered lost.

Considering new trends in networking where there are multiple paths from the source to the destination, this thesis is also examining the packet loss recovery mechanism tailored to improve the performance in networks with such topologies. Particularly, the application of 2-D packet level R-S (R-S) codes is customized to accommodate load balancing, and to reduce delay when developing packet loss recovery schemes. This is explained in detail in Chapter 4.

1.3 Thesis Organization

This thesis is organized as follows:

Chapter 2 discusses the background and problem formulation. Chapter 3 discusses hybrid packet level FEC and ARQ in multi-hop networks. Chapter 4 discusses two dimensional R-S product codes in multi-hop wireless networks. Finally, Chapter 5 presents the conclusions and future work.

Chapter 2

Background and Problem Formulation

This chapter provides background information for the types of packet erasure recovery mechanisms that currently exist for multi-hop wireless networks. The problems that exist in these packet recovery techniques are presented, and solutions to these problems are investigated.

Section 2.1 discusses the layer of the IP stack where packet loss/erasure recovery is typically performed, and further examines a proposed modification to this stack in an attempt to improve throughput. Section 2.2 analyzes throughput for conventional ARQ, ARQ with a finite number of retransmissions, and packet level FEC. The discussion initially focuses on single hop wireless networks, and then the results are expanded to cover multi-hop links. This leads in Section 2.3 to the development of the regenerating node concept that initially was proposed to improve the efficiency of packet loss recovery in multi-hop networks with packet level FEC. This section closes by discussing the problems that exist with such a technique, and presents some solutions to these problems. Finally, Section 2.4 provides a summary for this chapter.

2.1 Layers for Recovery from Lost Packets

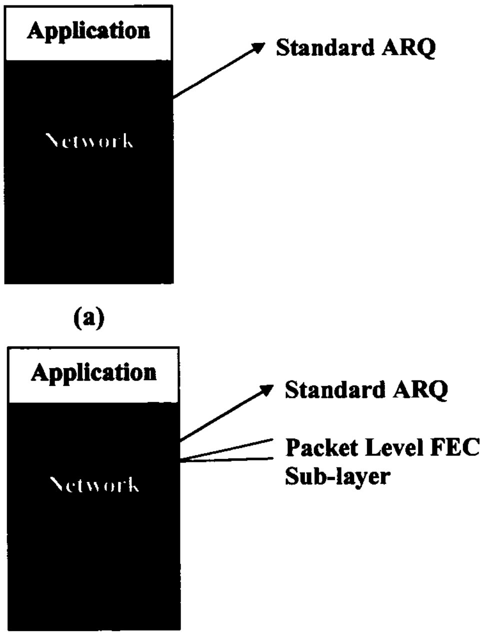
This section discusses the network layer of the IP stack where packet erasure recovery is typically performed, i.e. TCP, and further examines a proposed layering modification to this stack in an attempt to improve throughput.

2.1.1 Conventional IP Stack

Figure 2.1(a) shows the conventional IP stack where the packet loss recovery is performed in TCP using one of the standard ARQ techniques [Leo2000]. Figure 2.1(b) shows the co-location of the standard ARQ and the packet level FEC sub-layer for the packet loss recovery as investigated further on in this thesis.

For ARQ mechanisms, packet erasure recovery is normally implemented at the transport layer in the network protocol stack. For packet level FEC mechanisms to aid the operation of ARQ, packet erasure recovery could be performed in a sub-layer to the transport layer if the modification was permitted as it runs on top of the IP layer. The conventional ARQ and the recently introduced packet level FEC techniques are implemented in an end-to-end fashion, so the use of the transport layer for erasure recovery is practical in this situation.

In the techniques shown in Fig.2.1, only packet erasures are seen at the transport layer, as the FCS in the data link layer will drop packets that have individual packet bits in error as was previously discussed. Based on the sequence numbers of the packets, the location of packet erasures can be determined. The location of the packet erasures is useful for the ARQ packet recovery mechanism to determine which packet needs to be retransmitted from the source.



(a)

(b)

Figure 2.1 – Conventional IP Stack with Two Mechanisms for Packet Loss Recovery.

2.1.2 Positioning of the FEC/ARQ at Lower Layers

Figure 2.2 shows a modified IP stack, indicating the location of the new configuration for layers implementing packet erasure recovery with better than best effort service using hybrid packet level FEC/ARQ with a finite number of retransmissions. In this proposed layering, an ARQ mechanism with a finite number of transmissions is implemented between the data link and network layers of the IP stack. As discussed earlier, packet bit errors can be dealt with by the data link layer, so implementing an ARQ mechanism just after the data link layer still allows this mechanism to only be concerned with packet erasures. This positioning of the hybrid packet level FEC/ARQ is more in line with radio link control sub-layer where one talks about the transmission of frames. However, following the convention adopted in this thesis, we will still refer to this kind of a transmission unit as a packet. This is done so that one framework would encompass different positioning of the packet loss recovery mechanism and one common analysis would apply in all cases. The actual performance analysis of this proposed layering scheme is given in Chapter 3.

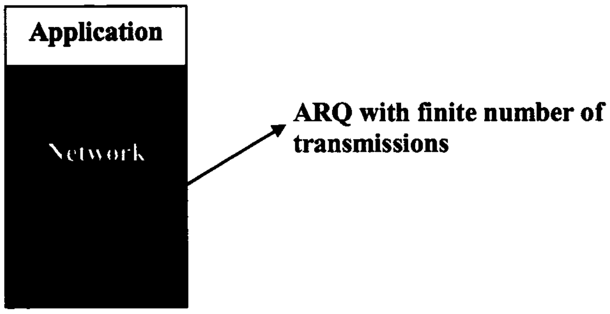


Figure 2.2: Modified IP Stack.

2.2 Performance Analysis

In this section, the throughput analysis for conventional ARQ, ARQ with a finite number of retransmissions, and packet level FEC is presented. This discussion only involves the case of a single link from the source to the destination. The throughput analysis for multi-hop networks is discussed in the next section.

2.2.1 Conventional ARQ

This section provides an overview of ARQ protocols required in all reliable networks. Conventional ARQ has three main types: Go Back N, Selective Repeat, and Stop and Wait. As Go Back N ARQ and Selective Repeat ARQ are typically used for packet erasure recovery mechanisms, they will be the two types that are analyzed throughout this thesis.

In all conventional ARQ mechanisms, some form of packet retransmission of lost packets is performed. Through retransmissions, ARQ achieves 100% packet loss recovery, but retransmissions can lead to unpredictable delays [Mor2002].

In the case that a transmitted packet has been dropped en route from the source to the destination, the destination will not be able to acknowledge the dropped packet. To address this scenario, a timer is established at the source for implementing a time-out mechanism. This time-out is a pre-determined time interval after which a transmitted packet is considered lost if an acknowledgement for it is not received at the destination. A transmitted packet which has timed out will trigger the retransmission process for that packet. It is assumed that for both of the Selective Repeat ARQ and Go Back N ARQ mechanisms described herein, that a time-out mechanism is incorporated [Gib2002].

The throughput expressions derived for Selective Repeat ARQ, and Go Back N ARQ in Section 2.2.1 are under the following assumptions:

1. It is assumed the positive and negative acknowledgements associated with these mechanisms are not lost during transmission in the feedback channel, and are received at the source correctly.

2. A feedback channel is always available for transmission of positive and negative acknowledgements.

3. There is no throughput reduction for the positive and negative acknowledgements.

4. All packets with individual bits in error are detected and dropped by the underlying link layer mechanism, and no packets are received with undetectable error patterns.

5. Protocol overhead is considered negligible, and is not considered in this formula.

These assumptions are made to allow the reasonable derivation of analytical expressions for the more complex mechanisms involving ARQ described in Chapter 3. These assumptions are used for all work shown in this thesis. Simulations can be used to verify the derived analytical expressions. These ARQ alone packet recovery mechanisms are expanded in Chapter 3 to describe their interaction with packet level forward error correction based upon Reed-Solomon codes.

2.2.1.1 Selective Repeat ARQ

This section examines the Selective Repeat ARQ retransmission mechanism in detail. A timing diagram for Selective Repeat ARQ is shown in Fig. 2.3. In this timing diagram, the source first sends a packet with sequence number 1 (packet 1) to the destination. Upon successfully receiving packet 1, the destination sends a positive acknowledgement (ACK1) back to the source to indicate to the source that packet 1 had arrived at the destination successfully. This process will continue until a packet is not received at the destination error-free. At this time, a negative acknowledgement (NACK) is sent back to the source, indicating the sequence number of which packet needs to be retransmitted. For the example given in Fig.2.3, packet 3 was received in error, and a negative acknowledgement NAK3 is sent back to the source. When NAK3 is received at the source, packet 3 is retransmitted. In the Selective Repeat ARQ mechanism, once a packet is not received correctly at the destination, all succeeding packets that arrive at the destination are buffered until the erroneous packet is received correctly. Once the erroneous packet is received correctly, the buffered packets are re-sequenced in order and processed at the destination. The disadvantage of such a mechanism is that it requires an infinite buffer at the destination. This process of re-transmission continues until the packet successfully arrives at the destination. For the example of Fig.2.3, during the time between packet 3 was found to be in error at the destination, until the time packet 3 was successfully retransmitted, packets 4, 5 and 6 arrived at the destination. These packets were buffered, and upon the correct reception of packet 3, these packets were re-sequenced in the right order and processed. It should be noted that if packet 3 had been dropped en route from the source to the destination instead of being in error as in Fig.2.3, the process would be the same except now the time out mechanism at the source would indicate packet 3 was not successfully received at the destination, and needs to be retransmitted [Lin1984].

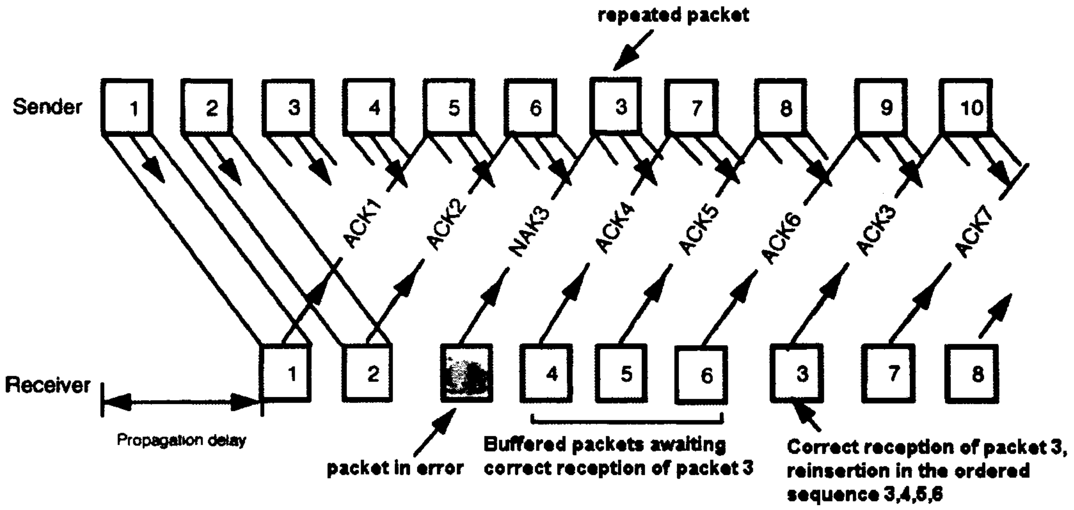


Figure 2.3: Selective Repeat ARQ Timing Diagram. [Gib2002]

Selective repeat ARQ with an unlimited number of retransmissions for lost packets will achieve a loss-free delivery guarantee; however a disadvantage of this is that theoretically an infinite buffer will be required at the receiver.

The throughput of Selective Repeat ARQ with an unlimited number of retransmissions, η_{SR-ARQ}, is given as [Leo2000]:

$$\eta_{SR-ARQ} = 1 - p \tag{4}$$

where:

p = raw channel packet loss rate

2.2.1.2 Go Back N ARQ

This section examines the Go Back N ARQ retransmission mechanism in detail. In Go Back N ARQ, packets are constantly being transmitted in a sequential fashion, so as to keep the channel busy [Yao1995].

In the Go Back N ARQ scheme, the source continuously transmits packets in order, and then stores them until a positive acknowledgement (ACK) or negative acknowledgement (NACK) is received. Packet sequence numbers are used to associate an acknowledgement to a particular packet. The acknowledgment for a packet arrives after a round trip delay, defined by the time interval between the transmission of a packet and the receipt of an acknowledgement for that packet.

During this round trip delay, N-1 other packets are also sent from the source. Whenever the source receives a NACK with a particular sequence number, x, associated with it, this indicates that packet x was received in error. At this point, the source will stop transmitting new packets, and will retransmit packet x and the N-1 succeeding packets after it. At the destination, packet x is dropped, along with the N-1 succeeding packets after it, regardless if they are in error or not. This process of retransmission will continue until packet x is positively acknowledged by the source, at which time the source will proceed to transmit new packets [Lin1984].

Figure 2.4 shows an example of a Go Back N mechanism, where N = 4. In Fig.2.4, the source begins transmitting packets in order starting with packet 0. Packet 0 is successfully received at the destination, so a positive acknowledgement, ACK0, is sent back to the source. Packets 1, and 2 also are successfully received at the destination, so positive acknowledgements ACK1, and ACK2 are sent back to the source. However, packet 3 was received in error at the destination, and a negative acknowledgement, NAK3 was sent to the source. When the source receives NAK3, it then knows that packet 3 was received in error. At this point, the source stops transmitting new packets, and retransmits packet 3 and the succeeding 3 packets after it. At the destination, the erroneously received packet 3 is dropped, along with the three succeeding packets after it (packets 4,5,6). The retransmitted packet 3 arrives successfully at the destination and a positive acknowledgement, ACK3 is sent to the source. It should be noted that if packet 3 had been dropped en route from the source to the destination instead of being in error as in Fig.2.4, the process would be the same except the time out mechanism at the source would indicate packet 3 was not successfully received at the destination, and needs to be retransmitted.

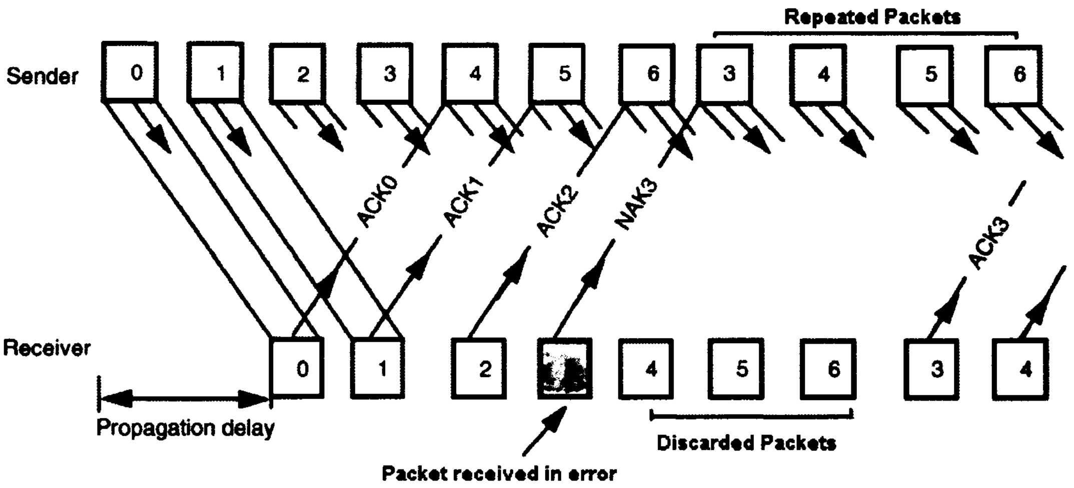


Figure 2.4: Go Back N ARQ Timing Diagram (N=4). [Gib2002]

The throughput of the Go Back N ARQ protocol, η_{GBN}, is given as [Kos2002]:

$$\eta_{GBN} = \frac{N - p\sum_{j=1}^{N} j(1-p)^{N-j}}{N} \tag{5}$$

where:

p = raw channel packet loss rate, and N is specified by the Go Back N protocol

2.2.2 Finite Number of Retransmissions in Selective Repeat ARQ

In order to eliminate the need for an infinite buffer, Selective Repeat ARQ with a finite number of retransmissions for lost packets is examined. The disadvantage of such a mechanism is that packet delivery is not guaranteed, as it is the case when there is no limit on the number of retransmissions.

In this thesis, when finite number of retransmissions ARQ is examined, the number of retransmissions allowed will be three. This is based on the general standard of radio link layer retransmission mechanisms [Leo2000]. The throughput of Selective Repeat ARQ with a maximum of three retransmissions, $\eta_{SR-ARQ,FIN}$, for a lost packet is given as [Skl1988]:

$$\eta_{SR-ARQ,FIN} = \frac{P_c + P_c(1-P_c) + (1-P_c)^2 P_c}{P_c + 2(1-P_c)P_c + 3(1-2P_c + P_c^{\,2})} \tag{6}$$

where in *(6)*:

P_c = probability of a packet being received correctly as passed to the ARQ.

2.2.3 Packet Level FEC

Packet level forward error correction is a packet erasure recovery technique, where redundancy is added by the source in sending packets to a destination. This type of erasure recovery is typically used in better than best effort networks, as it can only help reliability; not guarantee it.

For this type of recovery, the source groups k information packets and $n-k$ redundancy packets into a coded packet block, as shown in Fig 2.5. The parameters k and n are specified by the packet level FEC code that is employed [Rap1996]. This coded packet block is then sent as a group to the destination. Every packet level FEC code has an associated erasure packet recovery capability, t, which specifies how many packets lost in the coded group are guaranteed to be recovered at the destination.

Figure 2.5: Coded Packet Block.

A packet level FEC code is specified by the parameters (n,k,t), where:

n = total number of packets in a coded packet block.

k = number of information packets in a coded packet block.

t = erasure packet recovery capability.

$n-k$ = number of redundancy packets in a coded packet block.

It should be noted that sending redundancy packets requires extra channel bandwidth that otherwise could have been used for sending information packets. In this sense, redundancy packets represent coding overhead, reducing the link throughput by k/n [Non1998].

2.2.3.1 Reed-Solomon Coding

In this thesis, it is assumed that Reed-Solomon (R-S) codes are used for all packet level FEC. The error-correcting ability of a Reed-Solomon code is given by n−k, which represents the redundancy of the coding scheme. Reed-Solomon codes use symbols in their coding mechanism, and the details on symbol construction are given in [Wic1999]. If the locations of the symbols used in the coding are not known, then a Reed-Solomon code can correct up to (n−k)/2 symbols in error. If the locations of the symbols in error are known, these symbols in error are referred to as erasures. Like any linear code, a Reed-Solomon code is able to correct twice as many erasures as errors. Any combination of erasures and errors can be corrected if the condition $2e + s \leq (n-k)$ is satisfied, where e represents the number of errors and s is the number of erasures in the block. It is assumed that in this work, an underlying mechanism in the data link layer will drop any packets that have individual bits in error, so the packet recovery mechanism will only deal with packet erasures. Henceforth, the fundamental inequality that must be satisfied in this work for Reed-Solomon codes is $s \leq (n-k)$, as $e = 0$. In essence, Reed Solomon packet erasure correction schemes allow for the recovery of as many packet erasures as there are redundancy packets [Lee2000].

2.2.3.2 Packet Level FEC Example

A common packet level FEC coding scheme is the even parity FEC. An example for the operation of such a code is shown in Fig 2.6, where Fig.2.6(a) visualizes the encoding process at the source, and Fig 2.6(b) shows the decoding process at the destination when the first information packet is lost. The FEC code parameters are given by ($n = 4$, $k = 3$, $t = 1$). In Fig 2.6(a), three information packets; INFO 1, INFO 2, and INFO 3; are employed to construct the redundancy packet; FEC 1; using binary addition. These four packets constitute the coded packet block constructed by the source. The modulo-2 arithmetic is used bit column-wise on the information packets arranged in rows, where the packets are assumed to be of the same length. If the packets are not the same length, padding with zeroes could be performed. Since the erasure packet recovery capability of the even parity packet code is one, erasure recovery of up to one lost packet is possible. In the example considered in Fig 2.6(b), the information packet INFO 1 is lost in transmission to the destination, which represents raw packet loss. However, using modulo-2 bit column-wise addition of the three received packets, the missing information packet, INFO 1, can be recovered as shown. The fact that the packet is lost, i.e., packet to be reconstruct, is determined by following the received packet sequence number associated with the protocol overhead. It should be observed that if in this packet level FEC two packets were lost in the coded groups, the code could not recover from these lost packets as erasure recovery capability of the code is t=1.

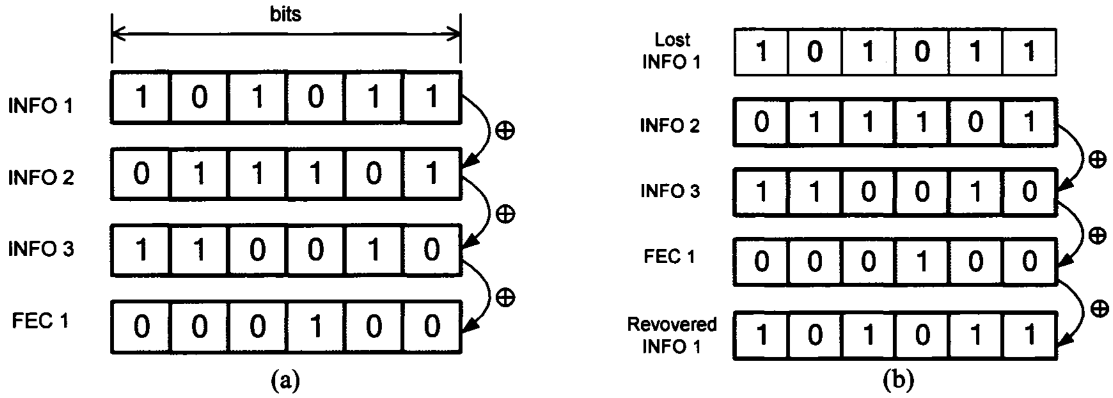


Figure 2.6: Even Parity Packet Level FEC Code.

2.2.3.3 Packet Level FEC in Multi-hop Networks

This section provides an introduction on how packet level FEC can be used in multi-hop wireless networks. Typically, in multi-hop networks, packet level forward error recovery is performed only at the destination node. We assume here that the packet level FEC has parameters (n, k, t). In such networks, the averaged end to end PLR, $PLR_{,corr,}$ after erasure recovery with packet level FEC is given as [Ma2003]:

$$PLR_{,corr} = \frac{1}{n}\sum_{i=t+1}^{n} i\binom{n}{i}PLR_{ee}^{i}(1-PLR_{ee})^{n-i} \qquad (7)$$

where in *(7)*:

M = number of links from the source to the destination

p = raw link PLR as before and,

$PLR_{ee} = 1-(1-p)^M$ = end to end PLR without packet erasure recovery.

The ``n choose k'' $\binom{n}{k} = \frac{n!}{(n-k)!k!}$ binomial coefficient with the $!$ mark standing for factorial represents number of subsets with k elements in the set of n elements and reflects on the different combinations for positions of k lost packets in a coded block of n packets.

The derivation of *(7)* parallels that for the bit error rate after error correction, except that here we deal with packets rather than bits. In the calculations of PLR_{ee}, we assume that the raw PLR, p, is the same on all M links. If this is not the case simple modifications into this formula can be introduced to account for more complex scenarios.

Figure 2.7 shows a 4 hop serial network, where packet loss recovery is performed only at the destination node. In this network, node S is the source node, node D is the destination node, and nodes A, B, and C are forwarding nodes.

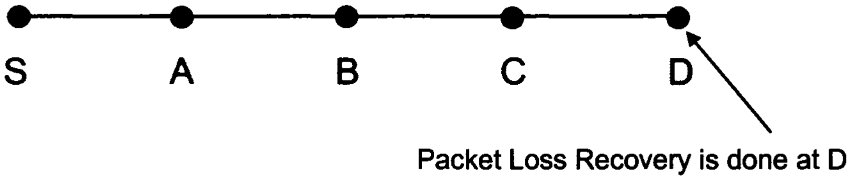


Figure 2.7: Serial Network with Packet Loss Recovery at Destination.

For the network shown in Fig. 2.7, $M = 4$, and $PLR_{ee} = 1-(1-p)^4$. In this example, the packet level FEC code used is ($n = 15$, $k = 13$, $t = 2$). Henceforth, for the network shown in Fig 2.7 is given by:

$$\text{PLR}_{\text{corr}} = \frac{1}{15}\sum_{i=3}^{15} i\binom{15}{i} PLR_{ee}^{\,i}(1-PLR_{ee})^{15-i} \qquad (8)$$

Figure 2.8 shows the end-to-end PLR versus signal to noise ratio (SNR) for before packet erasure recovery, and after erasure recovery with packet level FEC. The green curve represents the former, and the red curve represents the latter. Examination of Fig 2.8 indicates that performing packet erasure recovery at the destination will require a smaller signal-to-noise ratio (SNR) to achieve a specified end-to-end PLR than the uncoded approach.

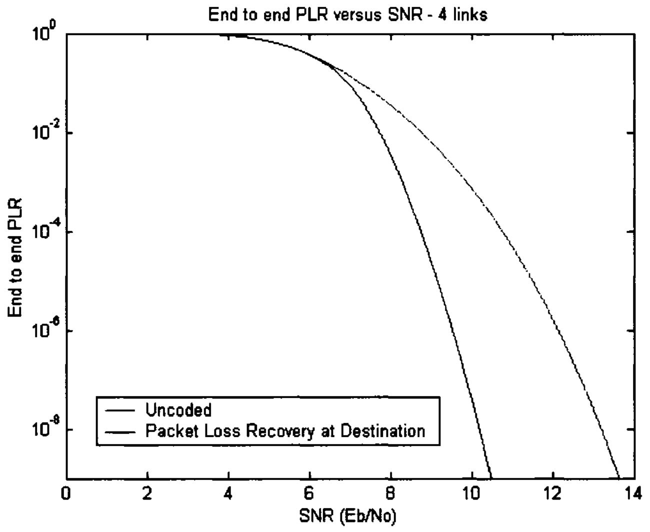


Figure 2.8: End to End PLR in a Serial Network with 5 Hops.

2.3 Regenerating Node Concept

In this section, the use of regenerating nodes (RN) for the purpose of packet loss recovery is reviewed. The regenerating node concept was first introduced in [Ma2003], and involves adding redundant FEC packets at the source node, so that intermediate forward error correction can be performed en route in a multi path network from the source to the destination. The intermediate nodes where this type of packet erasure recovery takes place are called "regenerating nodes". It should be noted that the packet level FEC that takes place also occurs at the destination in order to maximize the beneficial dynamics of the coding scheme [Ma2003].

The functionality of the regenerating nodes is such that they are able to reconstruct lost packets along intermediate links, so that, the end-to-end PLR is theoretically limited to the PLR of the last hop [MaI2004]. The RNs avoid accumulation of lost packets between the source and the destination as they combat the packet loss throughout the whole network. Before the introduction of RN, FEC packet erasure recovery typically has been performed at the destination node only.

In the original proposal, the regenerating node scheme has been developed using exclusively FEC for packet loss recovery [MaI2003]. In this thesis, the packet level FEC is complemented with different implementations of ARQ for improving the PLR performance, and effectively the throughput of the system. Specifically, in Chapter 3, an examination of different configurations of Hybrid FEC/ARQ functionality in the regenerating nodes from the perspective of throughput, delay, and reliability is conducted. It should also be noted that the source routing techniques associated with the regenerating nodes are given in more detail in [Ma2003], and are similar to those presented in [Dra2004].

It is assumed that the topology of the network is quasi-stationary, in that the topology of the network is assumed to be constant for the duration of successfully sending one coded group of n packets from the source to the destination. This assumption of only considering quasi-stationary networks is extended for all of the work of this thesis.

2.3.1 Regenerating Node Example

This section provides an example for the operation of the regenerating nodes in a network as shown in Fig.2.9. This network is composed of four hops connected in series, where node S is the source, node D is the destination, and initially node B is the regenerating node, while nodes A and C are forwarding nodes. In this set up, packet erasure recovery will be performed at node B and at the destination D.

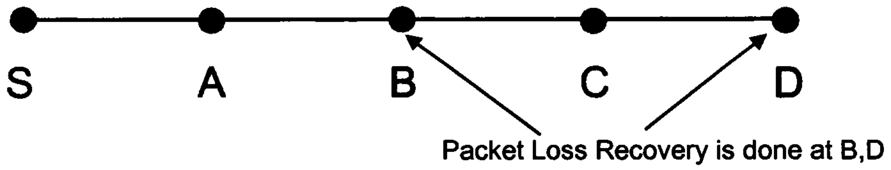


Figure 2.9: Serial Network with Intermediate Regenerating Node.

Figure 2.10 shows the end-to-end PLR performance versus SNR for three scenarios. The green curve represents the performance for the case of no packet erasure recovery being performed (best effort service). The red curve represents packet erasure recovery being performed at the destination only, and the blue curve represents packet erasure recovery being performed at the regenerating node B, and the destination. These results are for an R-S packet level FEC code, as specified by: (n = 15, k = 13, t = 2). Examination of Fig 2.10 indicates that performing packet erasure recovery at the destination and the regenerating node will require a smaller SNR to achieve a specified end-to-end PLR than the other two schemes.

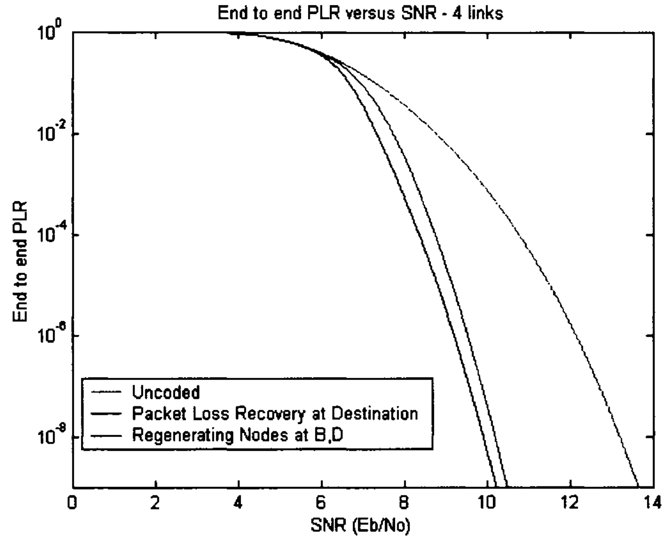


Figure 2.10: End to End PLR in a Serial Network with a Regenerating Node.

2.4 Summary

This chapter provided background information for the types of packet erasure recovery mechanisms that currently exist for multi-hop wireless networks. The next chapter examines modifications to these mechanisms in the form of hybrid packet level FEC and ARQ in multi-hop networks. The modifications in Chapter 3 attempt to improve the throughput, and delay performance criteria of the mechanisms examined in Chapter 2.

Chapter 3

Hybrid Packet Level FEC and ARQ in Multi-hop Networks

This chapter investigates different implementations of hybrid packet level FEC/ARQ in multi-hop, multi-path networks where the redundancy packets from packet level FEC are deployed first to recover from lost packets prior to using retransmissions. Both mechanisms, packet level FEC and ARQ, have their unique advantages and disadvantages from the throughput, delay and reliability point of view. The objective for deploying hybrid schemes is to overcome the limitations of individual packet loss recovery mechanisms without overly compromising the advantages of these mechanisms.

Two scenarios corresponding to single hop and multi-hop networks are considered in Sections 3.1 and 3.2, respectively. Specifically, Section 3.1 examines single hop hybrid packet erasure FEC/ARQ mechanisms using two configurations: reliable delivery in Section 3.1.1 and better than best effort delivery in Section 3.1.2. The results of a throughput and delay analysis are documented. A new scheme to improve throughput for reliable single hop networks by using a sub layer with packet fragments underneath the main ARQ layer is introduced. Section 3.2 first discusses generic hybrid packet erasure FEC/ARQ mechanisms for the case of multi-hop networks and then specializes these mechanisms to networks deploying regenerating nodes. Similarly as in the case of single hop networks, two configurations are considered: reliable delivery in Section 3.2.1 and best effort in Section 3.2.2. The trade-off between throughput and maximum delay in using packet erasure recovery in multi-hop networks is established. This trade-off is further exploited for the best choice of a hybrid packet level FEC/ARQ scheme, depending on the PLR conditions in the network. Finally, Section 3.3 provides a summary for this chapter. The results presented in this chapter are those which were analytically derived, and verified using Monte Carlo simulations.

It should be noted that for all of the simulations completed for Chapter 3, the assumptions made for the ARQ mechanisms as given in Chapter 2 are used. Also, it should be noted in this work that whenever the term "packet loss rate" is referred to, this is the loss rate due to erasures in the network.

3.1 Single Hop Hybrid Packet Level FEC/ARQ Mechanisms

In this section, hybrid packet erasure FEC/ARQ mechanisms are presented for the case where there is a single transmission link between the source and the destination.

3.1.1 Reliable Single Hop Networks

Reliable single hop networks ensure there is no data loss between the source and destination. A data delivery guarantee requires that some form of ARQ be present in order to recover from lost packets; the packet level FEC is just used to reduce the raw PLR from the data link layer. This section examines the performance of the following four packet loss recovery schemes:

1) Selective repeat ARQ
2) Go Back N ARQ
3) Hybrid FEC, selective repeat ARQ
4) Hybrid FEC, Go Back N ARQ

The first two schemes presented here are conventional ARQ schemes, and the other two are hybrid packet erasure FEC/ARQ schemes. Initially, in Section 3.1.1.1 the unit for data transmission in both packet level FEC and ARQ are of the same size, which summarizes some of the existing work in this area [Kos2002]. In Section 3.1.1.2 the units for data transmission in packet level FEC are smaller than the transmission units used in ARQ, which represent new results in this thesis. In both sections the performance is evaluated in terms of throughput.

3.1.1.1 Throughput Analysis of Reliable Single Hop Networks

Figure 3.1 shows the throughput of a reliable single hop network for the four packet loss recovery schemes as described in Section 3.1.1. The calculations for the throughput are performed using the formulas from Chapter 2. The throughput is only plotted for raw channel packet loss rates between 0 and 40%, as raw channel packet loss rates above this value are not realistic for typical wireless networks. The higher packet loss rates definitely do not apply at the network layer, and the results are included when the proposed schemes are applied at the data link layer, where the BER is in the range of 10^{-2} will produce frame loss rate close to 20% for the frame size of 175 bits. Covering a wide range of raw PLRs is in line with the previous work in this area, and allows to capture the trends in the protocol performance behaviour.

Examining Fig.3.1, it can be seen that in the case of the Go Back N ARQ protocol, adding packet level FEC is aiding the operation of the ARQ mechanism. For most values of raw packet loss rate, Hybrid FEC/Go Back N ARQ yields an improved throughput over Go Back N ARQ alone.

For the case of the selective repeat ARQ protocol, adding packet level FEC does not aid in the operation of the ARQ mechanism. In fact, for all values of raw packet loss rate, Hybrid FEC/Selective Repeat ARQ yields a degraded throughput in comparison to selective repeat ARQ alone. It should be noted that these results are obtained where the FEC and ARQ packets are assumed to be the same size.

Examining Fig.3.1, the overall performance rating of the packet recovery schemes are ranked as follows from best to worst in terms of throughput:

1. Selective repeat ARQ alone
2. Hybrid FEC, selective repeat ARQ
3. Hybrid FEC, Go Back N ARQ
4. Go Back N ARQ alone

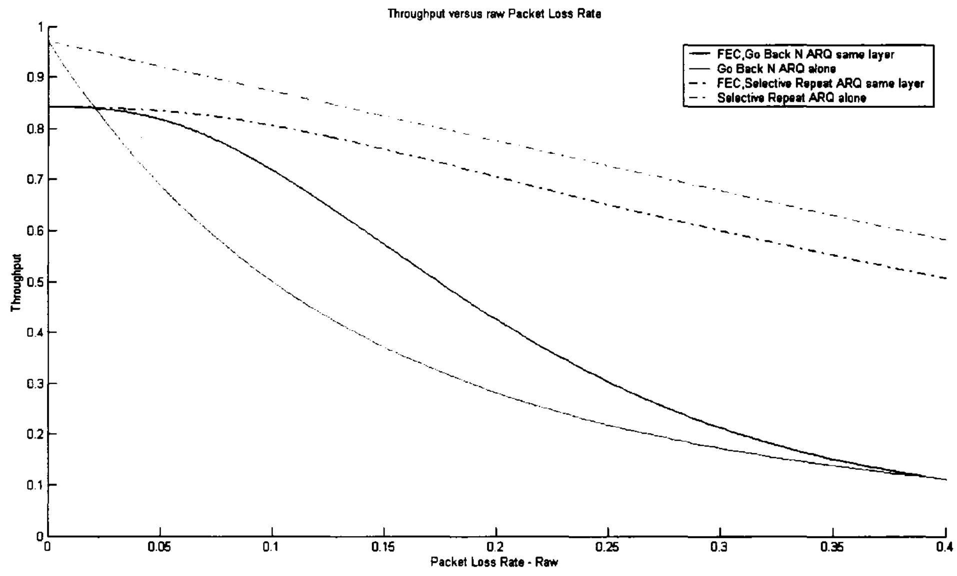


Figure 3.1: Throughput in a Reliable Single Hop Network.

3.1.1.2 Sub-layer Extension of the Packet Erasure Correction Layer

In this section, a proposed scheme to improve throughput performance in reliable single hop networks by introducing a sub layer to the main packet erasure correction layer is examined. In previous research, hybrid packet erasure FEC / ARQ is performed at the same layer in the network protocol stack with the unit for data transmission in both packet level FEC and ARQ being the same size. However, upon first examination, it would appear that introducing a sub layer to isolate the FEC mechanism from the ARQ mechanism would allow for throughput improvements.

It is proposed in this section to have the units for data transmission in packet level FEC to be of smaller size than in ARQ, with multiple units from packet level FEC building the units for retransmission in the ARQ. Four cases for a sub layer extension to the packet erasure correction layer are examined. In all cases, the reliable ARQ unit size is set to 1000B, while the sub-layer unit size is set to 50B. In the first two cases the sub-layer erasure recovery is based on packet level FEC, while in the remaining two cases the sub-layer erasure recovery is based on ARQ with a limited number of three retransmissions. For the reliable ARQ at the higher layer two implementations are considered: Selective Repeat and Go Back N with N=15. The actual size for the FEC unit and the ARQ unit are not influencing the results presented and it is the relative number of FEC packets contributing to the ARQ packet that actually affects the result. This is because all of the performance curves are given in terms of the raw PLR in the channel, and it is this parameter that depends on the packet length.

Case 1:

Figure 3.2 visualizes the location for the proposed sub-layer underneath the network layer in the IP protocol stack where the blue ARQ transmission unit (packet) is of larger size than the transmission unit (packet) associated with the sub-layer. The terminology used to refer to transmission units as packets for both packet loss recovery mechanisms is context sensitive. It has been decided to follow this terminology to be consistent with well established results in the literature on packet erasure recovery [Kos2002]. In the case considered here, an FEC network sub layer is used, with Go Back N ARQ being performed at the network layer. Packets of size 50B are used as the sub layer packet size, while packets of size 1000B are used as the basic network layer packet size. In this scheme, the source will group 20 50B information packets together in a coded block with three redundancy 50B packets. This corresponds to a (23,20,3) R-S packet erasure recovery scheme. This group of 23 packets is then sent across the channel to the destination. As this group of packets arrives at the network layer of the destination, the FEC sub layer mechanism is initiated. If 20 or more packets arrive correctly at the sub-network layer, then the FEC coding scheme can recover those erased packets. If less than 20 packets arrive correctly at the sub-network layer of the destination, the number of erasures is greater than what can be corrected for with the FEC erasure correction code. It is in the case that the FEC erasure correction capability is exceeded, that the Go Back N ARQ mechanism is initiated. Therefore, less dependence is put on Go Back N ARQ, as it is only initiated as a last resort.

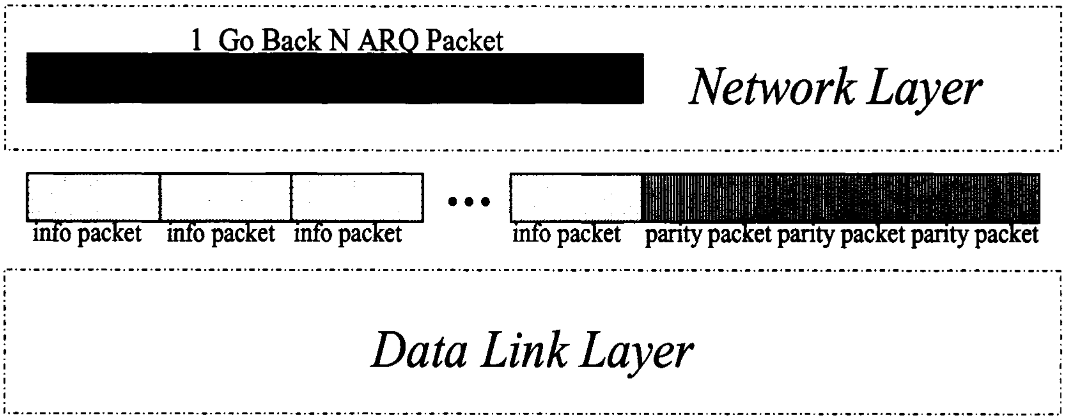


Figure 3.2: Sub-Layer Extension - Case 1.

Case 2:

Figure 3.3 shows the portion of the IP stack that is modified for case 2. In this case, an FEC network sub layer is used, with selective repeat ARQ being performed at the network layer. As similar to case 1, in this scheme, the source will group 20 50KB information packets together in a coded block with three redundancy 50KB packets. This corresponds to a (23,20,3) R-S packet erasure recovery scheme. The mechanism is the same as in Case 1, except if the FEC erasure correction capability is exceeded, that the selective repeat ARQ mechanism is initiated. Therefore, less dependence is put on selective repeat ARQ for packet erasure recovery, as it is only initiated if necessary.

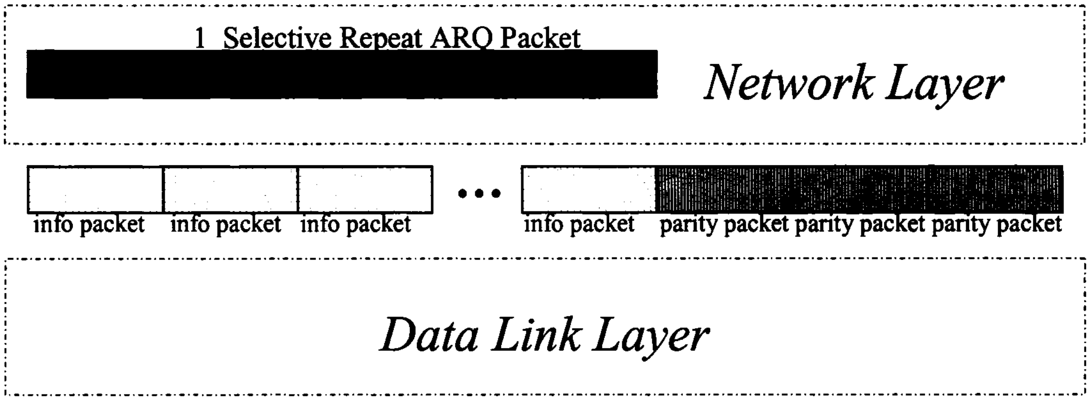


Figure 3.3: Sub-Layer Extension - Case 2.

Case 3:

Figure 3.4 illustrates the portion of the IP stack that is modified for case 3. In this case, instead of using FEC packet erasure correction at the network sub layer, selective repeat ARQ with a limited number of retransmissions is used at the network sub layer. At the network layer, standard selective repeat ARQ is performed. In this scheme, the source groups 20 50KB packets together in a coded block, and sends this coded block across the channel to the destination. As this group of packets arrives at the sub-network layer of the destination, the Selective Repeat ARQ sub layer mechanism is initiated, with three retransmissions of the smaller packets allowed. If the Selective Repeat ARQ mechanism is not successful at the sub layer, then the standard Selective Repeat ARQ at the network layer is initiated.

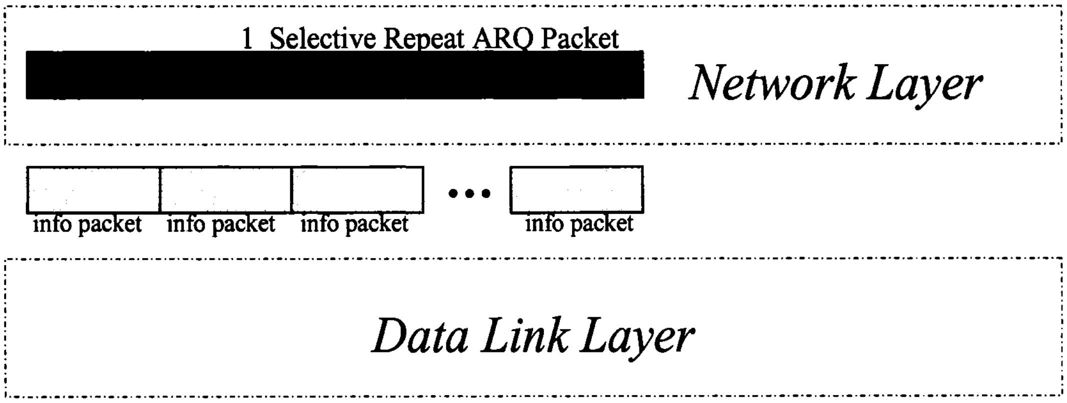


Figure 3.4: Sub-Layer Extension - Case 3.

Case 4:

Figure 3.5 illustrates the portion of the IP stack that is modified for case 4. This case is similar to case 3, except Go Back N ARQ is used at the network layer packet erasure correction mechanism. In this case, if three retransmissions of the smaller packets are not successful with Selective Repeat ARQ at the sub layer, standard Go Back N ARQ is initiated at the upper layer.

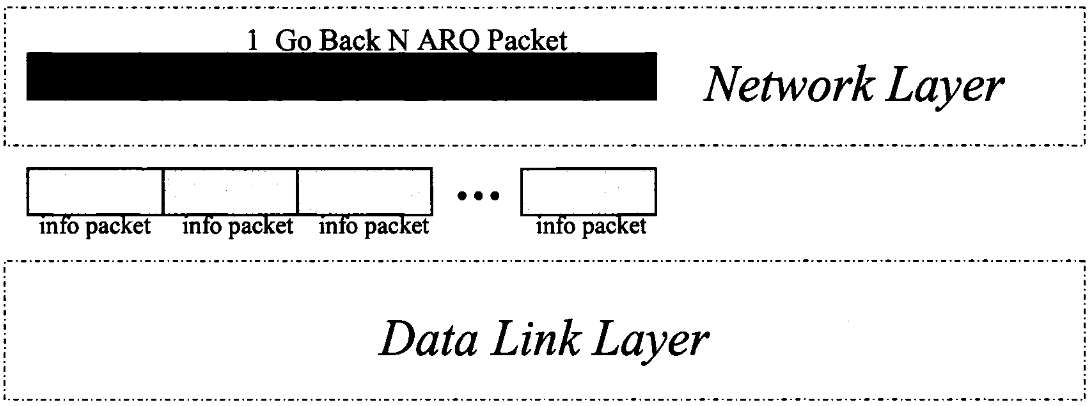


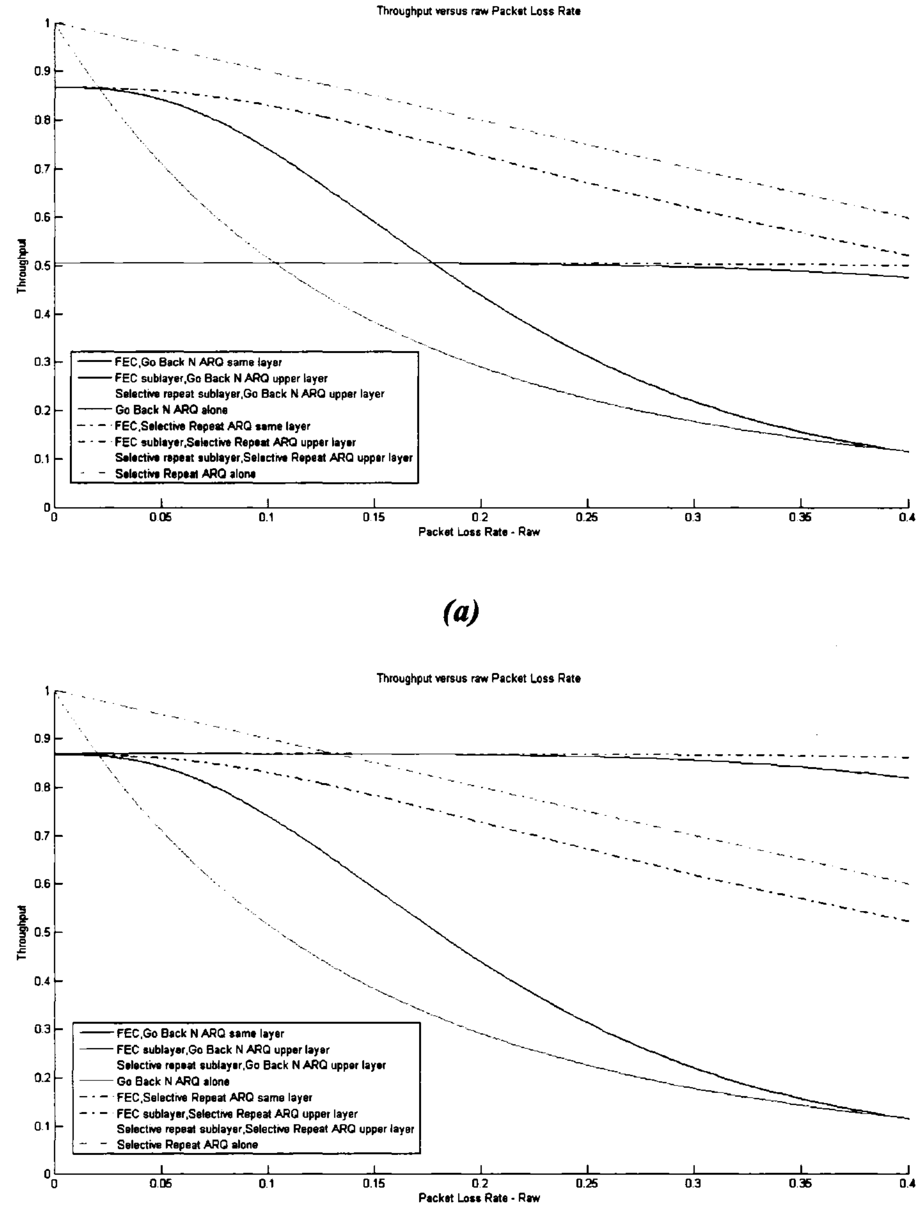
Figure 3.5: Sub-Layer Extension - Case 4.

The results of the throughput calculations for these four schemes are shown in Fig.3.6.

For comparison purposes the results from Section 3.1.1.1 are superimposed on the same diagram for the schemes without a network sub-layer. In order to have a fair comparison, the raw PLR rate in Fig.3.6 has been normalized from the raw PLR at the network sub-layer so that the PLR rate shown in Fig.3.6 corresponds to the size of the upper layer packet.

It should be emphasized that the results in Fig.3.6(a) are taking into account the reduction in throughput associated with protocol header overhead in the sub-layer. This overhead is set to be the same as the overhead in the network layer (30B) which heavily biases the results obtained against the sub-layer methods proposed. Figure 3.6(b) shows the same results by disregarding the header overhead at the sub-layer, assuming the sub-layer packet overhead (including sequence numbers) is part of the data link layer, and it does not have to be accounted for.

Examining Fig.3.6(a), it can be seen that the sub layer options suffer from extremely reduced throughput as compared to the performance of the pure selective retransmissions. However, it should be recalled that the Selective Repeat ARQ has limited applicability because of the theoretical requirement of an infinite buffer. The fact that the Go Back N ARQ with packet level FEC at the same layer has an improved performance over the Go Back N ARQ alone has been recently established in [Kos2002]. The pessimistic conclusion that can be drawn from Fig. 3.6 is that there is no benefit of introducing a sub layer extension to a packet erasure correction layer. However, this is because the results for the sub-layer are obtained under very pessimistic assumptions. Without taking into consideration the overhead at the sub-layer, the sub-network layer packet erasure recovery will offer superior throughput in comparison to having only packet erasure recovery at the network layer for raw PLRs above 10%, as can be seen in Fig.3.6(b).



(a)

(b)

Figure 3.6: Throughput versus raw PLR.

3.1.2 Better than Best Effort Single Hop Networks

Single hop better than best effort networks do not have a data delivery guarantee. Instead, an attempt is made to successfully transmit a packet from the source to the destination. In this sense, these networks are more applicable to multimedia networks where some degree of packet loss is acceptable. In this type of network, the packet delay is critically affecting the "real" PLR as packets arriving too late for playback in video or voice conversation are considered lost, even though they arrive at the destination.

This section examines the existing FEC alone and hybrid ARQ/FEC packet recovery schemes for single hop best effort networks in terms of a throughput analysis and a delay analysis.

3.1.2.1 Throughput Analysis

The general formula for throughput in networks with packet level FEC, η, is given by [Maj2002]:

$$\eta = \frac{k}{n} P_c \qquad (9)$$

where:

k = the number of information packets in a coded block

n = the total number of packets in a coded block

P_c = probability that a packet is received correctly across the channel after packet erasure recovery

In [Maj2002], it is shown that when there is a packet erasure correction mechanism that is based on FEC alone, the throughput, $\eta_{FEC,1}$, is given by:

$$\eta_{FEC,1} = \frac{k}{n} \sum_{j=0}^{n-k} P_e{}^{j} (1-P_e)^{n-j} \frac{n!}{j!(n-j)!} \qquad (10)$$

where:

P_e = raw PLR in the channel from the source to the destination

In this scheme, parity packets are added to a group of information packets to create a coded group to send across the channel. In [Maj2002], Reed Solomon coding was examined, with parameters (n, k, t), where n is the total number of packets in a coded group; k is the total number of information packets in a coded group; and $t = n - k$ represents the erasure correction capability of the code. That is, up to $n - k$ packets can be lost across the channel to allow for complete data packet recovery at the destination.

However, this expression represents the probability that an entire coded group of k information packets and $n - k$ redundancy packets will be received correctly after erasure recovery is performed. This expression assumes no information packets are received at the destination when the number of packet erasures is greater than that allowed for by the FEC code. This assumption is not true if a systematic code is used for packet erasure recovery.

When systematic FEC codes are used, a more accurate expression for the throughput is one that includes those packets that successfully arrive at the destination when the packet erasure recovery capability of the code is exceeded. Such an expression for throughput, $\eta_{FEC,2}$ is given by:

$$\eta_{FEC,2} = \frac{k}{n}\left(1 - \frac{1}{n}\sum_{i=t+1}^{n} i\binom{n}{i} P_e^{\,i}(1-P_e)^{n-i}\right) \qquad (11)$$

A single hop hybrid packet erasure FEC/ARQ scheme is examined in [Maj2002], where a group of k data packets are first sent across the channel. Then, parity packets are only sent from the source until a positive acknowledgement that k packets were sent correctly is received at the source. The erasure correction capability of the code stipulates that at least k packets must arrive at the destination. The receiver will send a positive acknowledgement back to the source once any k packets from the coded group are received. An advantage of such a scheme is a modest improvement in throughput over single hop FEC alone packet erasure correction. In the FEC alone scheme, parity packets are always sent regardless of whether they are required or not. The hybrid scheme just discussed will only send parity packets if they are required. For example, in good channel conditions where the average raw packet erasure rate is less than 10%, a lot of the time extra redundancy used for parity packets may not be required. A disadvantage of such a scheme is that it requires a path for retransmission, where pure FEC does not. Another disadvantage of such a scheme is an increase in delay, as is shown in the next section.

The throughput of this single hop hybrid packet erasure FEC/ARQ scheme, $\eta_{HARQ,1}$, is given by:

$$\eta_{HARQ,1} = \frac{k\left(1 - \frac{1}{n}\sum_{i=t+1}^{n} i\binom{n}{i} P_e^{\,i}(1-P_e)^{n-i}\right)}{\sum_{e=k}^{n} eP_c^{\,k}(1-P_c)^{e-k}\binom{e}{k} + n\left(1 - \sum_{e=k}^{n} P_c^{\,k}(1-P_c)^{e-k}\binom{e}{k}\right)} \qquad (12)$$

This expression has been modified from [Maj2002] to take into consideration the modified formula for (10).

A throughput comparison between these two packet erasure correction schemes is shown below in Fig.3.8 for the single hop network shown in Fig 3.7. In this comparison, the Reed Solomon packet erasure correction code used is (n=15, k=14, t=1). The modified formulas of (10) and (11) are used in this comparison. Examining Fig 3.8 shows that the hybrid FEC/ARQ erasure recovery scheme offers superior throughput performance over the FEC alone erasure recovery scheme for all values of PLR.

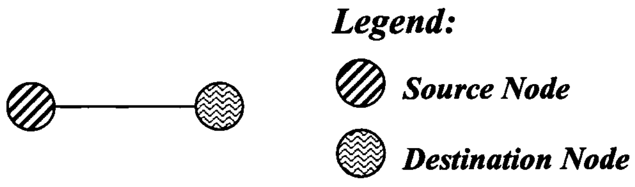


Figure 3.7: Single Hop Better than Best Effort Network.

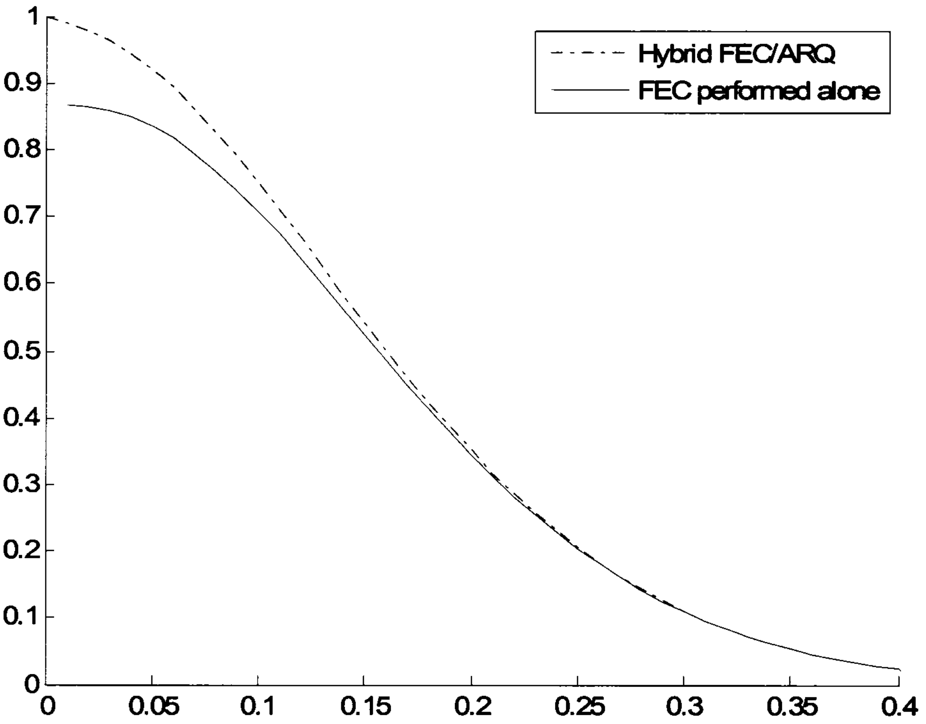


Figure 3.8: Throughput in a Single Hop Better than Best Effort Network.

3.1.2.2 Delay Analysis

In this section, delay is examined for the FEC alone and hybrid FEC/ARQ packet erasure recovery schemes as described in Section 3.1.2.1.

Delay in an FEC alone erasure recovery scheme is always fixed, if the number of packets within a coded packet block remains the same. In this work, this is an underlying assumption.

From (3) in Section 1.1.2, the expression for packet delivery delay, $D_{1\text{-PKT}}$, was found for a single hop network, and given again here as:

$$D_{1\text{-PKT}} = \left(\frac{PL}{R} + \frac{d}{c} \right) \tag{13}$$

Throughout this thesis, it is assumed that there always is a constant packet length, PL, constant channel rate, R, and constant maximum distance, d, between any two given nodes in the network. Since c; the speed of light; is constant, then the $\left(\frac{PL}{R}+\frac{d}{c}\right)$ term will be constant, and for simplicity of the formulae, this term will be represented in all packet delivery delay formulas as T, resulting in:

$$D_{1\text{-PKT}} = T \tag{14}$$

In an FEC alone packet erasure recovery scheme, all of the packets in the coded packet block must have arrived at the receiver before decoding can take place. If the transmitter is kept busy by having the packets of the block transmitted continuously to the destination, then the packet delivery delay for a coded packet block, D_2, will be given by:

$$D_2 = nT \tag{15}$$

where:

n = number of packets in a coded packet block

If there are multiple viable paths that can be used for transmission from the source to the destination, then the packet delivery delay for a coded packet block, $D_{FEC,1}$, will be given by:

$$D_{FEC,1} = \left(\left\lceil \frac{n}{q} \right\rceil\right)(T) \tag{16}$$

where:

q = number of viable paths from the source to the destination

A timing diagram is shown in Fig.3.9 to illustrate sending a packet across a best effort single hop network, where a FEC alone packet erasure recovery mechanism is in place. For this diagram, it is assumed that n = 15, and q = 4, corresponding to the network shown in Fig.3.7. As such, $D_{FEC,1} = \left(\left\lceil \frac{15}{4} \right\rceil\right)(T) = 3T$, and this is verified graphically in Fig.3.9.

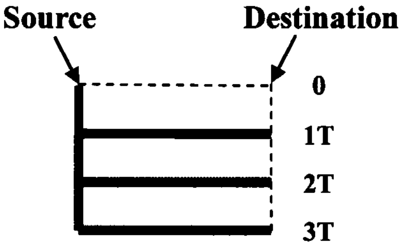


Figure 3.9: Timing Diagram for a Better than Best Effort Single Hop Network.

For the hybrid FEC/ARQ packet erasure recovery mechanism described in Section 3.2.1.1, the packet delivery delay will be variable as the number of packets that will be required to be sent in a coded packet block will vary between k and n, depending on the channel conditions. However, as there are a finite number of packets to be sent in transmitting a coded packet block, the delay is still bounded. The packet delivery delay for this hybrid mechanism, D_{HARQ}, is given by:

$$D_{HARQ} = D_{FEC,1}(n)\left(\frac{n_{red}}{n}\right) \qquad (17)$$

where:

$$n_{red} = \sum_{e=k}^{n} eP_c{}^{k}(1-P_c)^{e-k}\binom{e}{k} + n\left(1 - \sum_{e=k}^{n} P_c{}^{k}(1-P_c)^{e-k}\binom{e}{k}\right)$$

From (17), it can be seen that the delay of the hybrid FEC/ARQ erasure recovery mechanism is dependant upon the uncoded channel packet loss rate. As the uncoded channel packet loss rate is variable, the hybrid FEC/ARQ packet delivery time is variable. However, from (15), it can be seen that the FEC alone erasure recovery mechanism does not have this dependency, and henceforth is not variable. Figures 3.10 through 3.12 plot the packet delivery delay versus uncoded packet loss rate for the FEC alone and the hybrid FEC/ARQ packet erasure recovery schemes. Figure 3.10 represents the case where there is 1 viable path from the source to the destination. Figure 3.11 represents the case where there are 2 viable paths from the source to the destination, and figure 3.12 represents the case where there are 10 viable paths from the source to the destination.

In figures 3.10-3.12, the following assumptions were used, where R ,c ,d ,and PL are the variables as defined as in (3):

R	11 Mbps
C	$3(10^8)$ m/s
D	1000 m
n	15
k	13
PL	8240 bits (=1030 B)

In figures 3.10-3.12, it can be observed that as the number of viable paths is increased, the packet delivery delay of both the FEC alone and hybrid FEC/ARQ (HARQ) packet erasure recovery schemes is reduced. However, the HARQ packet erasure scheme offers superior delay performance regardless of the number of viable paths from the source to the destination. Henceforth, in terms of delay and throughput performance, there is no disadvantage in employing a hybrid FEC/ARQ packet erasure recovery scheme in single hop networks. It should be noted that this conclusion is reached here when using a positive acknowledgement based ARQ as described in Section 3.1.2.1.

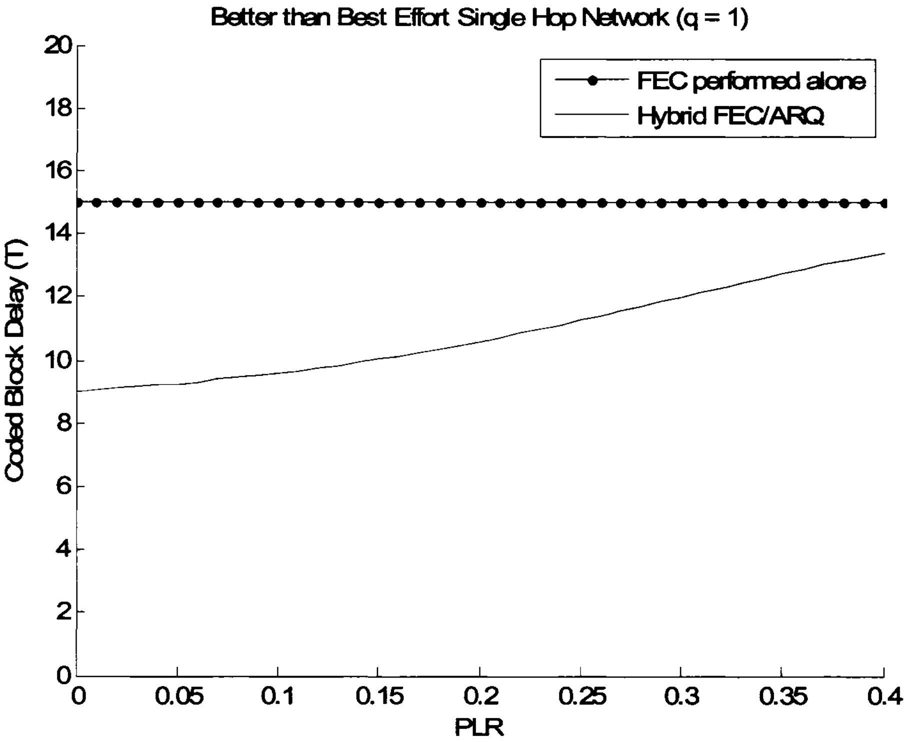


Figure 3.10: Delay in a Single Hop Better than Best Effort Network (q = 1).

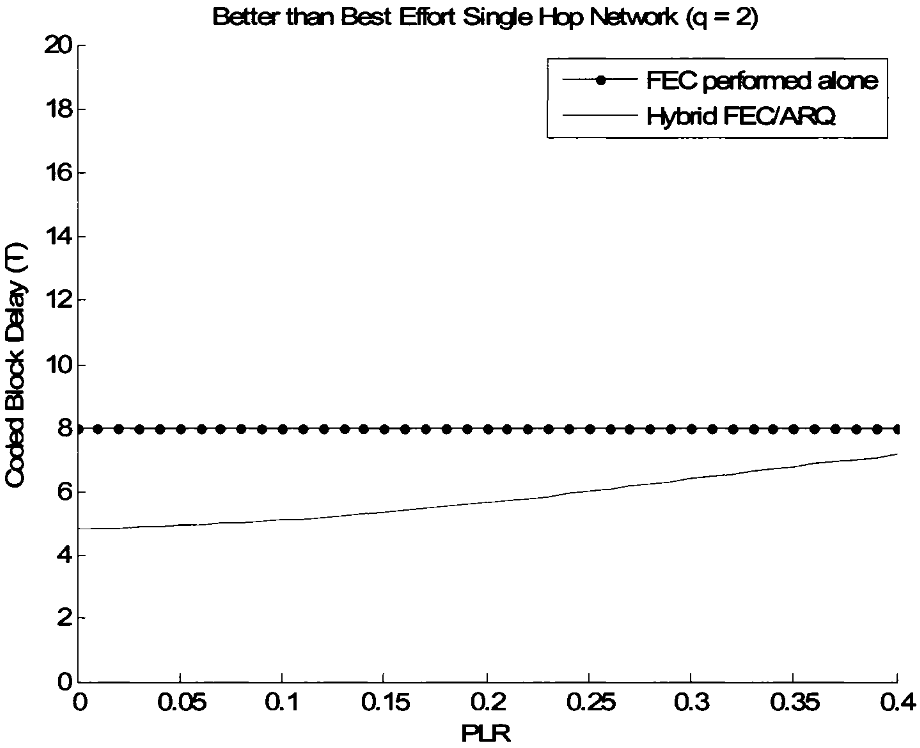


Figure 3.11: Delay in a Single Hop Better than Best Effort Network (q = 2).

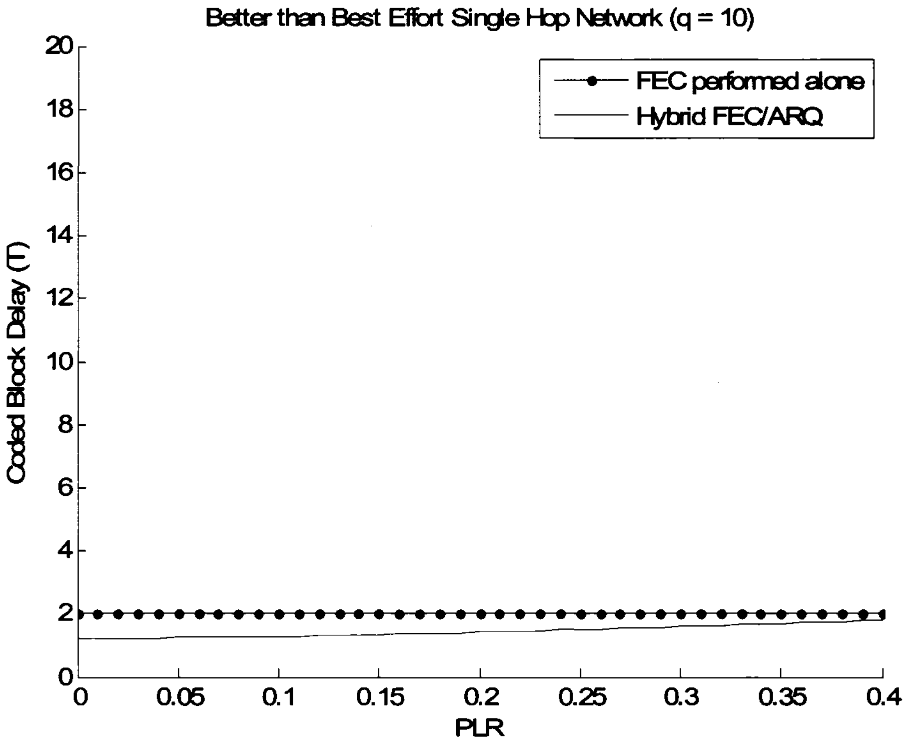


Figure 3.12: Delay in a Single Hop Better than Best Effort Network (q = 10).

3.2 Hybrid Packet Erasure FEC/ARQ Mechanisms for Multi-hop Networks

In this section, the dynamics of hybrid packet erasure FEC/ARQ packet loss recovery mechanisms are examined for multi-hop, multi-path wireless networks. The focus of this work is on better than best effort multi-hop networks. In this section the modified version of packet level FEC is considered where the packet level FEC positive acknowledgements are incorporated to inform the source that the receiver received k out of n packets. These k packets are sufficient to recover the k information packets in packet level FEC, and the implementation of positive acknowledgements improves the FEC layer throughput. Section 3.2.1 examines an analysis of the throughput and delay performance measures for best effort multi-hop networks. Section 3.2.2 examines an analysis for the same performance measures, but for best effort multi-hop networks with hybrid packet erasure FEC/ARQ packet loss recovery.

In general, it is found that the multi-hop performance measures are an aggregate of the single hop performance measures. For example, where throughput is reduced by a certain amount across a single hop, for a serial connection of these single hops, the throughput will be an aggregate of each of the single hop throughput reductions.

3.2.1 Performance Analysis of Better than Best Effort Multi-hop Networks

In this section, an analysis of the throughput of multi-hop better than best effort networks is performed. This section also examines the packet delivery delay of the two better than best effort multi-hop networks with packet erasure correction mechanisms described in Section 3.2.1.

3.2.1.1 Throughput

In this section, the throughput of multi-hop better than best effort networks is examined. In the analysis of this section, it is assumed that packet erasure recovery is only performed at the destination node. An examination of throughput when packet erasure recovery is performed at the intermediate nodes, as well as the destination node, is given in Section 3.3.

When the FEC packet erasure recovery method described in Section 3.1.2.1 is extended to the multi-hop scenario, P_e in (10) will be replaced by $P_T = 1\text{-}(1\text{-}P_e)^{hops}$, where *hops* represents the number of links between the source and destination. Changing P_e to P_T in (10) allows for a mathematical representation of the accumulation of lost packets across the multiple links between the source and the destination. The throughput when using FEC packet loss recovery in a multi-hop network, $\eta_{FEC,MULTI-HOP}$, becomes:

$$\eta_{FEC,MULT-HOP} = \frac{k}{n}\left(1 - \frac{1}{n}\sum_{i=t+1}^{n} i\binom{n}{i} P_T^{\,i}(1-P_T)^{n-i}\right) \tag{18}$$

where:

P_T = end-to-end uncoded packet loss rate

3.2.1.2 Delay

In this section, the average coded packet block delivery delay for a multi-hop better than best effort networks is examined. As in Section 3.2.1.1, it is assumed that FEC packet erasure recovery is only performed at the destination node.

A general delay expression for multi-hop networks is developed for comparison purposes. In general, a multi-hop network is given as shown in Fig.3.13, which is derived from [Ma2003]. In this general network there are a hops from the source to the destination, q_a viable paths between joint nodes a and $a-1$, and z_a is the largest number of serial paths on all q_a viable paths between joint nodes a and $a-1$. Note that the term "hop" refers to the connectivity between one joint node to the next joint node en route to the destination. In this work, it is assumed that all packet erasure recovery mechanisms will occur at joint nodes, as was in the case of [Ma2003].

For the general multi-hop network shown in Fig.3.13, the average coded packet block delivery delay for a code block of x packets is given by, $D_{FEC,2}$, as follows:

$$D_{FEC,2}(x) = ((\left\lceil \frac{x}{q_1} \right\rceil + z_1 + \sum_{i=2}^{a}(\Gamma(i) + z_i)) - 1)(T) \qquad (19)$$

where:

$\Gamma(i) = 0$ if $q_i \geq q_{i-1}$

$\Gamma(i) = \left\lceil \frac{n}{q_i} \right\rceil - \left\lceil \frac{n}{q_{i-1}} \right\rceil$ if $q_i < q_{i-1}$

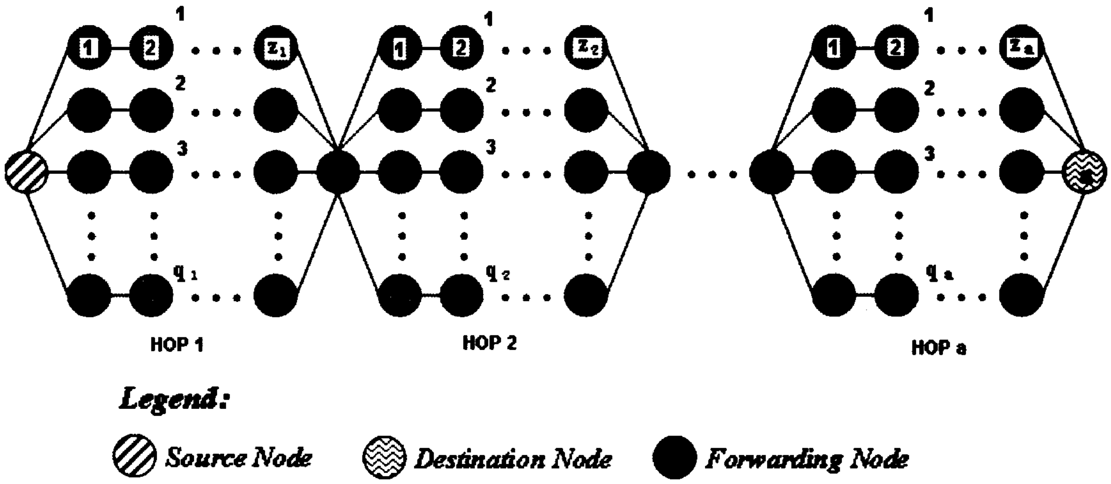


Figure 3.13: General Multi-path, Multi-hop Network.

In the simplified scenario, where the number of viable paths between joint nodes is the same for all hops (i.e. $q_1 = q_2 = q_3 = \ldots = q_a$), and the maximum number of serial links across each hop are the same (i.e. $z_1 = z_2 = z_3 = \ldots = z_a$), the delivery delay of coded packet block of x packets is given by, $D_{FEC,3}(x)$, as follows:

$$D_{FEC,3}(x) = (\left\lceil \frac{x}{q} \right\rceil + (z)(hops) - 1))(T) \qquad (20)$$

where:

q is defined as in (15), and:

$hops$ = number of hops between the source node and the destination

z = number of serial links per hop

A timing diagram to illustrate the average coded packet block delivery delay is shown in Fig.3.14(b) for the network of Fig.3.14(a). In the network of Fig.3.14(a), it is assumed that FEC packet loss recovery is performed only at the destination node. Examination of Fig.3.14(a) shows that for this network, $z = 2$, and $hops = 3$. For illustration purposes it is assumed that a coded block with $n = 15$ total packets is being sent from the source to the destination. From *(20)*, it is found that the delivery delay for this case is given by: $D_{FEC,2} = (\left\lceil \frac{15}{4} \right\rceil + (2)(3) - 1)(T) = 9T$, and this is verified graphically in Fig.3.17(b).

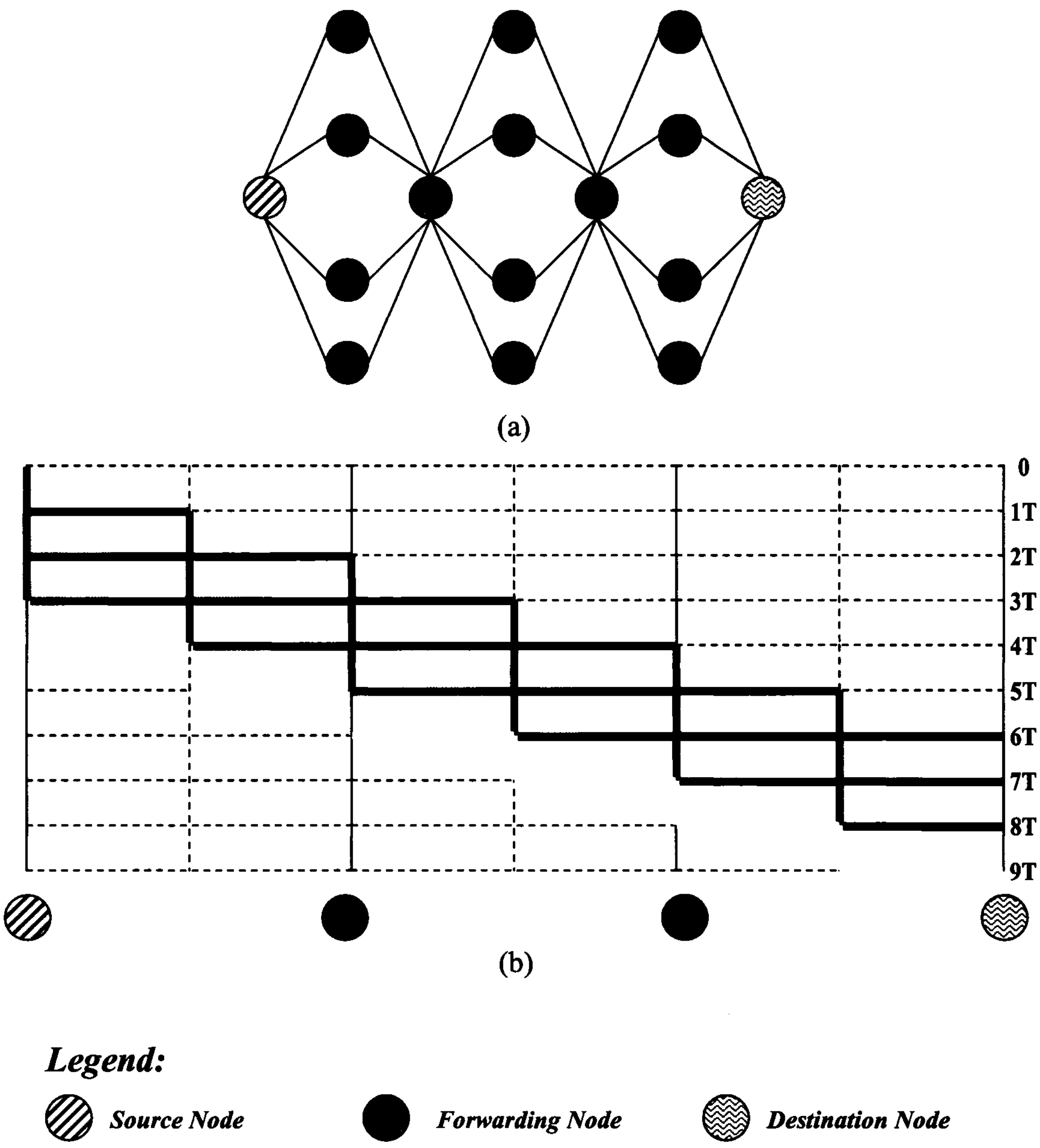


Figure 3.14: Timing diagram for a Better than Best Effort Multi-Hop Network.

3.2.2 Performance Analysis of Better than Best Effort Multi-hop Networks with HARQ

In this section, the results of Section 3.1.2.1 for better than best effort single hop networks with positive acknowledgement ARQ are expanded to examine their multi-hop counterparts. It should be noted that when referring to hybrid packet level FEC/ARQ (HARQ) in this section, it is this type of ARQ that is being examined. As well, the packet delivery delay for a better than best effort multi-hop network with an HARQ packet erasure recovery scheme is examined.

3.2.2.1 Throughput

When the hybrid FEC/ARQ packet erasure recovery mechanism described in Section 3.1.2.1 is extended to the multi-hop scenario, the throughput becomes, $\eta_{HARQ,2}$, as follows:

$$\eta_{HARQ,2} = \frac{k\left(1-\frac{1}{n}\sum_{i=t+1}^{n} i\binom{n}{i}P_e^{\,i}(1-P_e)^{n-i}\right)}{\min\left(\left(\sum_{e=k}^{n} e\frac{D_{FEC,3}(e)}{\left\lceil \frac{e}{q}\right\rceil}P_c^{\,k}(1-P_c)^{e-k}\binom{e}{k}+n\left(1-\sum_{e=k}^{n}P_c^{\,k}(1-P_c)^{e-k}\binom{e}{k}\right)\right),n\right)} \qquad \textit{(21)}$$

where: $D_{FEC,3}(k)$ is defined as in *(20)*, and:

n , q , and k are defined as in *(15)*, and:

hops = number of hops between the source node and the destination

z = number of serial links per hop

It should be noted that this HARQ system has benefit over a system with no positive acknowledgement ARQ if $n \geq \left(\frac{D_{FEC,3}(k)}{\left\lceil \frac{k}{q}\right\rceil}\right)k$. In such a case,

$\eta_{HARQ,2} > \eta_{FEC,MULTI-HOP}$. However, if $n < \left(\frac{D_{FEC,3}(k)}{\left\lceil \frac{k}{q} \right\rceil} \right) k$, then:

$\eta_{HARQ,2} = \eta_{FEC,MULTI-HOP}$ as in *(18)*.

Optimally, the positive acknowledgement ARQ mechanism will stop the source from transmitting any further packets in a coded packet block once the required k packets for packet erasure recovery are received at the destination. However, in a multi-hop network there is a delay in terms of the time it takes for the source to transmit k correct packets to the destination and have the source receive a positive acknowledgment. This delay constitutes a throughput reduction, as extra unnecessary redundancy packets are being sent from the source while it awaits the positive acknowledgement from the destination. The expression for the throughput in *(21)* is modified from *(18)* to account for the extra delay associated with the positive acknowledgement mechanism of this section.

If the transmission time to receive k correct packets at the destination is greater than the time it takes to transmit all n packets in the original coded group at the source, then there is no benefit in using the positive acknowledgement ARQ mechanism proposed in this section. The expression in *(21)* accounts for this by stating that if $n < \left(\frac{D_{FEC,3}(k)}{\left\lceil \frac{k}{q} \right\rceil} \right) k$, then $\eta_{HARQ,2} = \eta_{FEC,MULTI-HOP}$ as in *(18)*. As the number of hops from the source to the destination increases, the benefits of using a positive acknowledgment mechanism start to dwindle.

For the better than best effort multi-hop network shown in Fig.3.14(a), $z = 2$,

$hops = 3$, $n = 15$,$k = 13$,and q = 4. In this scenario, $\left(\frac{D_{FEC,3}(k)}{\left\lceil \frac{k}{q} \right\rceil}\right)k = 29.25$. As a result, $n < \left(\frac{D_{FEC,3}(k)}{\left\lceil \frac{k}{q} \right\rceil}\right)k$ for this case, and there will be no throughput improvements obtained by using the positive acknowledgement ARQ in this scenario. The plot of the throughput for this scenario is shown as the red curve labeled "Case 1" in Fig.3.15.

It can be seen by examination of *(20)*, that for smaller values of k,z and hops, there is an increased chance of positive acknowledgement ARQ having throughput benefits. If the network of Fig.3.13(a) is changed so that hops = 2, z = 1, and k = 9, then $\left(\frac{D_{FEC,3}(k)}{\left\lceil \frac{k}{q} \right\rceil}\right)k = 12$, and now throughput improvements will be obtained by using positive acknowledgment ARQ. This modified network is referred to as "Case 2", and Fig.3.15 shows two plots for throughput for the "Case 2" scenario: (a) when positive acknowledgment ARQ is used in conjunction with packet level FEC, and (b) when there is no positive acknowledgment ARQ used in conjunction with the packet level FEC packet erasure recovery mechanism.

Examining Fig 3.15 shows that the hybrid FEC/ARQ erasure recovery scheme offers superior throughput performance over the FEC alone erasure recovery scheme for values of PLR greater than 12% in "Case 2". For all values of PLR greater than 12%, both schemes offer the same throughput performance.

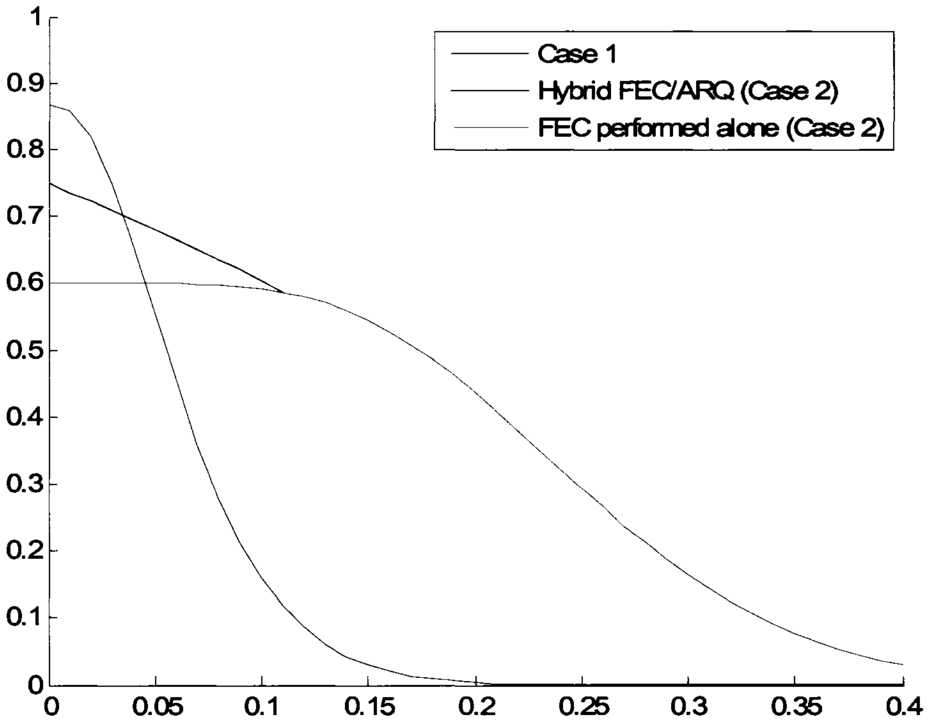


Figure 3.15: Throughput Analysis of a Better than Best Effort Multi-hop Network.

3.2.2.2 Delay

The packet delivery delay for a best effort multi-hop network with an HARQ packet erasure recovery scheme is given by $D_{HARQ,2}$ as:

$$D_{HARQ,2} = D_{FEC,3}(n)\left(\frac{n_{red}}{n}\right) \quad (22)$$

where:

$$n_{red} = \left(\min\left(\left(\sum_{e=k}^{n} e \frac{D_{FEC,3}(e)}{\left\lceil \frac{e}{q} \right\rceil} P_c^{\,k} (1-P_c)^{e-k} \binom{e}{k} + n\left(1 - \sum_{e=k}^{n} P_c^{\,k} (1-P_c)^{e-k} \binom{e}{k}\right) \right), n \right) \right)$$

For *(22)*, if $n < \left(\frac{D_{FEC,3}(k)}{\left\lceil \frac{k}{q} \right\rceil} \right) k$, then $D_{HARQ,2} = D_{FEC,3}(n)$.

Figures 3.16-3.18 plot the packet delivery delay versus uncoded packet loss rate for the FEC alone and the hybrid FEC/ARQ packet erasure recovery schemes. These plots are all normalized by the transmission time to send a packet across one link, T. For these plots, the network conditions are the same as for "Case 2" in Section 3.2.2.1. However, in "Case 2", the number of viable paths between the joint nodes in the network was fixed as q. Figures 3.16-3.18 represent the normalized coded packet group delay where the number of viable paths between the joint nodes is varied as: (a) one, (b) two, and (c) ten.

In figures 3.16-3.18, it can be observed that as the number of viable paths is increased, the packet delivery delay of both the FEC alone and hybrid FEC/ARQ (HARQ) packet erasure recovery schemes is reduced. However, as the number of viable paths between joint nodes is increased, the practicality of using positive acknowledgements is beginning to decrease. When $q = 1$, the HARQ packet erasure scheme has a smaller delay than the FEC alone scheme for values of PLR < 30%, as shown in Fig.3.16. When $q = 2$, the HARQ packet erasure scheme has a smaller delay than the FEC alone scheme for values of PLR < 20%. When $q = 10$, there is no benefit in using the HARQ packet erasure scheme in terms of packet block delivery delay, as shown in Fig.3.20. Other topologies were examined, and it was found that as the number of hops is increased from the source to the destination, the FEC and HARQ packet erasure schemes both increase in terms of packet delivery delay. However, the general trend with any topology is that as the number of multiple paths between joint nodes en route to the destination is increased, the benefits of HARQ are reduced.

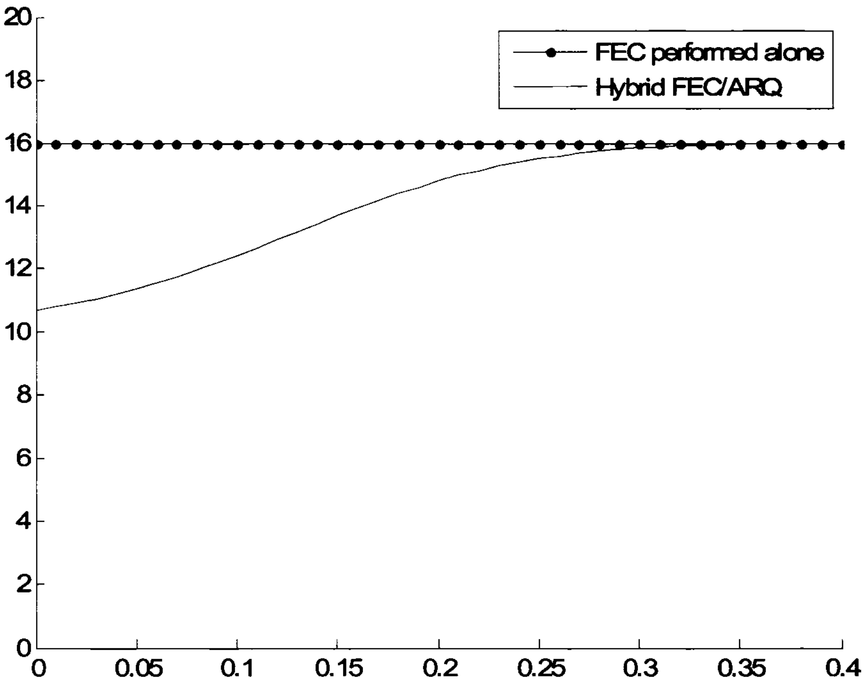


Figure 3.16: Delay with 2 hops, Better than Best Effort Network (q = 1).

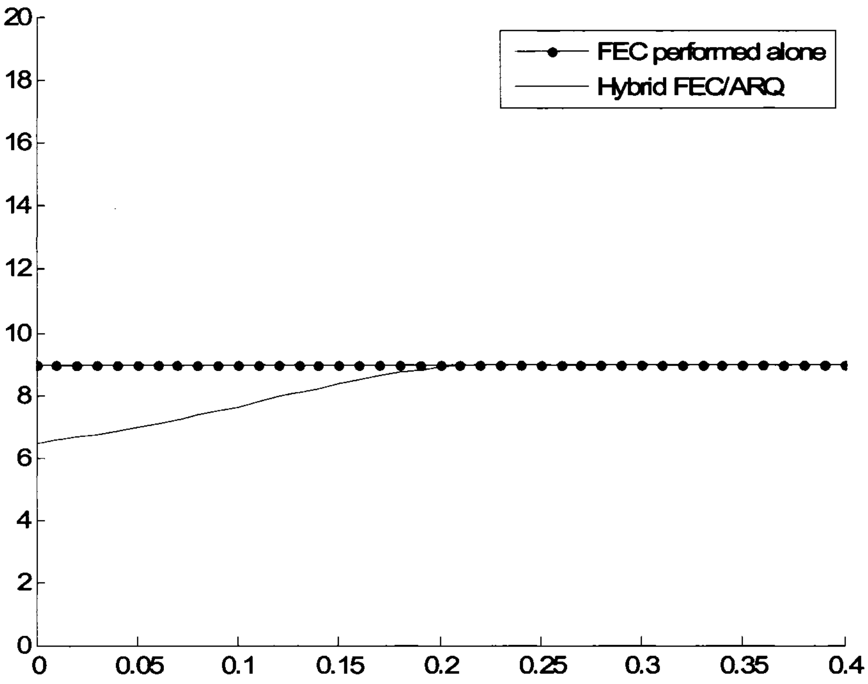


Figure 3.17: Delay with 2 hops, Better than Best Effort Network (q = 2).

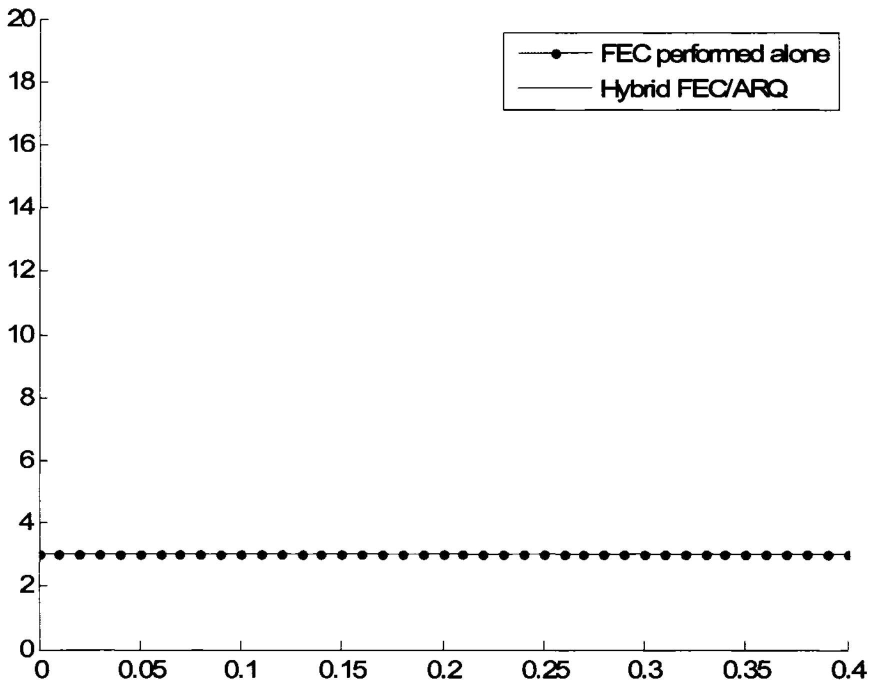


Figure 3.18: Delay with 2 hops, Better than Best Effort Network (q = 10).

3.2.3 Performance Analysis of Better than Best Effort Multi-hop Networks with SR-ARQ

This section examines the throughput and delay performance analysis of better than best effort multi-hop networks with Selective Repeat ARQ.

3.2.3.1 Throughput

The expression for throughput for such a mechanism is given by:

$$\eta = PLR(BWeff) \tag{23}$$

where:

$$PLR = \frac{1}{n}\left(\sum_{i=t+1}^{n} i\binom{n}{i}P_T{}^{i}(1-P_T)^{n-i}(1-(P_c+(1-P_c)P_c+(1-P_c)^2P_c))^{i-t}\right)$$

$$BWeff = \frac{k}{n+\sum_{i=t+1}^{n}\binom{n}{i}P_T{}^{i}(1-P_T)^{n-i}\left(((P_c+(1-P_c)P_c+(1-P_c)^2P_c)^{i-t-1})(P_c+2(1-P_c)P_c+3(1-2P_c+P_c{}^2)\right)}$$

and, $P_c=1-P_T$.

Equation *(23)* is based on Selective Repeat ARQ with a limited number of retransmissions, where n-t packets in a coded group are allowed up to three transmissions. For the better than best effort multi-hop network shown in Fig.3.14(a), ($z = 2$, $hops = 3$, $n = 15$,$k = 13$,and $q = 4$), Fig.3.19 plots the PLR versus throughput for such a scheme in 2 cases: (a) pure packet level FEC erasure recovery at the destination, (b) selective repeat ARQ with up to 3 retransmissions for every packet less than what is required for packet erasure recovery. Examining Fig.3.19 below, it shows that for all ranges of PLR of interest, the selective repeat ARQ/ FEC functionality provides the best packet erasure recovery mechanism. However, this improvement in throughput comes at a significant increase in the decoding delay as will be seen in the next section.

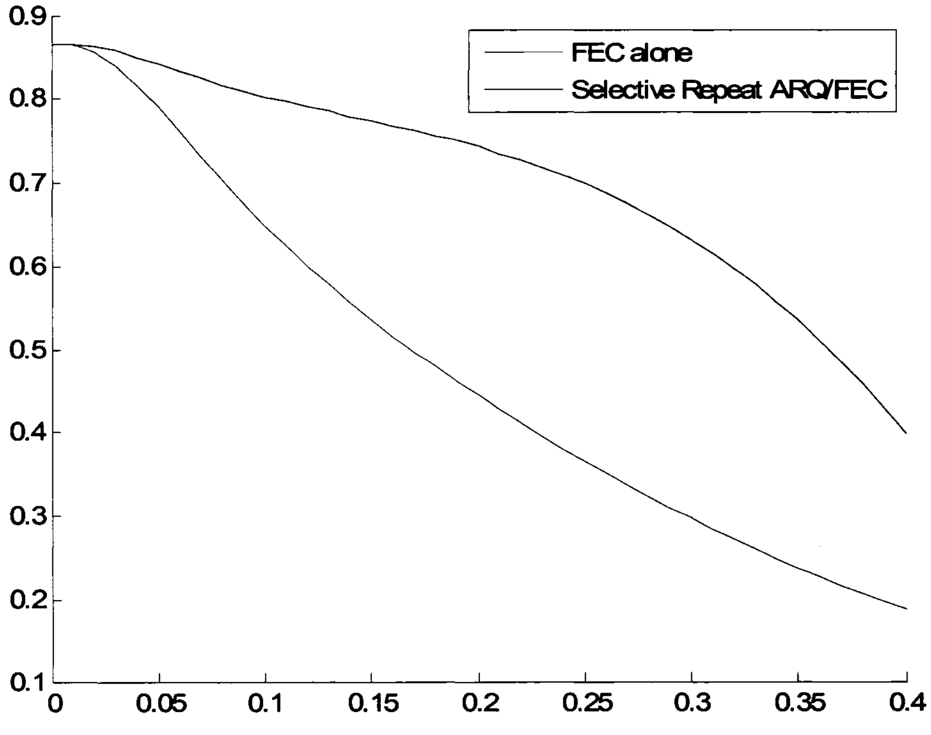


Figure 3.19: Throughput Performance of SR-ARQ/FEC.

3.2.3.2 Delay

Selective Repeat ARQ is a very time consuming method when dealing with multi-hop networks. The expression for delay for the Selective Repeat ARQ mechanism described in Section 3.2.3.1 when packet level FEC is only performed at the destination is given by, D_{SR}, as follows:

$$D_{SR} = D_{FEC,3}(n) + (nadd + z(hops) - 1)T \tag{24}$$

where:

$$nadd = \sum_{i=t+1}^{n} \binom{n}{i} {P_T}^i (1-P_T)^{n-i} \Big(((P_c + (1-P_c)P_c + (1-P_c)^2 P_c)^{i-t-1})(P_c + 2(1-P_c)P_c + 3(1-2P_c + {P_c}^2)) \Big)$$

Fig.3.20 shows a plot of the network described in section 3.2.1.2 where there are 3 hops from the source to the destination, and four multiple paths per hop. Examining Fig.3.20 shows that the delay of Selective Repeat Hybrid FEC/ARQ is much worse than that for FEC performed alone for all values of PLR.

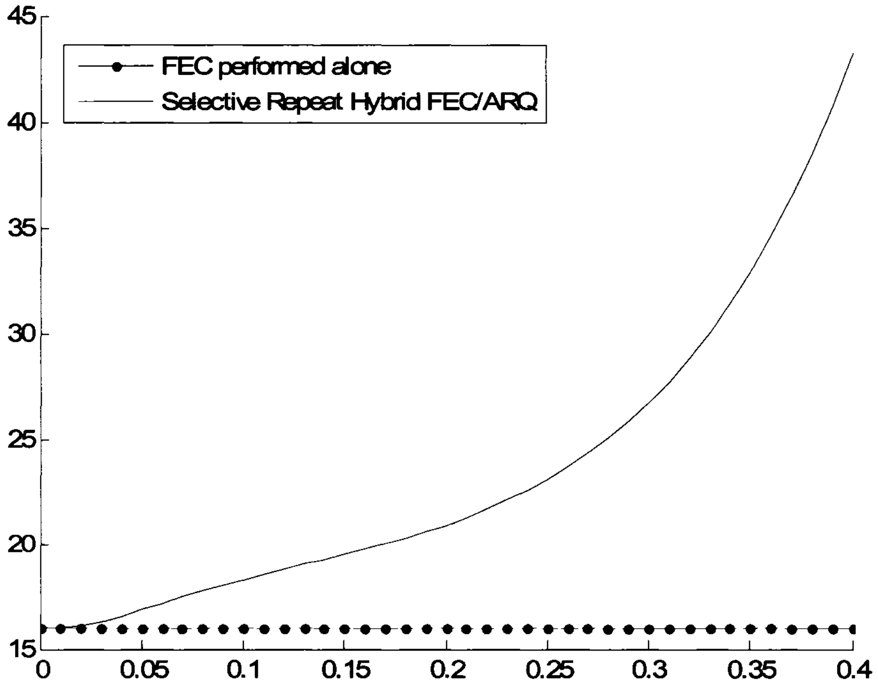


Figure 3.20: Delay Performance of SR-ARQ/FEC.

3.3 Regenerating Nodes in Multi-Hop Networks

The extension of the hybrid packet erasure FEC/ARQ mechanism to the concept of the regenerating node is examined in this section. In the current form of the regenerating node, FEC alone packet recovery is performed at the intermediate nodes and at the destination. An investigation of the validity and boundaries of the regenerating node concept in multi-hop networks is examined in conjunction with the hybrid packet erasure FEC/ARQ mechanism. This investigation is focused on better than best effort multi-hop wireless networks.

3.3.1 Better than Best Effort Multi-hop Networks with Regenerating Nodes

In this section, the performance measures of throughput and delay are examined for better than best effort multi-hop networks with regenerating nodes.

In order to simplify the notation associated with regenerating nodes, a regeneration vector, r, is introduced that determines which joint nodes en route from the source to the destination act as regenerating nodes. This regeneration vector, r, is defined as:

$$r = [r_1 \;\; r_2 \;\; r_3 \ldots r_{a-1} \;\; r_a] \tag{25}$$

where:

a = number of hops from the source to the destination

$r_x = 0$ if there is no regeneration occurring at node x

$r_x = 1$ if there is regeneration occurring at node x.

For example, in the multi-hop network shown in Fig.3.21, the joint nodes labeled 2 and 4 act as regenerating nodes. However, the destination node labeled 5 also has regenerative ability. Henceforth, the regeneration vector, r, associated with the network shown in Fig.3.21 is given by:

$$r = [0 \;\; 1 \;\; 0 \;\; 1 \;\; 1] \tag{26}$$

Since it is assumed in this thesis that the destination node will always have a packet erasure recovery mechanism, r_a in *(25)* will equal one for all networks considered in this work.

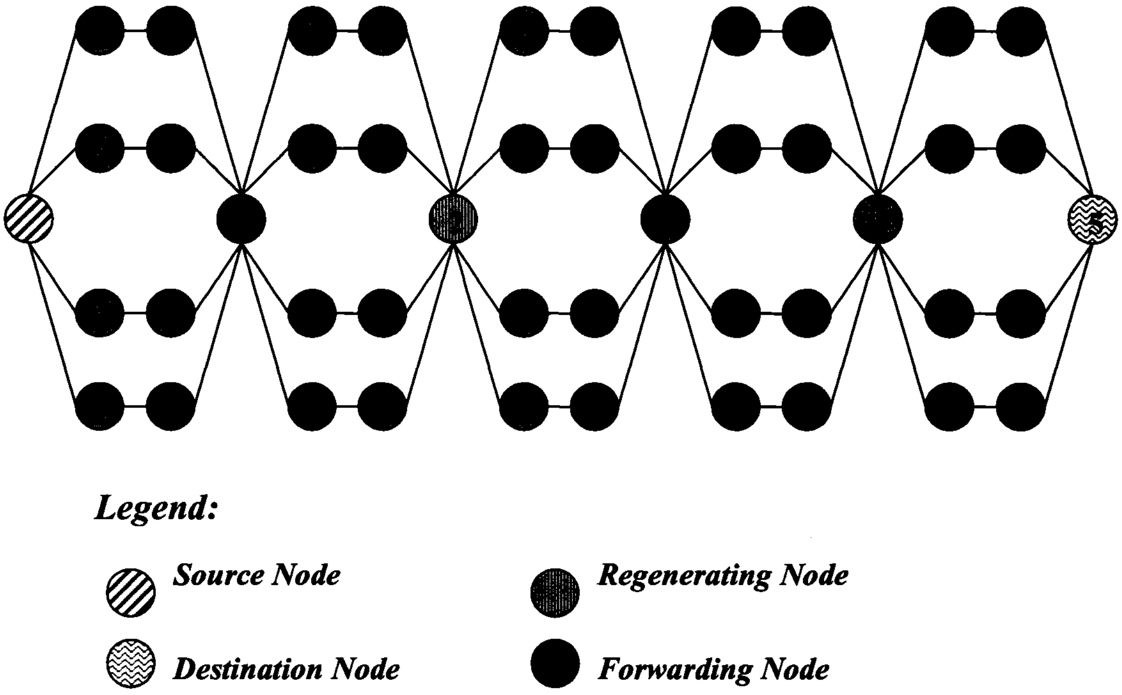


Figure 3.21: Multi-hop Network with Regenerating Nodes.

3.3.1.1 Throughput

The throughput of a multi-hop network with regenerative capabilities and a hops from the source to the destination, η_{REG}, is given by:

$$\eta_{REG} = \frac{k}{n}\left(1 - PLR(a)\right) \tag{27}$$

where:

PLR(a) represents the packet loss rate experienced at the destination node, a, as defined in *(28),(29)*.

The fundamental formulae representing the packet loss rate at node x in a multi-hop network after packet loss recovery has taken place, *PLR(x),* are given as follows:

If x > 1,

$$PLR(x) = (1 - r_x)(1 - (1 - PLR(x-1))(1-p)) + \\ r_x\left(\frac{1}{N}\sum_{i=t+1}^{N} i\binom{N}{i}(1-(1-PLR(x-1))(1-p))^i(1-(1-(1-PLR(x-1))(1-p)))^{N-i}\right) \tag{28}$$

If x = 1,

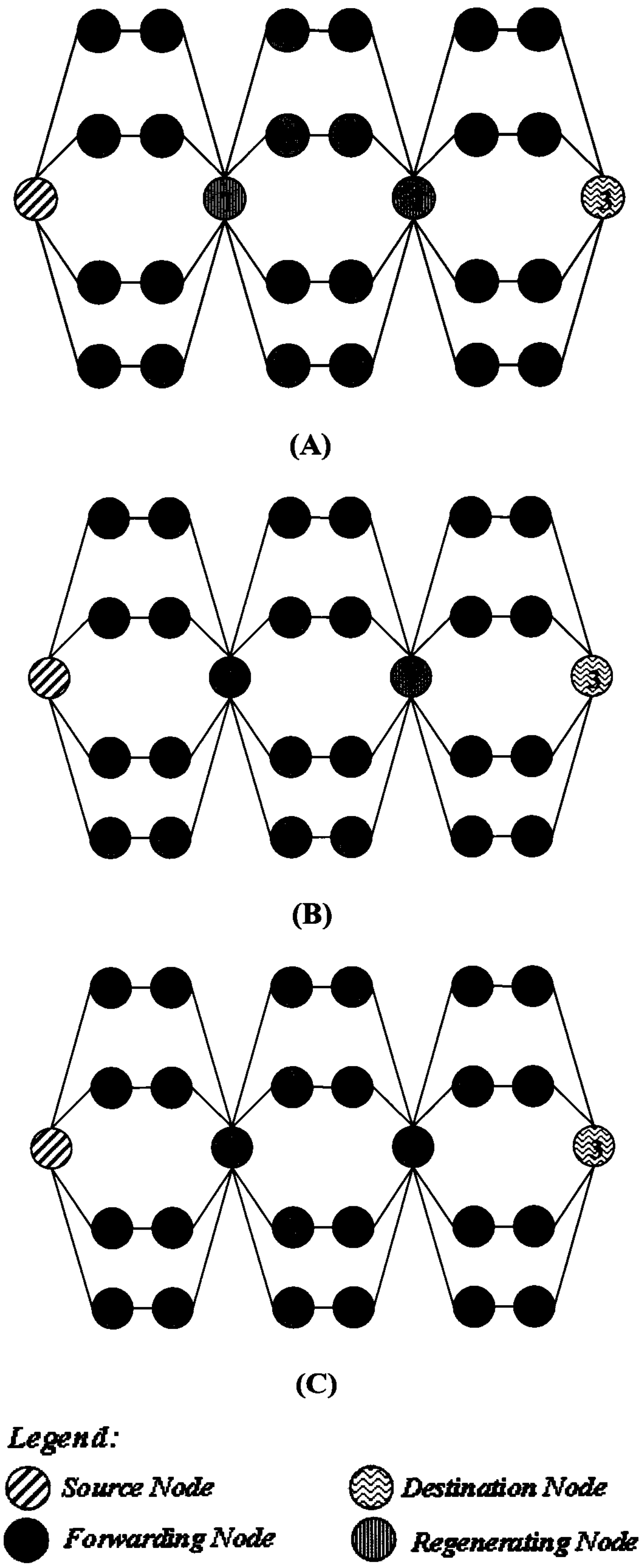
$$PLR(x=1) = (1-r_1)p + r_1\left(\frac{1}{N}\sum_{i=t+1}^{N} i\binom{N}{i}p^i(1-p)^{N-i}\right) \tag{29}$$

where:

r_x is defined as in *(25)*.

Examination of *(28)* and *(29)* indicates that these formulas are recursive in nature, as the packet loss rate experienced at node *x* depends on the accumulated packet loss rate from the source to node *x*.

Figure 3.23 shows the throughput for the three multi-hop network scenarios shown in Fig.3.22. In these network scenarios, there are three hops from the source node to the destination, and the regenerating nodes are shown as the blue nodes. Examining Fig.3.23 reveals that as more regenerating nodes are added at the joint nodes in the network, the throughput at the destination increases. However, these throughput increases are at the cost of additional delay, as will be shown in the next section.



(A)

(B)

(C)

Figure 3.22: Multi-hop Network Scenarios.

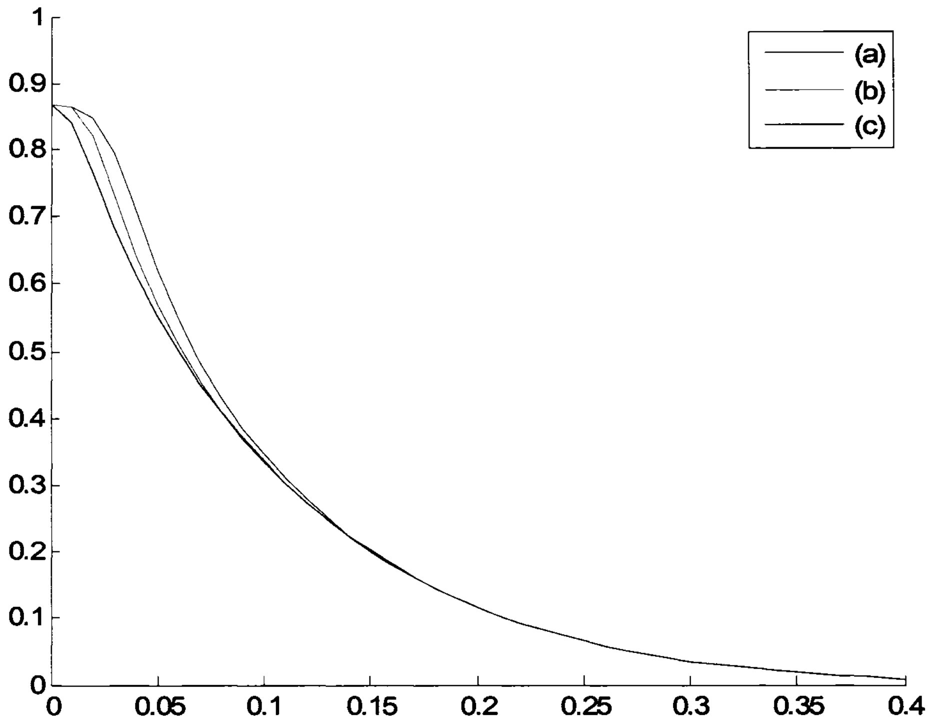


Figure 3.23: Throughput Analysis of a Multi-hop Network with Regeneration.

3.3.1.2 Delay

The delay in sending a coded block from the source to the destination if regeneration is performed at every node in a multi-hop network is given by $D_{REG,FEC}$ as follows:

$$D_{REG,FEC} = (\left\lceil \frac{n}{q} \right\rceil + (z)(hops) - 1 + (\left\lceil \frac{n}{q} \right\rceil - 1)(r_{sum} - 1))(T) \qquad (30)$$

where:

$$r_{sum} = \sum_{i=1}^{a} r_a$$

$r = [r_1\ r_2\ r_3 \ldots r_{a-1}\ r_a]$, as defined in *(25)*.

It should be noted that *(30)* is for an FEC alone erasure correction mechanism, and where the parameters are the same as those defined in *(20)*.

A timing diagram is shown in Fig.3.24 to illustrate sending a packet across a best effort multi-hop network, where packet erasure recovery is performed at every node. For this diagram, it is assumed that $z = 2$, $n = 15$, $q = 4$, and $hops = 3$.

For this case, $D_{REG,FEC} = (\left\lceil \frac{15}{4} \right\rceil + (2)(3) - 1) + (\left\lceil \frac{15}{4} \right\rceil - 1)(3 - 1))(T) = 15T$, and this is verified graphically in Fig.3.24.

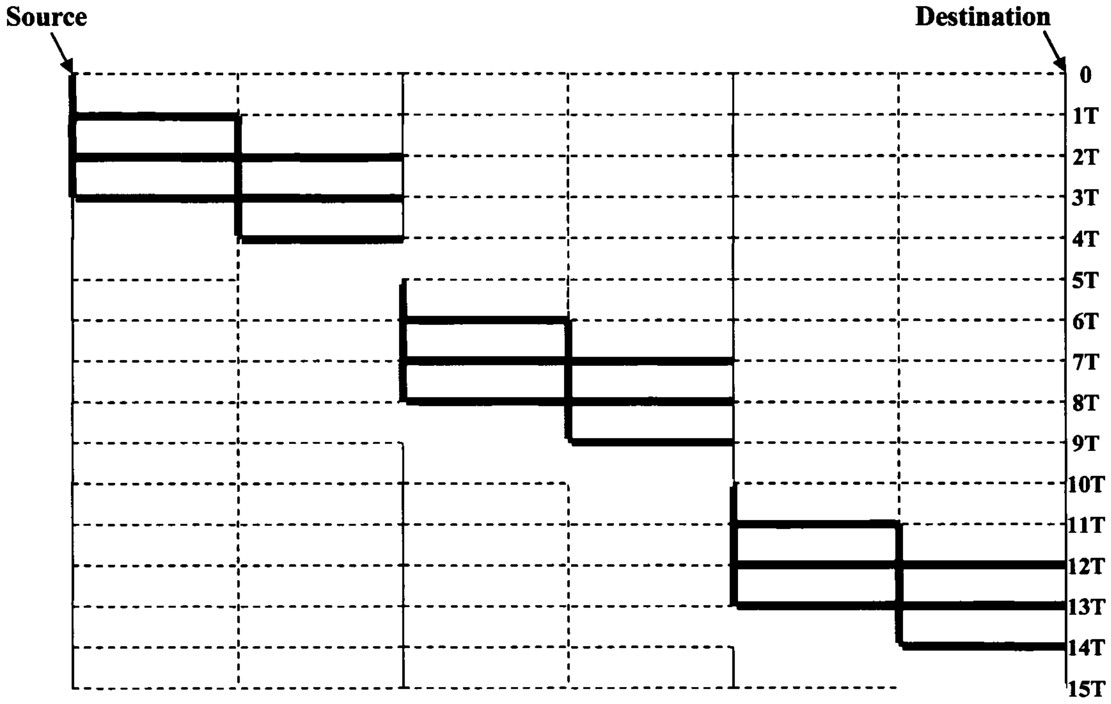


Figure 3.24: Timing Diagram for a Multi-Hop Network with Regeneration.

3.3.2 Better than Best Effort Multi-hop Networks with Regenerating Nodes and HARQ

In this section, a throughput analysis is performed on better than best effort multi-hop networks with positive acknowledgement ARQ. The results of Section 3.1.2.1 for better than best effort single hop networks with positive acknowledgement ARQ are expanded to examine their multi-hop counterparts. As well, the packet delivery delay for a best effort multi-hop network with an HARQ packet erasure recovery scheme is examined.

3.3.2.1 Throughput

The throughput of a multi-hop network with regenerative capabilities and positive acknowledgement ARQ, $\eta_{HARQ,REG}$, is given by:

$$\eta_{HARQ,REG} = \frac{ak(1-PLR(a)}{\Phi(1)\Psi(1)+\Phi(2)\Psi(2)+......+\Phi(a)\Psi(a)}, \qquad (31)$$

where: *T, n , q ,z ,x ,a ,PLR(a),*r_a*,k* are defined as in *(22)*, and:

For values of x > 1,

$$\begin{aligned}\Phi(x) = (&r_a r_{a-x}(1-r_{a-1})(1-r_{a-2})....(1-r_{a-(x+1)})+\\ &r_{a-1}r_{a-x-1}(1-r_{a-2})(1-r_{a-3})....(1-r_{a-x})+\\ &r_{a-2}r_{a-x-2}(1-r_{a-3})(1-r_{a-4})....(1-r_{a-(x-1)})+\\ &....\\ &r_x(1-r_{x-1})(1-r_{x-2})(1-r_{x-3})....(1-r_2)(1-r_1))\end{aligned}$$

When x = 1,

$$\Phi(1) = r_a r_{a-1} + r_{a-1}r_{a-2} + ... + r_2 r_1 + r_1$$

$$\Psi(x) = \min\left(\left(\sum_{e=k}^{n} e\frac{D_{REG,X}(e)}{\left\lceil \frac{e}{q} \right\rceil} P_c{}^k(1-P_c)^{e-k}\binom{e}{k} + n\left(1-\sum_{e=k}^{n} P_c{}^k(1-P_c)^{e-k}\binom{e}{k}\right)\right), n\right)$$

$$D_{REG,X}(e) = \left(\left\lceil \frac{e}{q} \right\rceil + (z)(x) - 1\right)T$$

Figure 3.25 shows the throughput obtained for a network with parameters z = 2, hops = 3, q = 1. It can be seen that the positive acknowledgement ARQ method allows for a throughput improvement in good channel conditions, and does not deteriorate below the throughput of the packet level FEC alone erasure recovery for any value of PLR. Performing simulations under a variety of different topologies found that HARQ based on positive acknowledgments offers improvements in throughput in all situations.

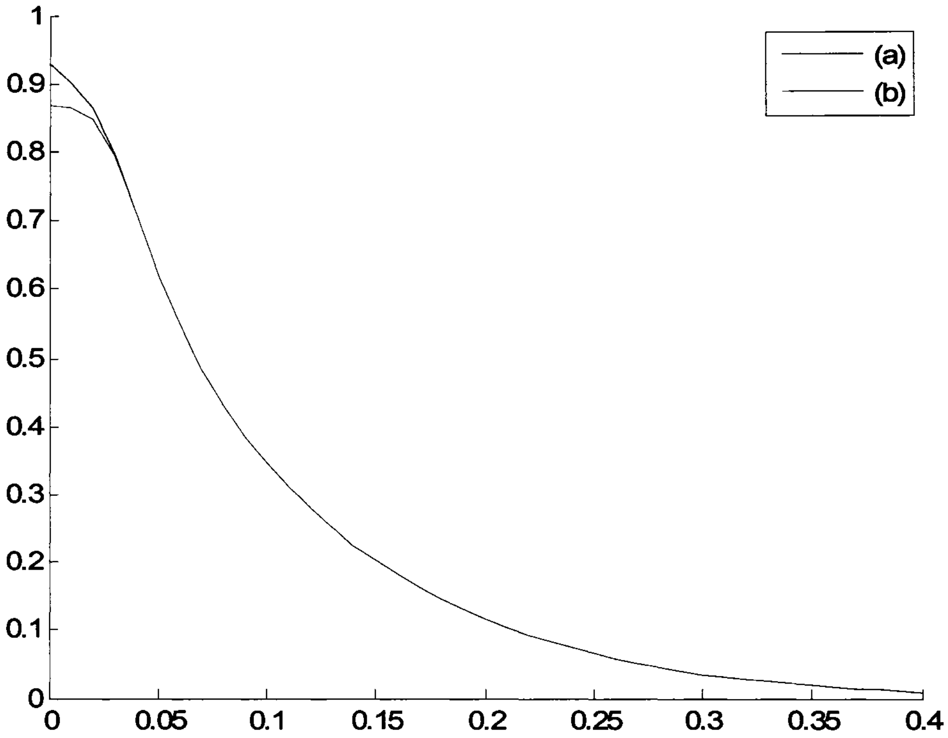


Figure 3.25: Throughput Analysis of a Multi-hop Network with Regeneration.

3.3.2.2 Delay

The packet delivery delay for a best effort multi-hop network with regeneration at every node and an HARQ packet erasure recovery scheme is given by $D_{REG,HARQ}$:

$$D_{REG,HARQ} = D_{REG,FEC}\left(\frac{n_{red,2}}{n}\right) \tag{32}$$

$$n_{red,2} = \frac{ak}{\Phi(1)\Psi(1) + \Phi(2)\Psi(2) + \ldots\ldots + \Phi(a)\Psi(a)}$$

where the parameters of this equation are the same as in *(31)*.

For this situation, there are improvements in delay for small values of PLR, however most importantly this mechanism does not introduce delay into the system.

HARQ with positive acknowledgements has the benefit of increasing throughput, while at the same time decreasing packet group decoding delay. This is opposite to that of Selective Repeat ARQ, where increases in throughput come at the expense of additional decoding delay in the network.

3.3.3 Better than Best Effort Multi-hop Networks with Regenerating Nodes and SR-ARQ

This section examines the throughput and delay performance of better than best effort multi-hop networks with Regenerating Nodes and Selective Repeat ARQ (with a limited number of retransmissions) for two distinct cases: (a) with positive acknowledgement ARQ, (b) without positive acknowledgement ARQ.

Upon analyzing throughput for better than best effort multi-hop networks with regenerating nodes and selective repeat ARQ for a number of different topologies with both of the cases described above, it was found that the incorporation of Selective Repeat ARQ always allows for a substantial increase in throughput. However, upon analyzing the delay of Selective Repeat ARQ on all of the different types of networks discussed in this chapter, it was found that the delay associated with Selective Repeat ARQ is too prohibitive for better than best effort multi-hop networks, where often packet delivery delay is an important factor.

It is found that a regenerating node scheme with positive acknowledgement feedback is a good compromise for increasing the throughput of the system, without adversely affecting the delay as is the case with Selective Repeat ARQ.

3.4 Summary

This chapter examined hybrid packet erasure FEC/ARQ in multi-hop, multi-path networks. Existing single hop hybrid packet erasure FEC/ARQ mechanisms were discussed. The results for a throughput analysis and a delay analysis for single hop networks were shown. A proposed scheme to improve throughput for reliable single hop networks by introducing a sub layer to a main packet erasure correction layer was examined, and found to be beneficial when not considering overhead considerations. Two hybrid packet erasure FEC/ARQ mechanisms for the case of multi-hop networks were shown, and the tradeoff between throughput and maximum delay was examined. It was found that for Selective Repeat ARQ, an end to end improvement in throughput can be achieved at the cost of an increased in delay. However, for a hybrid packet erasure FEC/ARQ mechanism based on positive acknowledgements, it was shown that an increased throughput can be achieved without a need for an increase in decoding delay.

An extension of the hybrid packet erasure FEC/ARQ mechanism to the concept of the regenerating node was shown. In the case of a multi-hop wireless best effort network, it was found that regenerating nodes that use a hybrid FEC/ARQ packet erasure correction mechanism based on positive acknowledgements yield the best throughput performance. The delay in such schemes is found to have a maximum bound, and the number of regenerating nodes deployed should be selected so that the application packet delivery delay requirement is not exceeded. This delay is not fixed as in the case of a pure FEC packet erasure correction mechanism, but never grows exponentially like the case of Selective Repeat ARQ.

Chapter 4

2-D Reed-Solomon Product Codes in Multi-hop Wireless Networks

This chapter builds on the results from Chapter 3 by examining 2-D R-S FEC codes for packet erasure recovery in multi-hop wireless networks with regenerating nodes. While 2-D R-S can be interpreted as yet another version of the packet level FEC, in this chapter 2-D R-S codes are applied to take advantage of the existence of multiple paths from the source to the destination. Specifically, the intermediate nodes in the network are utilized to recover lost packets based on one component code in the 2-D R-S product code. At the destination, both component codes are used in concert using iterative decoding to recover accumulated lost packets in the entire 2-D packet matrix.

The organization of the chapter is as follows: Section 4.1 discusses the motivation behind using 2-D R-S product codes. Section 4.2 shows how 2-D R-S product codes can be used in single hop wireless networks for packet loss recovery. Section 4.3 develops a new implementation of 2-D R-S based packet erasure recovery in multi-hop wireless networks by exploiting the intermediate nodes through the regenerating node concept. Finally, Section 4.4 provides a summary for this chapter.

4.1 Two Dimensional R-S Product Codes

This section discusses the motivation behind using 2-D R-S product codes. Product codes are powerful codes that can be used to correct errors and/or recover erasures. The premise for our research in this chapter is that through iterative decoding of product codes at the destination, the product R-S codes can achieve higher throughput performance in comparison to 1-D R-S codes with a comparable coding rate. In general, the cost of this improvement in throughput is an increase in the decoding delay that is experienced in sending a packet from the source to the destination and is implementation specific. The nature of this tradeoff is examined thoroughly in this chapter.

The general form of a 2-D R-S FEC coding scheme is shown in Fig.4.1. In a 2-D R-S product code the information packets are arranged in a matrix of $k_1 x k_2$ and the redundancy is added in two dimensions: for every row there is $n_1 - k_1$ redundancy packet constructed using horizontal component R-S code, and for every column there are $n_2 - k_2$ redundancy packets constructed using vertical component R-S codes [Moo2005]. This arrangement of packets allows for an iterative approach in packet erasure recovery. For example, packet erasure recovery may be performed column-wise initially to try to recover as many packets as possible in the vertical dimension. Then, packet erasure recovery is performed row-wise as to recover as many packets as possible in the horizontal dimension. Once this is completed, packet erasure recovery is performed in the vertical dimension again, and so on, until the maximum number of lost packets that can be recovered by the 2-D FEC code is achieved. As such, 2-D FEC codes are more robust than their 1-D counterparts, which only allow one opportunity at packet erasure recovery [Swe2002]. It is this robustness that intuitively one would think would be beneficial for improving the throughput performance in multi-hop wireless networks.

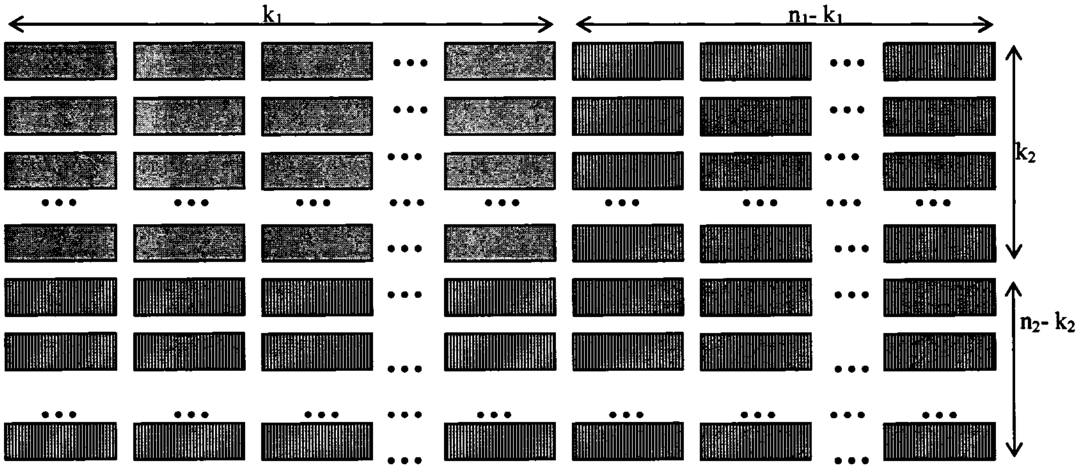


Figure 4.1: Two Dimensional R-S Coding.

The code rate factor, $\frac{k}{n}$, for the two dimensional R-S coding scheme is given by: $\frac{k_1 k_2}{n_1 n_2}$, where:

k_1 = the number of information packets in a coded group in the horizontal dimension

k_2 = the number of information packets in a coded group in the vertical dimension

n_1 = the total number of packets in a coded group in the horizontal dimension

n_2 = the total number of packets in a coded group in the vertical dimension

4.2 Two Dimensional R-S Product Codes in Single Hop Networks

This section discusses two dimensional R-S product codes in single hop wireless networks. Single hop network dynamics are discussed first, and are used to develop the results for multi-hop wireless networks.

4.2.1 Throughput Analysis

The general formula for throughput in better than best effort networks is given by *(9)* in Section 3.1.2.1. In *(9)*, k, n, and P_c must be determined in order to evaluate throughput. P_e, the packet loss rate after decoding in 2-D R-S codes, could be evaluated in similar fashion as in the case of 1-D codes using:

$$P_e < \frac{1}{n_1 n_2} \sum_{i=d_1 d_2}^{n_1 n_2} i \binom{n_1 n_2}{i} p^i (1-p)^{n_1 n_2 - i} \qquad (33)$$

where

$d_1 = t_1+1$ is the minimum distance of the FEC code in the horizontal dimension, and

$d_2 = t_2+1$ is the minimum distance of the FEC code in the vertical dimension.

and $d_1 \cdot d_2 - 1$ is the erasure recovery capability of the 2-D R-S product code.

However, to obtain more reliable estimates for P_e, more precise formulas are deployed from [Al-S2006]. Even though originally these results were derived and verified at the bit level, they are equally applicable at the packet level. For i-erasures before decoding in a received n_2xn_1 codeword matrix, let *U(i)* denote the number of unrecoverable erasure patterns. It should be observed that even though a pattern of *i*-erasures before decoding is not recoverable, after decoding the number of not recovered erasures in this pattern in general is smaller than *i*. For the *U(i)* patterns, let e_i denotes the average number of remaining erasures after decoding an unrecoverable pattern with initial *i* erasures. With this P_e, the packet loss rate after decoding, is given as follows for two dimensional R-S codes [Al-S2006]:

$$P_e = \frac{1}{n_1 n_2} \sum_{i=1}^{n_1 n_2} e_i U(i) p^i (1-p)^{n_1 n_2 - i} \tag{34}$$

where:

P_c, the average probability that a packet will be correct after decoding is given by the expression $P_c = 1 - P_e$, and is:

$$P_c = 1 - \frac{1}{n_1 n_2} \sum_{i=1}^{n_1 n_2} e_i U(i) p^i (1-p)^{n_1 n_2 - i} \tag{35}$$

where $U_i \ll \binom{n_1 n_2}{i}$ since many of the *i*-erasures ($i \geq d_1 d_2$) within *U(i)* patterns are recoverable.

If $d_1 = d_2$, then from [Al-S2006],

$$U(d_1 d_2 + m) = \begin{cases} \binom{n_1}{d_1}\binom{n_2}{d_2}\binom{n_1 n_2 - d_1 d_2}{m} & 0 \leq m \leq d-1 \\ \binom{n_1}{d_1}\binom{n_2}{d_2}\left[\binom{n_1 n_2 - d_1 d_2}{m} - d_1\binom{n_1 - d_1}{d_1 + 1} - d_2\binom{n_2 - d_2}{d_2 + 1}\right] & d \leq m \leq \min(d_1 d_2 - 1, d_1 + d_2 - 1) \end{cases} \tag{36}$$

In the case when $d_1 \neq d_2$,

$$U(d_1 d_2 + m) = \begin{cases} \binom{n_1}{d_1}\binom{n_2}{d_2}\binom{n_1 n_2 - d_1 d_2}{m} & 0 \leq m \leq d_s - 1 \\ \binom{n_1}{d_1}\binom{n_2}{d_2}\left[\binom{n_1 n_2 - d_1 d_2}{m} - d_1\binom{n_1 - d_1}{d_1 + 1}\right] & d_s = d_2 \leq m \leq \min(2d_s - 1, d_x - 1) \\ \binom{n_1}{d_1}\binom{n_2}{d_2}\left[\binom{n_1 n_2 - d_1 d_2}{m} - d_2\binom{n_2 - d_2}{d_2 + 1}\right] & d_s = d_1 \leq m \leq \min(2d_s - 1, d_x - 1) \\ \binom{n_1}{d_1}\binom{n_2}{d_2}\left[\binom{n_1 n_2 - d_1 d_2}{m} - d_1\binom{n_1 - d_1}{d_1 + 1} - d_2\binom{n_2 - d_2}{d_2 + 1}\right] & d_x \leq m \leq 2d_s - 1 \end{cases} \tag{37}$$

Substituting *(32)*, *(33)*, and *(34)* into (9) for specific code rate parameters k_1, k_2, n_1, and n_2 will yield the throughput in a single hop best effort network, where a two dimensional R-S packet recovery code is employed.
Figure 4.2 shows a plot of throughput versus uncoded channel PLR for a single hop best effort network using a 2-D R-S packet erasure correction code. For comparison purposes, a plot of uncoded channel PLR versus throughput for a single hop best effort network using a 1-D R-S packet erasure correction code is shown. The coding rates of the 2-D and 1-D schemes are the same as to ensure a fair comparison. Examining Fig.4.2 it can be seen that in terms of throughput, 1-D R-S packet recovery outperforms 2-D R-S packet erasure recovery when no ARQ mechanism is present. However, when the PLR > 25%, 2-D R-S HARQ packet erasure recovery has a greater throughput than 1-D R-S HARQ packet recovery. Based upon the results of this section, on first observation it would appear that 1-D R-S packet recovery with FEC alone should be used when PLR < 25%, and 2-D R-S HARQ packet erasure recovery should be used when PLR > 25%. However, as it is shown in the next section, the delay between these schemes is not comparable, and delay should also be a factor of consideration when deciding which packet erasure recovery mechanism to incorporate. This becomes especially important when delay sensitive applications, such as multimedia, are being used in the network.

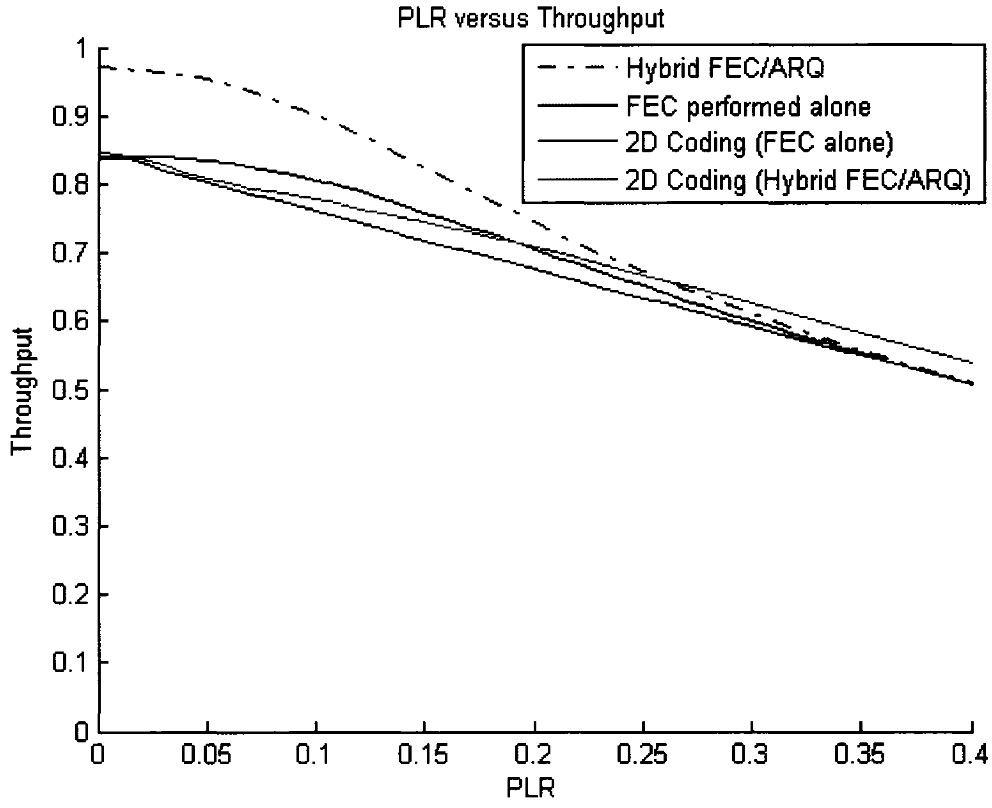


Figure 4.2: PLR versus Throughput for a Single Hop Network Using a 2-D R-S Packet Erasure Correction Code.

4.2.2 Delay Analysis

The packet delivery delay $D_{FEC,2D}$ for a best effort single hop network with a 2-D R-S FEC alone erasure recovery scheme is given by:

$$D_{FEC,2D} = (n + z - 1)T \qquad (38)$$

where:

n, T, and z are defined as in *(19)*.

Comparing *(35)* to the expression for the delay in a 1-D FEC alone scheme, it can be seen that the packet delivery delay in a pure 2D FEC scheme is greater by a scaling factor: $\frac{n+z-1}{\left\lceil \frac{n}{q} \right\rceil + z - 1}$.

Fig. 4.3 shows the delay analysis for the case where there is only one viable path from the source to the destination. Fig. 4.4 represents a delay analysis where there are ten viable paths from the source to the destination. In this analysis, the network assumptions made in Section 3.1.2.2 for the case of a single hop network with a one dimensional R-S product code are used here.

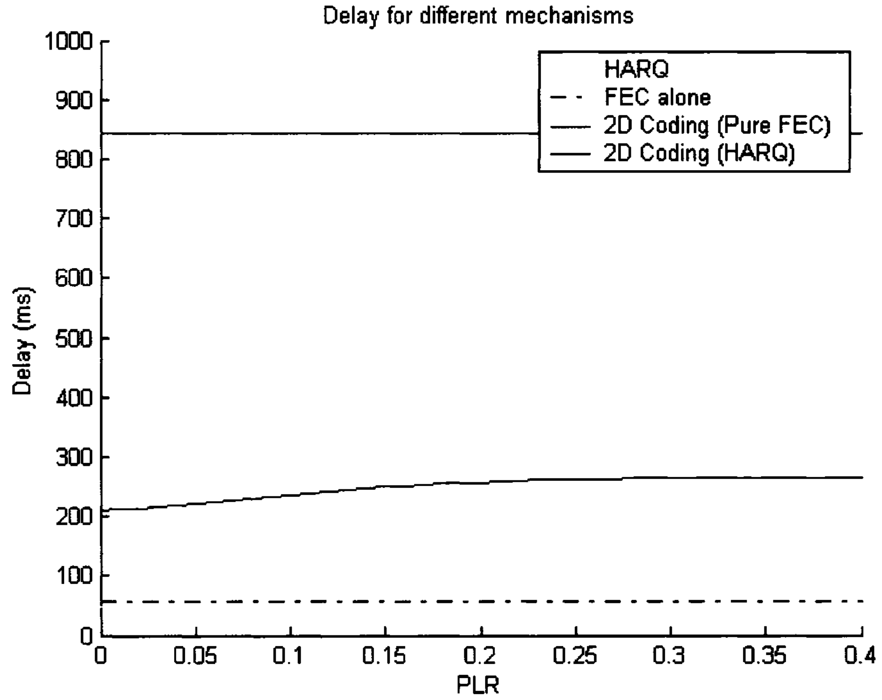


Figure 4.3: Delay Analysis of a Single Hop Network with a 2D Packet Erasure Code (q = 1).

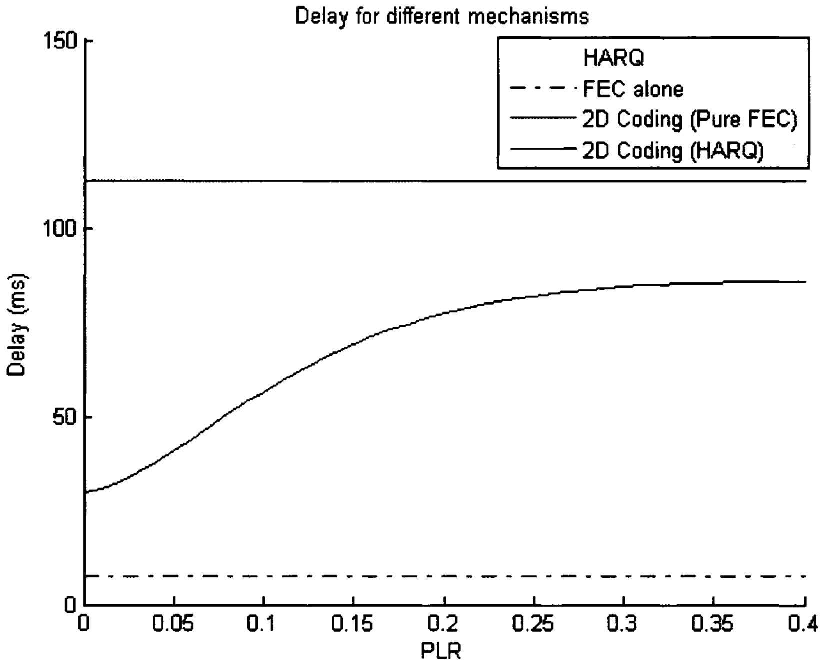


Figure 4.4: Delay Analysis of a Single Hop Network with a 2D Packet Erasure Code (q = 10).

In both figures 4.3 and 4.4, the packet delivery delay for the hybrid FEC/ARQ method for two dimensional R-S Product Codes is less than the delay for the 2-D FEC alone method. This differs from the 1-D case, where when there are ten available paths from the source to the destination, the delay for the hybrid FEC/ARQ method is greater.

However, examination of the above figures indicates that the decoding delay is much greater for 2-D coding. The marginal increases in throughput that are obtained in using 2-D HARQ based packet erasure recovery are not worth the huge increase in decoding delay. In conclusion, it is found that using a 1-D HARQ packet recovery mechanism is optimal for single hop wireless networks.

4.3 Two Dimensional R-S Product Codes in Multi-Hop Networks

This section discusses two dimensional R-S product codes in multi-hop mobile ad hoc networks. In this analysis, the network conditions are assumed to be the same as that given in Section 3.1.2.2. A throughput analysis is performed where packet erasure correction is performed only at the destination node. Another throughput analysis is performed where the regenerating node concept is employed, and packet erasure correction is performed at every intermediate node from the source to the destination.

4.3.1 Throughput Analysis

In this section, a throughput analysis of two dimensional R-S product codes is conducted for a multi-hop network where there are five hops from the source to the destination. Section 4.3.1.1 shows the results of this analysis where packet erasure correction is performed only at the destination. Section 4.3.1.2 shows the results of this analysis where packet erasure correction the regenerating node concept is employed, and packet erasure correction is performed at every node from the source to the destination.

4.3.1.1 Packet Erasure Correction Only at Destination

The results of a throughput analysis of a 2-D R-S product codes in a multi-hop network with five hops from the source to the destination are shown in Fig. 4.5.

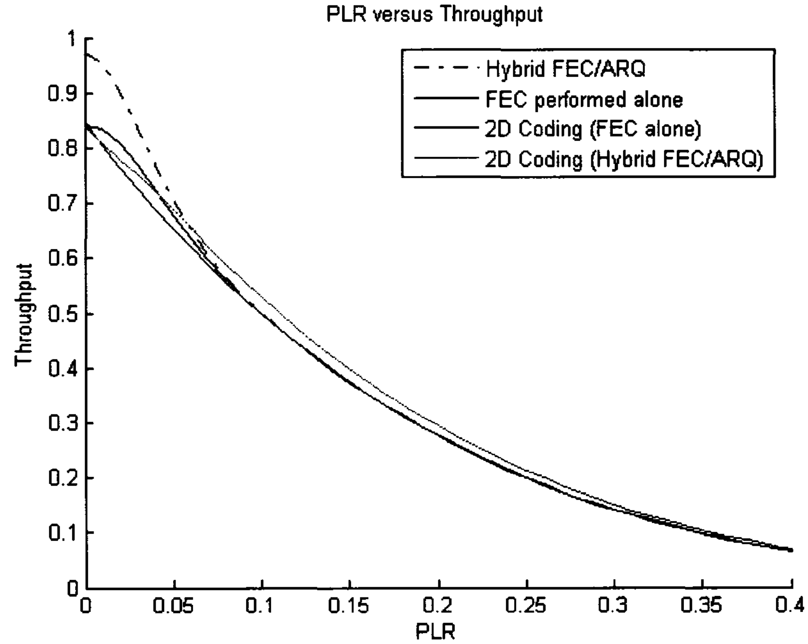


Figure 4.5: Throughput Analysis of a Multi-hop Network with a 2D Packet Erasure Code.

Examining Fig.4.5 it can be seen that in terms of throughput, 1-D R-S packet recovery outperforms 2-D R-S packet erasure recovery when no ARQ mechanism is present. However, when the PLR > 7%, 2-D R-S HARQ packet erasure recovery has a greater throughput than 1-D R-S HARQ packet recovery. However, as it is shown in the next section, the delay between these schemes is not comparable, and delay should also be a factor of consideration when deciding which packet erasure recovery mechanism to incorporate.

4.3.1.2 Packet Erasure Correction Performed at Every Node

The results of a throughput analysis where packet erasure correction is performed at every node are given in this subsection for two dimensional R-S packet erasure recovery.

Figure 4.6 shows the packet loss rate versus throughput for a multi-hop network, where there are five hops from the source to the destination. It should be noted that this plot is identical to Fig.4.2, where Fig.4.2 represents the same network conditions, but for a single hop. The throughput performance is identical, but the delay is prohibitively larger for the multi-hop scenario. In this work a prohibitively large delay is defined as a delay greater than 150ms.

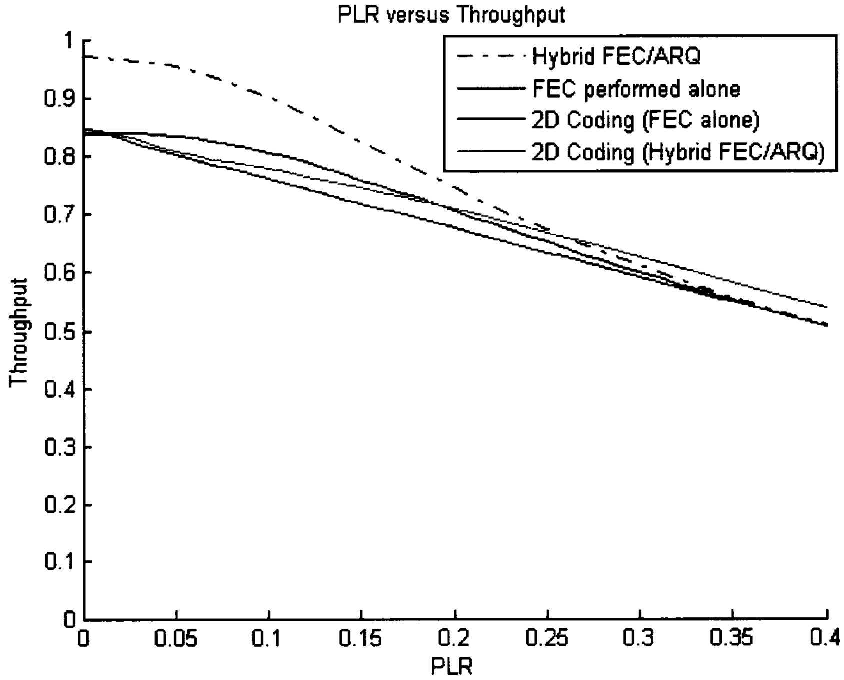


Figure 4.6: Throughput Analysis of a Multi-hop Network with a 2-D R-S Code (hops = 5).

As fewer regenerating nodes are employed, Fig.4.6 begins to converge towards Fig.4.2. The conclusion that can be drawn is that for a multi-hop network, as more regenerating nodes are employed from the network source to the destination, the range for which two dimensional coding is practical decreases. However, as with the case of a single hop network, the throughput advantage of 2-D HARQ over 1-D HARQ is marginal.

4.3.2 Delay Analysis

This subsection presents the delay analysis of using a two dimensional R-S product code for packet erasure recovery in multi-hop networks. Two scenarios are examined: Regeneration only being performed at the destination in Section 4.3.2.1, and Regeneration performed at every node in Section 4.3.2.2.

4.3.2.1 Regeneration is Performed Only at the Destination

The delay for the hybrid FEC/ARQ method for two dimensional R-S Product Codes is greater than the delay for the pure FEC method for two dimensional R-S Product Codes.

In this analysis, the network assumptions made in Section 3.1.2.2 for the case of a single hop network with a two dimensional R-S product code are used here. In this case, regeneration is performed only at the destination.

The expression for delay in a multi-hop network where a two dimensional R-S product code is employed is given by $D_{2D,FEC}$:

$$D_{2D,FEC} = (n + (z)(hops) - 1))\left(\frac{PL}{R} + \frac{d}{c}\right) \tag{39}$$

Comparing this expression to the expression for the delay in a pure 1-D FEC scheme for multi-hop networks given in Section 3.2.2.2, it can be seen that the delay in a pure 2-D FEC scheme is greater by a scaling factor: $\dfrac{n + (z)(hops) - 1}{\left\lceil \dfrac{n}{q} \right\rceil + (z)(hops) - 1}$.

Figure 4.7 shows a delay analysis of a multi-hop network with a 2-D Packet Erasure Code, where there are ten viable paths per hop, and five hops from the source node to the destination node.

Again, the delay for the hybrid FEC/ARQ method for two dimensional R-S Product Codes is less than the delay for the pure FEC method for two dimensional R-S Product Codes. Also, it should be noted that this delay is a scaled delay of the single hop case, where the scaling factor is equal to the number of hops. This scaling factor is equal to five in this case. The delay is significantly more for the multi-hop case than as for the single hop case, so even though there are throughput improvements for the case of using regeneration at every node, it is not practical to do so, in terms of the decoding delay that is experienced by such a mechanism. For example, in Fig.4.7, it can be seen that the maximum delay in sending a packet from the source to the destination is equal to 570ms, which is well beyond the standard real time maximum tolerable delay of 125ms.

As fewer regenerating nodes are employed, Fig.4.7 begins to converge towards Fig.4.4. The conclusion that can be drawn is that for a multi-hop network, as more regenerating nodes are employed from the network source to the destination, the delay that is experienced increases to the maximum delay case, where regeneration is performed at every node.

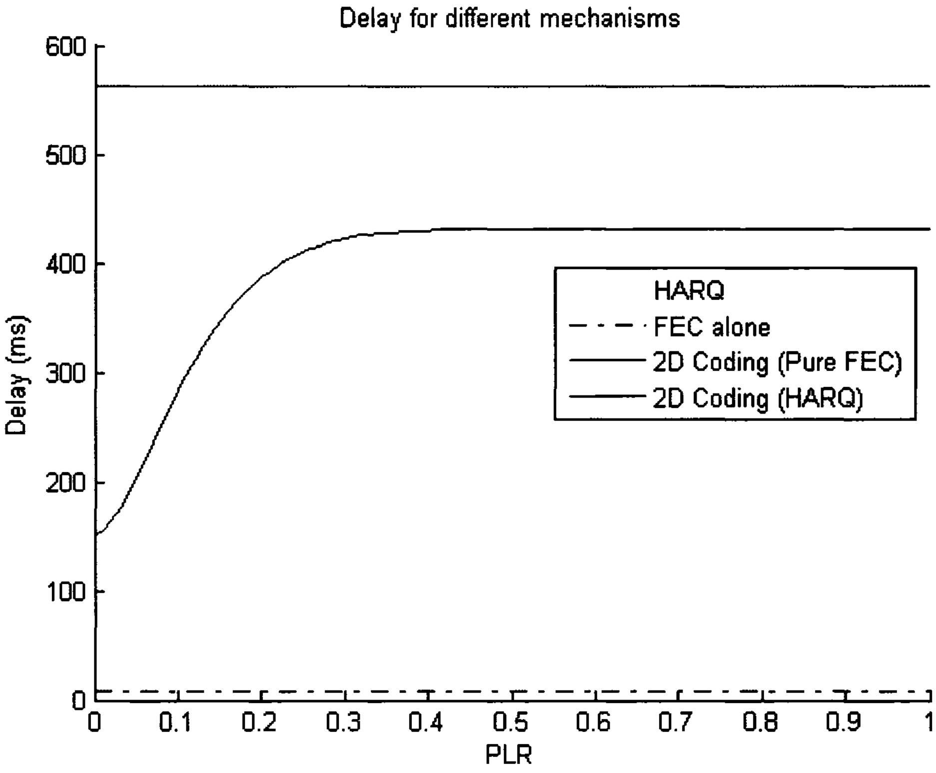


Figure 4.7: Delay Analysis of a Multi-Hop Network with a 2-D R-S Code (q = 10, hops = 5).

4.3.2.2 Regeneration is Performed at Every Node

The expression for packet delivery delay in a multi-hop network where a two dimensional R-S product code is employed for regeneration at every node is given as, $D_{REG,2D}$:

$$D_{REG,2D} = (n + (z)(hops) - 1 + (n-1)(hops-1))\left(\frac{PL}{R} + \frac{d}{c}\right) \tag{40}$$

Comparing this expression to the expression for the delay in a pure 1D FEC scheme for multi-hop networks given in Section 4.2.2, it can be seen that the delay in a pure 2D FEC scheme is greater by a scaling factor:

$$\frac{(n+(z)(hops)-1+(n-1)(hops-1)}{(\left\lceil \frac{n}{q} \right\rceil + (z)(hops) - 1 + (\left\lceil \frac{n}{q} \right\rceil - 1)(hops-1)}$$

4.3.3 Proper Regenerating Node (RN) Selection Scheme Using 2-D R-S Product Codes

In terms of using two dimensional R-S product codes, the delay is significantly more for the multi-hop case than for the single hop case. So, even though there are throughput improvements for the case of using regeneration at every node, it is not practical to do so, in terms of the decoding delay that is experienced by such a mechanism. This emphasizes the requirement for a proper regenerating node selection scheme. This selection scheme needs to properly address the tradeoff between delay and throughput, as specified by the Quality of Service (QoS) requirements of the network in question.

In [Ma2003], it was stated that the best regenerating node selection scheme was having the regenerating nodes evenly spread out across the intermediate nodes from the source to the destination. This scheme although superior in terms of throughput does not compensate for the prohibitive decoding delays that could result. It is found that the optimal regenerating node selection scheme is to use n regenerating nodes, where n is the maximum number the end to end decoding delay QoS limit will allow. To achieve the most benefit with these n regenerating nodes, they should be evenly spaced from the source to the destination. The focus of the work in [Ma2003] was on 1-D packet erasure recovery codes. However, upon completing simulations under a number of topologies, it was determined that this evenly spaced regenerating node selection scheme also yields the best throughput and delay performance for networks where regenerating nodes and the destination node both have 2-D packet erasure recovery.

4.3.4 Load Balancing Effects on R-S Erasure Correction Mechanisms

Load balancing effects in multi-hop networks are examined in terms of two scenarios: (i) encapsulated 1-D coding, and (ii) 2-D coding. Figure 4.8 illustrates the concept of load balancing with encapsulated 1-D coding, while Fig.4.9 illustrates load balancing in 2-D multi-hop networks. Figure 4.10 shows simulation results illustrating the end-to-end PLR for both of the fore mentioned load balancing schemes. The results are compared to encapsulated 1-D coding as this was the coding mechanism that was found to be most superior in [Ma2003]. Also, both of these schemes involve the same coding rate as the same net number of information packets and redundancy packets are used in both mechanisms. Examining Fig.4.10, it can be seen that 2-D coding does offer some improvement over the corresponding 1-D counterpart when coding gains are fairly compared. In performing extensive Monte-Carlo simulations, it was found that this conclusion does not vary when the topology of the network is changed and the coding rate used in the comparison is changed. Here 1-D coding is performed at the regenerating nodes, and the 2-D coding is performed only at the destination. This limits the prohibitive decoding delay that is associated with 2-D coding to only the destination.

In this scenario as shown in Fig.4.9, code 1 runs in the horizontal direction first to generate the red redundancy packets to be used at the destination in conjunction with 2-D coding. The green packets are then constructed to be used for 1-D coding at the intermediate nodes. By isolating the 2-D coding to the destination, and by using multiple paths via load balancing, it was found that 2-D can offer a benefit over pure 1-D FEC systems, as can be seen in Fig.4.10.

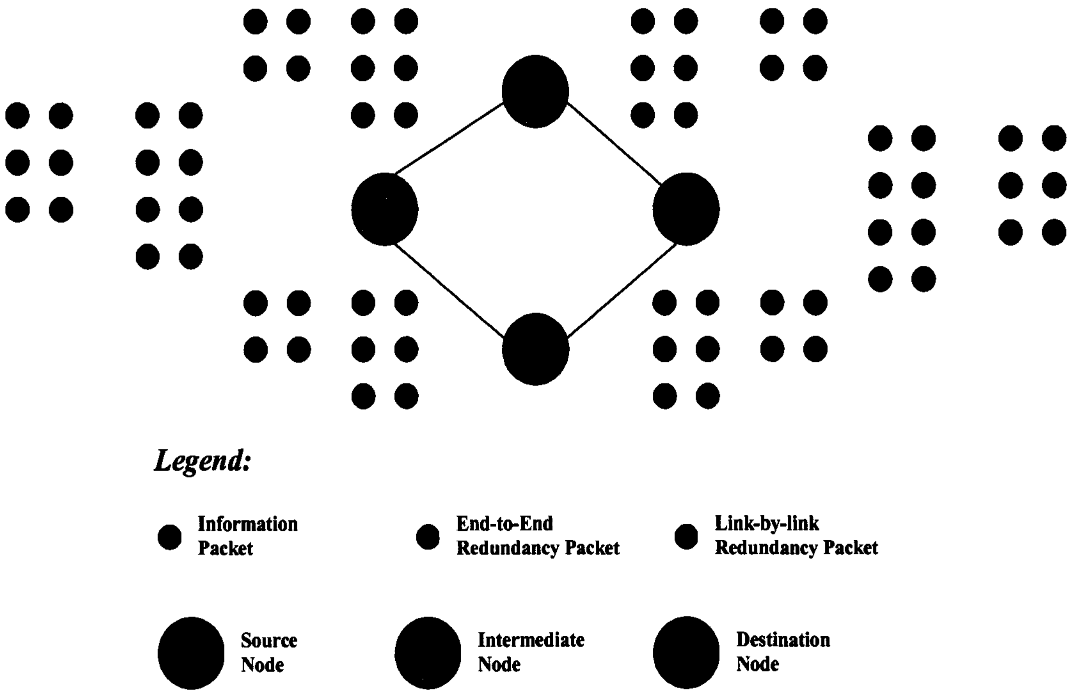


Figure 4.8: Encapsulated 1-D Coding.

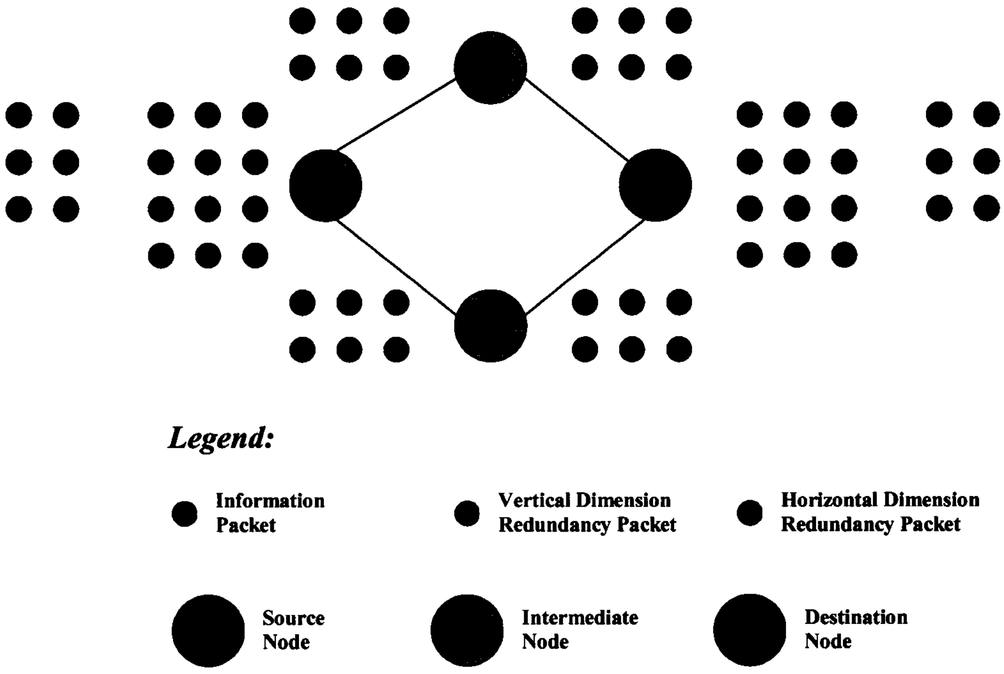


Figure 4.9: 2-D Coding.

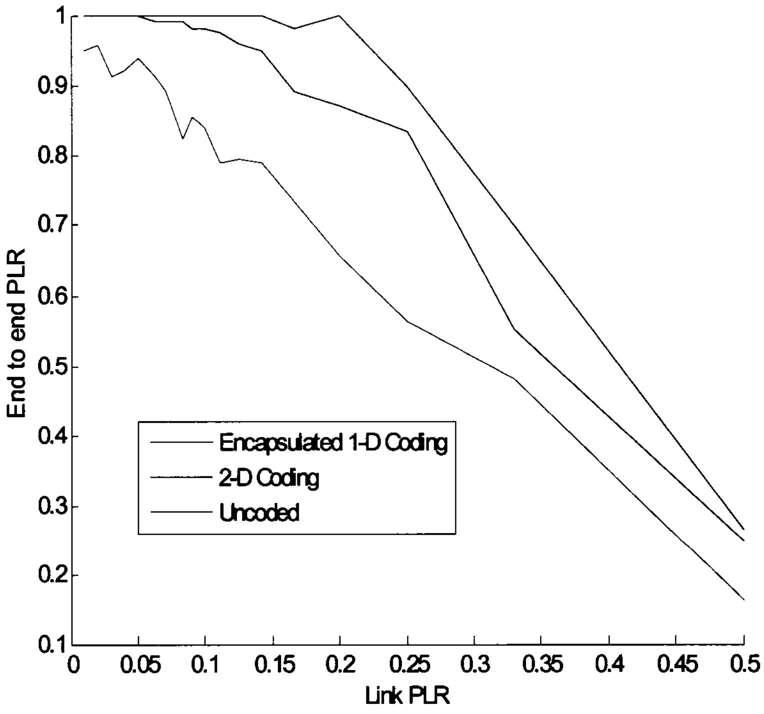


Figure 4.10: End to end PLR Comparison Between Load Balancing Schemes.

4.4 Summary

This chapter examined the application of 2-D R-S product codes in wireless networks to recover from lost packets. The motivation for using two dimensional R-S product codes was discussed. The application of two dimensional R-S product codes to single hop and multi-hop wireless networks was also analyzed in this chapter.

The fundamental tradeoff between delay and throughput was again confirmed for two dimensional product codes. Initially, the majority of the work in this chapter involved 2-D erasure correction functionality at the regenerating nodes, as well as the destination. However, in terms of using 2-D R-S product codes, the delay is significantly more for the multi-hop case than for the single hop case. So, even though there are throughput improvements for the case of using 2-D based regeneration at every node, it is not practical to do so, in terms of the decoding delay that is experienced by such a mechanism.

A proper regenerating node selection scheme can properly address the tradeoff between delay and throughput, as specified by the QoS requirements of the network in question. It is found that the optimal regenerating node selection scheme is to use n regenerating nodes, where n is the maximum number the end to end decoding delay QoS limit will allow. To achieve the most benefit with these n regenerating nodes, they should be evenly spaced from the source to the destination.

Additionally, it is should be noted that two dimensional packet erasure decoding coupled with hybrid FEC/ARQ will provide marginal throughput improvements. However these throughput improvements are at the cost of large increases in decoding delay. However, when minimizing where the 2-D coding takes place as with the load balancing scheme shown in Section 4.3.4, 2-D coding can be used to achieve throughput gains with minimized increases in decoding delay.

Chapter 5

Conclusions and Future Work

This chapter presents the conclusions and future work for this thesis.

5.1 Conclusions

The focus of this thesis was on introducing different configurations of packet level FEC to aid the operation of ARQ at the higher layer than that of the packet level FEC.

Two implementations of packet level FEC were initially pursued. In the first case, the transmission unit of the packet level FEC was at the same layer as the ARQ. In the second case, the transmission unit of the packet level FEC was shorter than that of the ARQ. When comparing the throughput performance between the two cases, it was found that a sub-layer to the network layer in reliable single hop networks may offer benefits in terms of throughput depending on the interpretation of protocol overhead at this sub-layer. When the overhead associated with the FEC sub-layer is negligible or does not have to be accounted for as it is in the case of the data link layer, an improved throughput performance is obtained in the proposed scheme for a raw PLR of 10%. In the pessimistic approach, when the header overhead at the FEC packet layer is comparable to that of the ARQ layer, the proposed scheme does not offer any benefit in terms of throughput improvement. This is because the overhead associated with the extra packets sent for this sub-layer mechanism reduces throughput too significantly.

In incorporating the regenerating node concept in multi-hop networks, it is beneficial to use a hybrid ARQ/FEC packet erasure correction mechanism, rather than an FEC alone packet erasure correction mechanism as was originally proposed. A hybrid FEC/ARQ mechanism; in the form of positive acknowledgements; offers improved throughput in 1-D erasure recovery schemes when compared to FEC alone 1-D erasure recovery schemes. This mechanism was first proposed in [Maj2002], and was developed to be used an end-to-end protocol at the transport layer. However, in this thesis, the hybrid FEC/ARQ mechanism is at the network layer, allowing it to be used at the intermediate nodes from the source to the destination. These improvements in throughput for this hybrid FEC/ARQ mechanism do not come at the cost of an increased delay. More significant throughput improvements are realized with a hybrid FEC/Selective Repeat ARQ mechanism incorporated into regenerating nodes. However, with a hybrid FEC/Selective Repeat ARQ mechanism, the packet group decoding delay is significantly more, hindering its practical used in better than best effort networks, where packet delay usually is critical.

It was found that 2-D R-S packet erasure correction coding can only give slight improvements in throughput when compared to 1-D coding schemes with the same coding rates. However, because 2-D R-S codes have significantly higher decoding delays associated with them, they are not effective in multi-hop wireless networks with regenerating node functionality. It was found that 2-D R-S codes are most effective when using a load balancing scheme like the one shown in Section 4.3.4. By using such a load balancing scheme, and isolating the 2-D coding to only the destination, throughput gains can be obtained with minimized increases in decoding delay.

Even though there are throughput improvements for the case of using regeneration at every node, it is not practical to do so in terms of the decoding delay that is experienced by such a mechanism. This emphasizes the requirement for a proper regenerating node selection scheme. This regenerating node selection scheme needs to properly address the tradeoff between delay and throughput, as specified by the QoS requirements of the network in question. It is found that the optimal regenerating node selection scheme is to use n regenerating nodes, where n is the maximum number the end to end decoding delay QoS limit will allow. To achieve the most benefit with these n regenerating nodes, they should be evenly spaced from the source to the destination. This was verified to be true for both 1-D and 2-D R-S packet erasure recovery schemes.

5.2 Future Work

All simulations up to this point have been done using MATLAB software and running C programs. The results presented were obtained using analytical expressions for erasure recovery in different FEC codes, and for throughput performance in different implementations of ARQ. The results were later verified using Monte-Carlo simulations. It is recommended that these results be complemented using OPNET or NS-2 network modeling software, so as to more accurately model the protocol interactions that may take in networks with more realistic topologies.

Queuing models should be incorporated into the delay analysis of multi-hop networks, where currently it is not considered in this thesis. Models as seen in [BiA2006] would be appropriate for this kind of analysis.

For future work, a delay analysis could be performed for a reliable single hop and multi-hop networks, where the packet erasure correction mechanism at the network layer of the protocol stack is:

1. Selective Repeat ARQ alone
2. Hybrid FEC, Selective Repeat ARQ
3. Hybrid FEC, Go Back N ARQ
4. Go Back N ARQ alone

It is recommended that a throughput analysis be performed on reliable multi-hop networks, where the focus of this thesis was on better than best effort multi-hop networks.

An examination of R-S coding to correct for symbol erasures within the transmitted packets could be examined in conjunction with the regenerating node concept at the packet level.

Bibliography

[Leo2000] Leon-Garcia, A., Widjaja, I., *Communication Networks,* McGraw-Hill, 2000.

[Lee2000] Lee, L., *Error-Control Block Codes for Communications Engineers,* Artech House, 2000.

[Mor2002] Morelos-Zaragoza, R., *The Art of Error Correcting Coding,* John Wiley & Sons, 2002.

[Ple2003] Pless, V.S., Huffman, W.C., *Fundamentals of Error-Correcting Codes,* Cambridge University Press, 2003.

[Moo2005] Moon, T.K., *Error Correction Coding: Mathematical Methods and Algorithms,* John Wiley & Sons, 2005.

[Wic1995] Wicker, S.B., *Error Control Systems for Digital Communication and Storage,* Englewood Cliffs: Prentice Hall, 1995.

[Swe2002] Sweeney, P., *Error Control Coding from Theory to Practice,* John Wiley & Sons, 2002.

[Lin2004] Lin, S., Costello,Jr., D., *Error Control Coding, Second Edition*, Prentice Hall, 2004.

[MaI2003] Ma, R., Ilow, J., "Reliable multipath routing with fixed delays in MANET using regenerating nodes," in 28th Annual IEEE International Conference on Local Computer Networks, Bonn/Konigswinter, Germany, 2003, pp.719–725.

[MaI2004] Ma, R., Ilow, J., "Regenerating Nodes for Real-Time Transmissions in Multi-Hop Wireless Networks," in 29th Annual IEEE International Conference on Local Computer Networks, Tampa, Florida, USA, 2004, pp.378-384.

[Maj2002] Majumdar, A., Sachs, D.G., Kozintsev, I.V., Ramchandran, K., Yeung, M.M., "Multicast and Unicast Real Time Video Streaming over Wireless LANs", IEEE Trans. Circuits Syst. Video Technol., vol. 12, pp. 524-534, 2002.

[Kos2002] Kostas, T., Jordan, S., "Packet Erasure FEC on ARQ Protocols", Proceedings of SPIE, vol.4866, pp.126-137, 2002.

[Al-S2006] Al-Shaikhi, A.A., Ilow, J., "Erasure Rate Analysis and Tighter Upper Bound for Binary Product Codes", IEEE Communication Letters, vol. 10, issue 7, 2006.

[Khe2004] Kherani, A., Shorey, R., "Throughput Analysis of TCP in Multi-Hop Wireless Networks with IEEE 802.11 MAC," in Proceedings of IEEE Wireless Communications and Networking Conference, Atlanta, GA, 2004.

[Ma2003] Ma, R.,"Regenerating Nodes for Real-time Transmissions in Mobile Ad Hoc Networks", Dalhousie University, M.A.Sc Thesis, Halifax, NS, Canada, 2003.

[McA1990] McAuley, A.J., Reliable broadband communication using a burst erasure correcting code, Proceedings of the ACM symposium on Communications architectures & protocols, 1990, Pages 297 – 306.

[Non1998] Nonnenmacher, J.; Biersack, E.W.; Towsley, D., Parity-based loss recovery for reliable multicast transmission, Networking, IEEE/ACM Transactions on Volume: 6, Page(s): 349 -361, 1998.

[Yao1995] Yao, Y., "An effective go-back-N ARQ scheme for variable-error-rate channels", IEEE Transactions on Communications, vol.43, issue 1, pp. 20-23, 1995.

[Skl1988] Sklar, B., *Digital Communications : Fundamentals and Applications*, Prentice-Hall, 1988.

[Rap1996] Rappaport, T.S., *Wireless Communications - Principles & Practice*, IEEE Press, 1996

[BiA2006] Bisnik, N., Abouzeid, A., "Queuing Network Models for Delay Analysis of Multihop Wireless Ad Hoc Networks", in proceeding of the 2006 International Conference on Communications and Mobile Computing (IWCMC'06), Vancouver, British Columbia, Canada ,2006, pp.773-778.

[Che2004] Chen, Y., Farley, T., and Ye, N., "Qos Requirements of Network Applications on the Internet", Information, Knowledge, and Systems Management, 4:1, 2004, pp.55-76.

[Gar1996] Garg ,V., Wilkes, J., *Wireless and Personal Communications Systems*, Prentice Hall, 1996.

[Dra2004] Draves, R., Padhye, J., Zill, B., "Routing in Multi-Radio, Multi-hop Wireless Mesh Networks", in proceedings of the 10th Annual International Conference on Mobile Computing and Networking (MobiCom'04) ,Philadelphia, PA, USA, 2004, pp.114-128.

[Lin1984] Lin, S., Costello, D., Miller, M., "Automatic-repeat-request error-control schemes", IEEE Communications Magazine, vol.22, issue 12, pp.5-17, 1984.

[Gib2002] Gibson, J., *The Communications Handbook*, Second Edition, CRC, 2002.

[Wic1999] Wicker, S., Bhargava, V., *Reed-Solomon Codes and Their Applications*, Wiley-IEEE Press, 1999.