TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

THESIS NO.: 069/MSCS/652

A Cooperative Scheme for Collision Resolution in Data Networks

by
Bharat Sharma

A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRONICS AND COMPUTER ENGINEERING IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN COMPUTER SYSTEM AND KNOWLEDGE ENGINEERING

DEPARTMENT OF ELECTRONICS AND COMPUTER ENGINEERING
LALITPUR, NEPAL

NOVEMBER, 2016

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer System and Knowledge Engineering

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November, 2016

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Recommendation

The undersigned certify that they have read and recommended to the Department of Electronics and Computer Engineering for acceptance, a thesis entitled **“A Cooperative Scheme for Collision Resolution in Data Networks”**, submitted by **Bharat Sharma** in partial fulfillment of the requirement for the award of the degree of **“Master of Science in Computer System and Knowledge Engineering”**.

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The thesis entitled **“A Cooperative Scheme for Collision Resolution in Data Networks”** submitted by **Bharat Sharma** in partial fulfillment of the requirement for the award of the degree of “**Master of Science in Computer System and Knowledge Engineering**” has been accepted as a bonafide record of work independently carried out by him in the department.

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ACKNOWLEDGMENT

It is a great pleasure for me to acknowledge the assistance and contributions of many individuals in making this thesis a success. I would like to extend thanks to many people who played an important role in accomplishing this thesis work. First and foremost, I would like to thank my supervisor, **Prof. Dr. Shashidhar Ram Joshi** for his assistance, ideas, and feedbacks during the process in doing this thesis. Without his guidance and support, this work cannot be completed.

Secondly, I would like to express my sincere gratitude to our Head of Department **Dr. Dr. Dibakar Raj Pant**, Prof **Dr. Subarna Shakya**, **Dr. Aman Shakya**, **Dr. Sanjeeb Prasad Panday** for their encouragement and precious guidance during the thesis work. I would like to thank Department of Computer and Electronics, Pulchowk Campus for providing the opportunity to have a thesis.

I also wish to thank my classmates and friends who have helped in completing this thesis work.

Lastly, I wish to express my sincere gratitude to my family for their encouragement and moral support.

ABSTRACT

Cooperative communication is one of the latest techniques in wireless communication to form virtual antenna arrays. Cooperative communication is an alternative method for MIMO (Multiple input multiple output) system. Cooperative cross-layer techniques are studied in the collision resolution areas of data networks. Generally rate limited traffic and bursty traffic is analyzed considering the use of channels and random subchannel selection scheme respectively. In this report, a concept of cooperative scheme C based on the feedback mechanism is explored. It is used in cooperative communication in order to attain efficient use to overcome bandwidth inefficiency.

Keywords: Collision Resolution, Cross Layer, Scheme C, Cooperative Communication

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ALLIANCES	ALLow Improved Access in the Network via Cooperation and Energy Savings
AP	Access Point
BS	Base Station
CDMA	Code Division Multiple Access
CR	Collision Resolution
CSMA	Carrier Sensing Multiple Access
CSMA/CD	Carrier sensing Multiple Access with Collision Detection
CSMA/CA	Carrier sensing Multiple Access with Collision Avoidance
CTE	Cooperative Transmission Epoch
MAC	Medium Access Control
MIMO	Multiple-Input Multiple-Output
NDMA	Network Assisted Diversity Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
PHY	Physical Layer
RTS	Request To Send
SNR	Signal to Noise Ratio

CHAPTER I

INTRODUCTION

1.1 BACKGROUND

In recent years the communication technology has developed exponentially in order to meet user needs. Cooperation and cross-layer design are two emerging techniques for improving the performance of wireless networks. Cooperative communication helps to achieve a very high data rate.

1.1.1 Cooperation in data networks

It is well known that multiple-input multiple-output (MIMO) systems can significantly improve the performance of wireless systems, e.g., increase data rate, reduce interference, and improve link reliability. However, due to the cost, size or hardware limitations, multiple antennas are not available at network nodes in many scenarios. For such scenarios, user cooperation can create a virtual MIMO system and thus enable a single-antenna user to enjoy the benefits of MIMO systems. Transmissions via cooperation can be typically modeled as a traditional relay channel.

The first type of relaying strategy is referred to as fixed relaying, in which the relay transmits all of the times. In fixed relaying, the source first transmits its message to the destination; the relay overhears the message due to the broadcast nature of the wireless channel. Then, the relay forwards the message to the destination in either a “decode-and-forward” (DF) or, an “amplify-and-forward” (AF) fashion. The destination then appropriately combines the signals from the two transmissions (from the source and from the relay, respectively) to decode the message. Note that, during the relay forwarding, the source may also retransmit its message at the same time. In the DF scenario, the relay first decodes its received signal, and then forwards the decoded message to the destination. In the AF scenario, the relay amplifies the received signal and then forwards it to the destination. As compared with DF, AF has a lower complexity, as the relay does not decode the message. However, the noise at the relay is also amplified and thus AF typically achieves worse performance than DF. It is easy to see that the transmission time in fixed relaying is longer as compared to direct transmission without relaying.

Another type of relaying strategy is referred to as incremental relaying, in which the relay is used only if the initial transmission from the source to the destination fails. In incremental relaying, the source first transmits its message to the destination. Then, the destination decodes the received message and indicates successful or unsuccessful decoding by broadcasting a single bit of feedback to the source and the relay, which is assumed to be detected reliably by at least the relay. If the source-destination link is sufficiently good and leads to successful decoding, the feedback indicates the success of the direct transmission, and the relay does nothing. Otherwise, the feedback indicates an unsuccessful decoding and the relay forwards the signal that it received from the source in a DF or AF fashion. At the destination, both the source and relay transmissions are combined for decoding. Incremental relaying can be viewed as a variant of automatic repeat request or incremental redundancy.

1.2 MOTIVATION OF THE THESIS

It can be expected that the use of both cross-layer techniques and cooperation could further enhance the performance of wireless networks. In this thesis, my particular emphasis is on cross-layer approaches to collision resolution problem.

Future wireless network will need to accommodate multimedia traffic which is bursty and has diverse quality of service (QoS) requirements. Fixed bandwidth allocation schemes are inefficient for such traffic. Random access (RA) schemes have been shown to be effective for bursty traffic at low to moderate traffic loads. For a long time, the networking literature has focused on collision avoidance schemes. When collisions do occur, i.e., multiple users access the channel at the same time, the collided packets are discarded and users have to retransmit at a later time. By borrowing signal detection/separation techniques, a network assisted diversity was proposed in [1] for collision resolution. According to the method named network-assisted diversity multiple access (NDMA), in the event of a K-fold collision, the collided users are required to keep retransmitting their packets during K - 1 slots following the collision slot. Combining the originally collided packets and their retransmissions, the base station (BS) formulates a MIMO problem to recover the collided packets. NDMA requires the channel to change between slots, which are valid in low-rate communications only. In [2], a scheme named ALLIANCES was proposed for solving the same problem, which works even in the case of a completely static channel. It relies on cooperative diversity as well as time diversity, where the cooperative diversity is introduced through the use of relays [3]. The cooperative medium access protocol was developed for a flat fading channel. However, in a situation of practical interest, the broadband wireless channel is usually frequency selective. Furthermore, the initial cooperative medium access protocol assumes that all transmitted packets use the same modulation and coding scheme and all wireless traffic has the same priority and quality of service (QoS), and thus does not take into account heterogeneous traffic with diverse QoS requirements which degrades the performance of the systems.

1.3 OBJECTIVE OF THE THESIS

The main objective of this thesis is to analyze and improve collision resolution in data networks in order to achieve better performance of the system. In order to achieve the objective of the thesis MATLAB software is used.

1.4 CONTRIBUTION OF THE THESIS

A multichannel extension of cooperative protocol, which is a PHY-MAC cross-layer cooperative protocol for collision resolution in data networks, is presented. At the PHY layer, the considered approach is based on orthogonal frequency division multiple access (OFDMA). At the MAC layer, various schemes for subchannel allocation depending on the types of the wireless traffic are considered. A new scheme C is considered which attempts to drastically improve the performance of the traditional system

1.5 OUTLINE OF THE THESIS

Chapter 1 provides the introduction where brief background and motivation of this thesis are illustrated. Followed by the objective is the contribution of the thesis.

Chapter 2 reviews the literature, which includes literature survey of different IEEE journals and papers. Besides, a brief description of cooperative MAC protocol has also been covered.

Chapter 3 describes the methodological processes by showing detailed system model of the methods implemented as well as highlighting briefly the steps those have been followed to achieve the objective of this thesis.

Chapter 4 presents the results derived from the methods explained where simulations were done based on cross-layer cooperative MAC protocol.

Chapter 5 provides the summary and conclusions of this thesis, as well as some suggestions for future work are summed up.

CHAPTER II

LITERATURE REVIEW

2.1 GENERAL SURVEY

Future wireless networks are complex extensions of cellular networks. They will need to accommodate multimedia services such as video, teleconferencing, internet access, and voice communications. Multimedia sources have diverse bandwidth requirements and are bursty in nature, thus fixed bandwidth allocation schemes are inefficient for them. Simple medium access schemes for bursty sources include random access methods. An example of such system is the slotted ALOHA [5], which allow users to transmit in an uncoordinated fashion every time they have a packet to transmit. Being a connectionless system ALOHA does not require overhead for connection establishment before each transmission. The reason behind the throughput limit of these systems is the fact that traditional media access control (MAC) layer design cannot handle multiple packets without declaring a collision, in which case the packets that collided are totally discarded. The reservation based ALOHA can achieve higher overall throughput. However, it suffers performance loss during the reservation slot, since during that slot a slotted ALOHA approach is applied.

The IEEE 802.11 standard, which is the most widely implemented protocol, defines the MAC mechanism as a Distributed Coordination Function, which is basically a Carrier-Sensing Multiple Access with Collision Avoidance (CSMA/CA) mechanism. To overcome the hidden node problem, the IEEE 802.11 incorporates a positive acknowledgment scheme, i.e., Request To Send (RTS) followed by Clear To Send (CTS). CSMA/CA together with RTS/CTS has been central in several other protocols as well. Examples include the Multiple Access with Collision Avoidance Wireless approach in [5]. In the mentioned protocols, the collisions more frequently occur as the traffic load increases. As a result, the RTS/CTS scheme becomes less effective because collisions of the short RTS reservation packets occur. To overcome this problem, a time-division multiple access (TDMA)-based channel reservation method was proposed in [4], where the RTS short packet is transmitted in a TDMA fashion. Although this was shown to be more effective than an ALOHA-type reservation scheme under high traffic load, it is not efficient under low traffic load or when the network population is large. The maximum attainable throughput for the MAC of IEEE 802.11a/b/g is typically 50% of the available bandwidth. Moreover, due to the random arrival nature of network traffic, the collisions cannot be completely avoided.

Another little studied drawback of traditional random access systems is the assumption that a collision is the only scenario under which a packet can get lost. However, in wireless communications, the wireless channel can create fading conditions that render the transmitted packet unreadable and thus effectively lost. In such cases, in the absence of an acknowledgment, the transmitter will interpret the silence as a collision and will retransmit. Since the channel can remain in deep fade over several slots, subsequent retransmissions can be unsuccessful and Wasteful of bandwidth. Collision resolution (CR) has been investigated from both the MAC and physical layer perspectives. Examples include the tree algorithm and capture effect, forward error control coding, spread spectrum, multiple receive antennas. As of very recently, several works appeared, suggesting that CR can be achieved with single antenna systems and without relying on coding. In [7] the diversity was provided by the network, thus the approach was referred to as network-assisted diversity multiple access (NDMA). According to [7], in a K-fold collision, the packets involved in the collision are not discarded but rather stored in memory and later combined with retransmissions initiated during the slots following the collision slot. In each of those slots, the receiver receives a linear mixture of the original packets, with the mixing coefficients depending on the wireless channel. Assuming that those mixtures are linearly independent, and assuming that the channel coefficients can be estimated using training data, one can setup a multiple-input–multiple-output (MIMO) problem, which can be solved for the originally transmitted packets. This scheme avoids the throughput penalty induced by collision, while it maintains the low delay benefit of random access protocols. However, the packet mixtures which are received during the retransmissions will be linearly independent only in the case of fading channels with coherence time in the order of the packet slot. This is not a very practical case since the channel coefficients are usually correlated over adjacent slots. Moreover, in this approach certain adverse effects of the channel cannot be mitigated; if the channel during a certain slot is in deep fade, it will most probably continue to be in deep fade over subsequent slots. This compromises the rank of the mixing matrix and leads to a degraded quality of service. Moreover, to avoid extra control overhead, the NDMA scheme requires that all collided users retransmit in each of the time slots following the collision, which may drain the battery power of users involved in high order collisions.

The concept of cooperative diversity was proposed in [8]. The users in the system act like distributed antennas, except that now these antennas are linked via the wireless channel. Each packet requires two slots for transmission. Each node transmits its own packet in the first slot, and a relay node forwards this packet in the second slot. These schemes are still based on the fixed bandwidth allocation where a certain channel or bandwidth is assigned to each node for the purpose of transmitting its packets or relaying other packets.

Recently a new cooperative media access control (MAC) protocol of random access wireless network was proposed in [5]. Due to that scheme, when there is a collision, the destination node (base station) does not discard the collided packets but rather saves them in a buffer. In the slots following the collision, a set of nodes designated as relays, form an alliance and forward the signal that they received during the collision slot. Based on these transmissions, the base station formulates a multiple-input multiple-output (MIMO) problem, the solution of which yields the collided packets. The method of [5], referred to here as ALLIANCES, maintains the benefits of ALOHA systems in the sense that all nodes share access to media resources efficiently and with minimal scheduling overhead, and enables efficient use of network power.

In this thesis, Multichannel cooperative MAC protocol - a multichannel extension of cooperative MAC protocol that can exploit multipath as well as cooperative and time diversity is presented.

2.2 COOPERATIVE MEDIUM ACCESS PROTOCOL

The cooperative medium access protocol scheme described in the context of cellular networks or wireless LAN, where a set of nodes, denoted by, $\mathcal{R} = \{1, 2, \dots \dots, J\}$, communicates with the Access Point (AP). Thus all the transmission initiated by a source node $i \in \mathcal{R}$ are directed to a single destination $d \notin \mathcal{R}$ which is the base station or the access point.

Consider a small-scale slotted multi-access system with J users, where each node can hear from a base station or access point (BS/AP) on a control channel. Link delay and online processing (packet decoding) time are ignored and all transmitters are assumed synchronized. Each user operates in a half-duplex mode. Every user and the BS/AP are equipped with only one antenna. All transmitted packets have the same length and each packet requires one time unit/slot for transmission. The system model is as shown in the figure below:

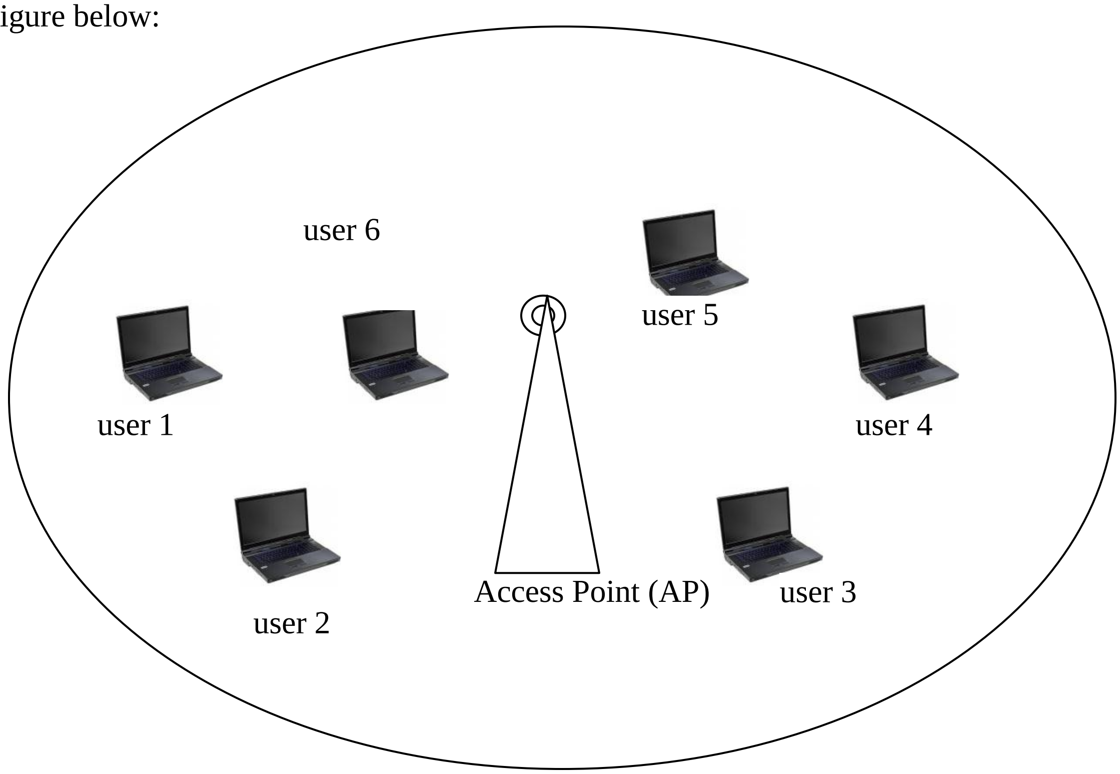


Fig 2.1: System Model

Let us consider a network with J nodes. Suppose that K packets have collided in the n-th slot. All nodes not involved in the collision enter a waiting mode and remain there until the collision is resolved. The collision resolution period is defined as a cooperative transmission epoch (CTE), beginning with the n-th slot. The AP will send a control bit to all nodes indicating the beginning of CTE and will continue sending this bit until the CTE is over.

Let the packet transmitted by the i-th node in slot n consist of N symbols, i.e., $x_i(n) = [x_{i,0}(n), \dots\dots, x_{i,N-1}(n)]$. Let $S(n) = \{i_1, \dots\dots, i_k\}$ be the set of sources and $\mathcal{R}(n) = \{r_1, \dots\dots, r_{\hat{k}-1}\}$, be the set of nodes that will serve as relays, and 'd' denotes the destination node. During the n-th slot, the signal heard by the AP and also the source node is:

$$y_r(n) = \sum_{i \in S(n)} a_{ir}(n)\, x_i(\text{n}) + w_r(n) \tag{1}$$

where, $r \in \{d\} \cup \mathcal{R}(n)$, $\text{r} \notin S(n)$, $a_{ir}(n)$ denotes the channel coefficient between the i-th node and the receiving node r; and $w_r(n)$ represents the noise.

Once the collision is detected, the AP sends a control bit, for example '1' to all the nodes indicating the beginning of a cooperative transmission epoch (CTE). The CTE consists of $\hat{k} - 1$ slots with $\hat{k} \geq K$. The BS keeps sending the same control bit in the beginning of each CTE slot. During slot $n + 1$, $1 \leq K \leq \hat{k} - 1$, one node is selected as a relay. The selection is based on the predetermined order, for example, each node computes the function $r = \text{mod}\,(n + K, J) + 1$, and the node which ID equals to r knows that it has to serve as a relay Due to the half duplex assumption, if the chosen node happened to be a source node during the collision slot, it will simply retransmit its own packet.

Thus, only one relay is active during each of the slots of the CTE. Nodes that are neither involved in the collision nor act as relays remain silent until the CTE is over. When the CTE is over the BS sends a '0' to all nodes, informing them of the end of the CTE. The received signal at the BS is

$$z_d(n+k) = \begin{cases} a_{rd}(n+k)x_r(n) + w_d(n+k), \\ \quad r \in \mathcal{R}(n) \cap S(n) \\ \\ a_{ir}(n+k)c(n+k)y_r(n) + w_d(n+k), \\ \quad r \in \mathcal{R}(n), r \notin S(n) \end{cases} \quad (2)$$

where, $z_d(n+k)$ is a 1 × N vector

$w_d(n+k)$ denotes the noise vector at the access point

$c(n+k)$ is the scaling constant

An example of this procedure for a collision of two users is as shown in the figure below:

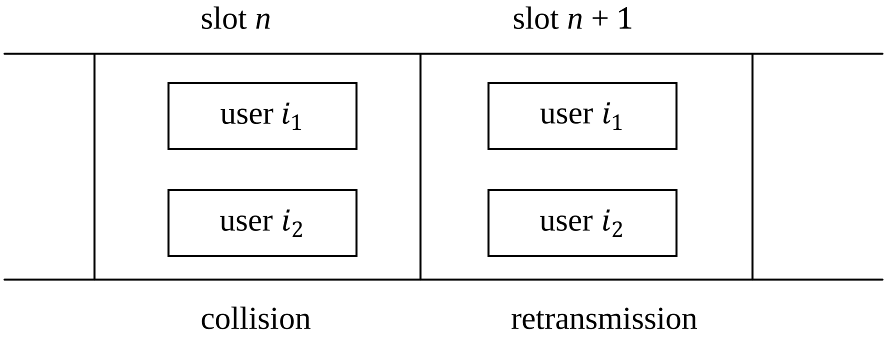


Fig. 2.2 Packet Collision and Retransmission

Let us define matrices X, whose rows are the signals sent by source nodes i.e. $x_{i_1}(n), \dots\dots, x_{i_k}(n)$, and Z, whose rows are the signals heard by the destination node during slots n, $n+1, \dots\dots$, $n+\hat{k}-1$, i.e. $z_d(n)$, $z_d(n+1)$, $z_d(n+\hat{k}-1)$ with $z_d(n) = y_d(n)$. Without loss of generality, let us assume that among the $\hat{k}-1$ nodes, the first l nodes are non-source relays nodes, while the next η nodes are the source relays, where, $l + \eta + 1 = \hat{k}$

The received signal at the destination can be written in matrix form as

$$\mathbf{Z} = \mathbf{H}\,\mathbf{X} + \mathbf{W} \quad (3)$$

where, the matrix **H** and **W** contains channel coefficients and noise respectively. Once, if the **H** i.e. the $\hat{k} \times K$ matrix is estimated, the transmitted packet can be obtained via maximum likelihood decoder.

The channel estimation and active user detection is done through the orthogonal ID sequences, s_i (i is the user index) that are attached to each packet as in [7]. The ID sequences are also used as pilots for channel estimation. At the BS, the correlation of the received signal and the ID sequences s_i, is performed.

Due to the orthogonality of the s_i's, it holds:

$$u_i(n) = z_s(n)\, s_i^H = \begin{cases} 0 & \text{user } i \text{ is absent} \\ 1 & user\ i\ is\ present \end{cases} \tag{4}$$

The collision order *K*, can be detected by comparing $|u_i(n)|$ to a pre-defined threshold. The CTE extends over $\hat{k} - 1$ slots with $\hat{k} \geq K$. If the channel conditions between relay and destination during a certain CTE slot is so bad that it impossible for the BS to collect information, the BS will increase by one. The BS will continue updating until enough information is gathered for resolving the packets.

After detection of the collided user set $i_1, \dots\dots, i_k$, the channel matrix **H** can be obtained based on $u_{i_k}(n + m)$ with $0 \leq m \leq \hat{k} - 1$. Once the receiver collects independent mixtures of the original transmitted packets, the collision is then resolved.

CHAPTER III

RESEARCH METHODOLOGY

In this chapter, Multichannel Cooperative MAC protocol - a multichannel extension of cooperative MAC protocol that further improves throughput in case of high traffic load is explained and studied.

3.1 GENERAL

A multichannel extension of cooperative medium access protocol - a cross-layer cooperative protocol for collision resolution in broadband data network is presented. The available bandwidth is divided into non-interfering subchannels and each packet occupies one subchannel for its transmission. First, two schemes for rate limited traffic is considered. Users transmit packets on all subchannels. Collisions on a subchannel are resolved via cooperative transmissions, involving either the subchannel on which they occurred only (Scheme A), or all subchannels in a shared fashion (Scheme B). It is shown that the latter scheme results in smaller packet delays. Second, for the case of bursty traffic, a random subchannel selection scheme is considered to adaptively control the number of transmitted packets for each active user and thus keeping the collision orders small. Resolving a smaller order collision requires less complexity and involves smaller error.

3.2 MULTICHANNEL COOPERATIVE PROTOCOL

Assuming that the channel does not change between the CTE slots, it was shown in [5] that the diversity order for a given collision order and a number of non-source cooperating relays *l*, is proportional to *l*. However, in reality the channel is usually frequency selective. Although frequency selective fading is difficult to deal with, if compensated for successfully, it can be viewed as a source of multipath/frequency diversity. In the following schemes that exploit multipath/frequency diversity as well as cooperative and time diversity are discussed.

The physical layer is based on an orthogonal frequency division multiplexing (OFDM) system with F carriers. The carriers are grouped into groups of F/M, to form M subchannels, C_m, $m = 0, \dots \dots, M-1$. Without loss of generality, assume that F/M is an integer. Also, we assume that the subchannels are non-interfering with each other.

A user cannot hear and transmit on the same subchannel at the same time. Each packet has a fixed length, contains b bits, and occupies one subchannel for its transmission. If B blocks of OFDM symbols, say QPSK symbols, are transmitted in one slot, then each packet contains $b = 2BF/M$ bits.

3.2.1 Transmission on All Subchannels

Each user transmits on all subchannels simultaneously. Therefore, if a collision occurs, the collision order is the same on all subchannels. Let us term the process of resolving packets that collided over C_m as CTE_m. Two different schemes for resolving collisions will be considered and compared.

Two different schemes for resolving collisions will be considered and compared.

Scheme A - Collisions on each subchannel are resolved independently

A collision on subchannel C_m is resolved by involving C_m only. For a K-fold collision on C_m, the subchannel C_m will be reserved for the next $K-1$ slot, and the collision will be resolved along the lines of [5]. For simplicity, we take $\hat{k} = K$. From the MAC layer point of view, K slots are needed to resolve the M collisions of order K, thus the delay is exactly the same as in cooperative protocol and NDMA. Therefore, the analysis of [7] applies in this case.

Scheme B - Subchannels are used in a shared fashion to resolve collision on a particular subchannel

In this scheme, advantage of the available subchannels is taken to reduce the average processing time, i.e., the time that a packet spends on the channel. Let the collision order on each subchannel in slot *n* be *K*. During CTE_m, a set of nodes designated as relays use a set of subchannels indicated to them by the AP to retransmit what they heard during the collision slot on C_m. If the relay node is a source node that transmitted over C_m, it will retransmit its original packet but on another subchannel. Following a collision slot, the BS will first allocate all available and necessary subchannels for CTE_0, then allocates subchannels for CTE_1, until CTE_{M-1}. Let τ_m denote the processing time on the channel (in slots) for each packet that collided on C_m, or equivalently, the duration of CTE_m plus one.

The average processing time is $\tau = \frac{1}{M}\sum_{m=0}^{M-1}\tau_m$ (5)

Considering a system with only two subchannels, in slot *n*, three packets collide over each of C_0 and C_1 respectively. The average processing time for Scheme B was found to be 2.5 slots as proposed by L. Dong. Note that the average processing time of Scheme A is 3 slots. We can now see that CTE_0 and CTE_1 are resolved by using both C_0 and C_1.

Scheme C – Shared Subchannel are used to resolve collision irrespective of the adjacent slot to resolve collision on a particular subchannel

Case I:

In this scheme also we take the advantage of the available subchannels to reduce the average processing time i.e., the time that a packet spends on the channel.

Table 3.1: Subchannel Allocation for Scheme C

slot Subchannel	$n + 1$	$n + 2$
C_0	CTE_0	CTE_1
C_1	CTE_0	CTE_1

Let us consider a system with only two subchannels. In slot n, three packets collide over each of C_0 and C_1 respectively. The subchannel allocation of the multichannel scheme is shown in Table 3.1. In the (n + 1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot n + 2, it allocates two subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. At the end of the (n + 1)th slot, we consider the collision that occurred over C_0 has not been resolved. The collision that occurred over C_1 is resolved at the end of (n + 2)th slot. So the processing time for packets over C_0 is 3 slots, while the processing time for packets over C_1 is 2 slots. Therefore, the average processing time is $(3 \times 3 + 3 \times 2)/6 = 2.5$ slots. Note that the average processing time of Scheme A is 3 slots.

Case II:

Table 3.2: Subchannel Allocation for Scheme C

slot Subchannel	$n + 1$	$n + 2$	$n + 3$
C_0	CTE_0	CTE_1	CTE_2
C_1	CTE_0	CTE_1	CTE_2
C_2	CTE_0	CTE_1	CTE_2

Here, in this scheme also, we take the advantage of the available subchannels to reduce the average processing time i.e., the time that a packet spends on the channel. Let us consider a system with only three subchannels. In slot n, four packets collide over each of C_0 and C_1 respectively. The subchannel allocation of the multichannel scheme is shown in Table 3.2. In the (n + 1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot n + 2, it allocates two subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. At the end of the (n + 1)th slot, we consider the collision that occurred over C_0 has not been resolved. The collision that occurred over C_1 is resolved at the end of (n + 2)th slot. So the processing time for packets over C_0 is 4 slots, while the processing time for packets over C_1 is 3 slots. Therefore, the average processing time is (4 × 4 + 4 × 3 + 4 × 4) / 12 = 3.66 slots.

Case III:

In this scheme also we take the advantage of the available subchannels to reduce the average processing time i.e., the time that a packet spends on the channel.

Table 3.3: Subchannel Allocation for Scheme C

Subchannel	$n + 1$	$n + 2$	$n + 3$	$n + 4$
C_0	CTE_0	CTE_1	CTE_2	CTE_3
C_1	CTE_0	CTE_1	CTE_2	CTE_3
C_2	CTE_0	CTE_1	CTE_2	CTE_3
C_3	CTE_0	CTE_1	CTE_2	CTE_3

Let us consider a system with only four subchannels. In slot n, five packets collide over each of C_0 and C_1 respectively. The subchannel allocation of the multichannel scheme is shown in Table 3.1. In the (n + 1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot n + 2, it allocates two subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. At the end of the (n + 1)th slot, we consider the collision that occurred over C_0 has not been resolved. The collision that occurred over C_1 is resolved at the end of (n + 2)th slot. So the processing time for packets over C_0 is 5 slots, while the processing time for packets over C_1 is 4 slots. Therefore, the average processing time is (5 × 5 + 5 × 4 + 5 × 5 + 5 × 5)/20 = 4.75 slots.

3.2.2 Random Subchannel Selection

The Poisson traffic model may not well reflect real wireless traffic in some scenarios, because it assumes that the incoming packet rate λ is static over time. The incoming packet rate is required to satisfy $\lambda J < 1$, which can be low as J increases. A rate $\lambda > 1/J$ would yield an unstable system with infinite packet delay.

There are cases of practical interest, for example in multimedia communications, where a user generates bursty traffic, i.e., traffic that alternates between periods of high-rate bit streams and periods of silence. If many users have bit streams to transmit during the same time period, the collision order for schemes A and schemes B will be very high. For high-order collisions the ML equalizer becomes impractical, while suboptimal equalizers (e.g. ZF) although are feasible, they result in higher BER and lower throughput.

One way to reduce the collision order is to implement traffic control by taking advantage of the available multiple subchannels. Let us assume that each active node is allowed to transmit over no more than p ($1 \leq p \leq M$) randomly selected subchannels in each slot. Again, each packet occupies one subchannel for its transmission. We assume that the subchannels are selected sequentially, i.e., once a channel is selected it is taken off the list of available subchannels. This approach prevents collisions of packets of the same user.

The maximum number of transmitted packets for each active user, p, can be selected by taking into account the throughput or traffic load, so that the use of bandwidth is maximized while the collision orders are kept properly small. An adaptive approach was followed for selecting p. Based on the average system throughput during the previous time interval, the BS will take one of the following three actions: increase p by 1, decrease p by 1, or keep p unchanged. Then, the BS will broadcast its decision via the error-free control channel to all users using one bit at the end of a slot (0 sent: decrease p by 1; 1 sent: increase p by 1; nothing sent: keep p the same as in previous slot). During the startup period, the value of p can be predetermined by the BS, for example $p = \left[\frac{M}{2}\right]$.

Resolving collisions: the "highest-to-lowest" scheme - Following a collision slot, the BS will decide how to allocate subchannels to resolve collisions according to some predefined strategy. In the following, a simple strategy was proposed that achieve the least average processing time.

Let $K(n)$ denote the number of packets that were transmitted in the n-th slot, and $K_m(n)$ denotes the number of packets that were transmitted over subchannel C_m in the n-th slot. The average processing time is:

$$T_m = \frac{1}{K(n)} \sum_{m=0}^{M\text{-}1} K_m(n)\ \tau_m(n) \tag{6}$$

Where, $\tau_m(n)$ denotes the processing time (in slots) for each packet that collided over C_m, or equivalently, the duration of CTE_m plus one.

The optimum scheme would be that the BS performs an exhaustive search to evaluate all possibilities and then chooses the collision resolution order with the least average processing time. However, the computational complexity of such approach would be $M!$, which may be very high when M is large. In the following, a sub optimal scheme is proposed.

From equation (4) collisions of higher order carry more weight in the calculation of the average processing time. We allocate all available and necessary subchannels to re-solve collisions over one subchannel at a time, starting from the highest order collision and moving towards the lowest order collision. If the number of available subchannels is larger than the collision order, the collision can be resolved in only one additional slot. Otherwise, more slots will be required. Depending on the availability of sub-channels, collision resolution on several subchannels can be carried out in parallel (i.e., in the same slot).

Considering a system with only two subchannels, in slot n, three packets collide over C_0, and two packets collide over C_1. The subchannel allocation is shown in table below:

Table 3.4: Subchannel Allocation of Highest-to-Lowest Scheme

Subchannel \ slot	$n + 1$	$n + 2$
C_0	CTE_0	CTE_1
C_1	CTE_0	

The processing time for three packets over C_0 is 2 slots, while the processing time for two packets over C_1 is 3 slots. Therefore, the average processing time is (3 × 2 + 2 × 3)/5 = 2.4 slots.

Scheme C – Shared Subchannel are used to resolve collision irrespective of the adjacent slot to resolve collision on a particular subchannel

Case I:

In this scheme also we take the advantage of the available subchannels to reduce the average processing time i.e., the time that a packet spends on the channel.

Table 3.5: Subchannel Allocation of Highest to Lowest, Scheme C

Subchannel \ slot	$n + 1$	$n + 2$
C_0	CTE_0	CTE_1
C_1	CTE_0	

Let us consider a system with only two subchannels. In slot n, three packets collide over each of C_0 and C_1 respectively. The subchannel allocation of the multichannel scheme is shown in Table 3.5. In the (n + 1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot n + 2, it allocates one subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. At the end of the (n + 1)th slot, we consider the collision that occurred over C_0 has not been resolved. The collision that occurred over C_1 is resolved at the end of (n + 2)th slot. So the processing time for packets over C_0 is 3 slots, while the processing time for packets over C_1 is 2 slots. Therefore, the average processing time is (3 × 3 + 2 × 1)/5 = 2.2 slots.

Case II:

Here, in this scheme also, we take the advantage of the available subchannels to reduce the average processing time i.e., the time that a packet spends on the channel.

Table 3.6: Subchannel Allocation for Scheme C

Subchannel \ slot	n + 1	n + 2	n + 3
C_0	CTE_0	CTE_1	CTE_2
C_1	CTE_0	CTE_1	CTE_2
C_2	CTE_0	CTE_1	

Let us consider a system with only three subchannels. In slot *n*, four packets collide over each of C_0 and C_1 respectively. The subchannel allocation of the multichannel scheme is shown in Table 3.2. In the (n + 1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot n + 2, it allocates two subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. So the processing time for packets over C_0 is 4 slots, while the processing time for packets over C_1 is 3 slots. Therefore, the average processing time is (4 × 4 + 4 × 3 + 3 × 3)/11 = 3.36 slots.

Case III:

In this scheme also we take the advantage of the available subchannels to reduce the average processing time i.e., the time that a packet spends on the channel.

Table 3.7: Subchannel Allocation for Scheme C

Subchannel	$n + 1$	$n + 2$	$n + 3$	$n + 4$
C_0	CTE_0	CTE_1	CTE_2	CTE_3
C_1	CTE_0	CTE_1	CTE_2	CTE_3
C_2	CTE_0	CTE_1	CTE_2	CTE_3
C_3	CTE_0	CTE_1	CTE_2	

Let us consider a system with only four subchannels. In slot *n*, five packets collide over each of C_0 and C_1 respectively. The subchannel allocation of the multichannel scheme is shown in Table 3.1. In the (*n* + 1)th slot, the BS allocates both subchannels for CTE_0, i.e., to resolve the collision that occurred over C_0, and in slot *n* + 2, it allocates two subchannels for CTE_1, i.e., to resolve collisions that occurred over C_1. At the end of the (*n* + 1)th slot, we consider the collision that occurred over C_0 has not been resolved. The collision that occurred over C_1 is resolved at the end of (*n* + 2)th slot. So the processing time for packets over C_0 is 5 slots, while the processing time for packets over C_1 is 4 slots. Therefore, the average processing time is (5 × 5 + 5 × 4 + 5 × 5 + 4 × 4)/20 = 4.52 slots.

Control Overhead and Relay Selection

To indicate the state of each subchannel, in the beginning of every slot, the BS will broadcasts an α-bit control message over every subchannel to all nodes. The α-bit message conveys to the nodes one of the following $M + 1$ possible states of that subchannel: State 0: subchannel reserved for CTE_0 , ……, State (M $- 1$): subchannel reserved for CTE_{M-1}; State M: subchannel reserved for new packets.

For relay node selection, a simple scheme is proposed that establishes a predetermined order. A counter, w is maintained by each user, generated by some predetermined function of the slot number. Looking at the control channels, nodes know the states of all subchannels. All states, except State M, imply that a relay is needed. Counting the total number of such states yields the number of needed relays in a given slot. Suppose that the number of needed relays during slot n is χ. Those relays will be determined based on the outcome of r = mod ($w + m$, J) + 1 (J: the number of network users), for m = 1, ……, χ, that is computed by all nodes. Then node whose ID equals r knows that it has to serve as a relay. The subchannels over which the relays retransmit can also be determined based on some predefined rule, e.g., mod (w + m, M). Such scheme prevents the relays from overlapping in frequency, thus facilitating packet recovery at the BS.

Example 3.2: Consider a two-subchannel system with J = 6 users. During slot n = 0, $K_0 = 3$ packets collide over C_0, and K_1 = 2 packets collide over C_1. The counter is defined as w = 2n + 5. Two relays are required to resolve the collision over C_0. This is indicated to all nodes in the next slot via 4 control bits. During slot n = 1, the nodes r_1 = mod (w + 1, J) + 1 = mod (8, 6) + 1 = 3 and r_2 = mod (9, 6) + 1 = 4 are selected as relays. These nodes will respectively transmit on subchannels $C_{\text{mod}\,(8,2)} = C_0$, and $C_{\text{mod}\,(9,2)} = C_1$. During slot n = 2, one more subchannel is needed to resolve the collision on C_1. This is shown to all users in the control bits that are sent to them in slot n = 2. The node with ID equal to 5 is selected as relay.

More complex cases, where more collisions occur on more subchannels, can be handled in an analogous manner. According to this approach, within the same CTE, a relay will not be reused until all relays have been used.

3.3 MATHEMATICAL FORMULATION

Let us consider that the physical layer is an F-carrier OFDM system, where the carriers are divided into groups of N carriers each, i.e., $C_0, \ldots\ldots, C_{M-1}$ with $N = F/M$. Let $h_{ij}(m; n)$; $m = 0, \ldots\ldots, L-1$ denote the L channel taps between nodes i and j during slot n. We will assume that L is the length of the longest among all internodes channels. The F-point discrete Fourier Transform (DFT) of $h_{ij}(m; n)$ is:

$$H_{ij}(k; n) = \sum_{m=0}^{L-1} h_{ij}(m; n) \quad e^{-j\frac{2\pi k_m}{F}} \; ; k = 0, \ldots\ldots, F-1 \tag{7}$$

OFDM with sufficiently long Cyclic Prefix (CP) can convert a frequency selective channel into multiple flat fading channels. The effect of the channel over the k-th carrier is just a multiplication by the carrier gain, $H_{ij}(k; n)$.

A packet consists of B OFDM symbols. Let $x_i^m(n)$ be a $B \times N$ matrix denoting the packet sent by user i over subchannel m, in slot n. Each row of that matrix contains an OFDM symbol before modulation. In the absence of collision and after demodulation, the received packet at the BS equals:

$$\mathbf{y}_d^m(n) = \mathbf{x}_i^m(n) + \mathbf{H}_{id}^m(n) + \mathbf{w}_d^m(n) \tag{8}$$

where, $\mathbf{H}_{id}^m(n) = [\mathbf{H}_{id}(mN; n), \ldots\ldots, \mathbf{H}_{id}((m+1)N-1; n)]$ $(N \times N)$, and $\mathbf{w}_d^m(n)$ a $B \times N$ matrix denoting noise at the BS over C_m.

Now, suppose that a collision of order C_m occurs on subchannel C_m in slot n. Let us focus on CTE_m. Suppose that node r is selected as the j-th relay ($j = 1, \ldots\ldots, \hat{k}_m - 1$) during slot $n + k$ ($\hat{k}_m \geq k_m$). Note that k may be different than j, since according to [4], multiple relays can be used in the same slot. The value of k is determined by the availability of subchannels and the subchannel allocation scheme. If r was a source node during the collision slot, it will simply retransmit its packet at a subchannel that is selected according to some rule (not necessarily on C_m). Otherwise, it will transmit over C_l, the signal that it received during slot n over C_m. Since relays use different subchannels or slots, their transmissions do not overlap. Therefore, each relay transmission provides the

BS with a linear equation that contains the initially collided packets.

Without loss of generality, let us assume that among the $\hat{k}_m - 1$ nodes, the first η nodes are source relays, and the next l nodes are non-source relays. It holds $\eta + l + 1 = k_m$.

Let us form a matrix, Z, ($B \times k_m N$), whose first block column is the packet received at the BS during the collision slot, and subsequent blocks are packets from relay transmissions received at the BS during CTE_m.

It holds:

$$\mathbf{Z} = \mathbf{X}^m \mathbf{H} + \mathbf{W} \tag{9}$$

where,

- $\mathbf{X}^m$ is a ($B \times k_m N$) matrix based on the packets of users that collided over C_m.
- **H is** a ($k_m N \times k_m N$) channel matrix.
- **W** is a ($B \times k_m N$) matrix formed based on the noise at the BS during the collision slot, and each subsequent retransmission.

3.3.1 Collision Detection and Estimation

For collision detection we need to include a user ID in the packet of each user, with ID's being orthogonal between different users. For channel estimation a number of pilot symbols in each packet of each user is included. At least one OFDM symbol full of pilots is needed.

CHAPTER IV

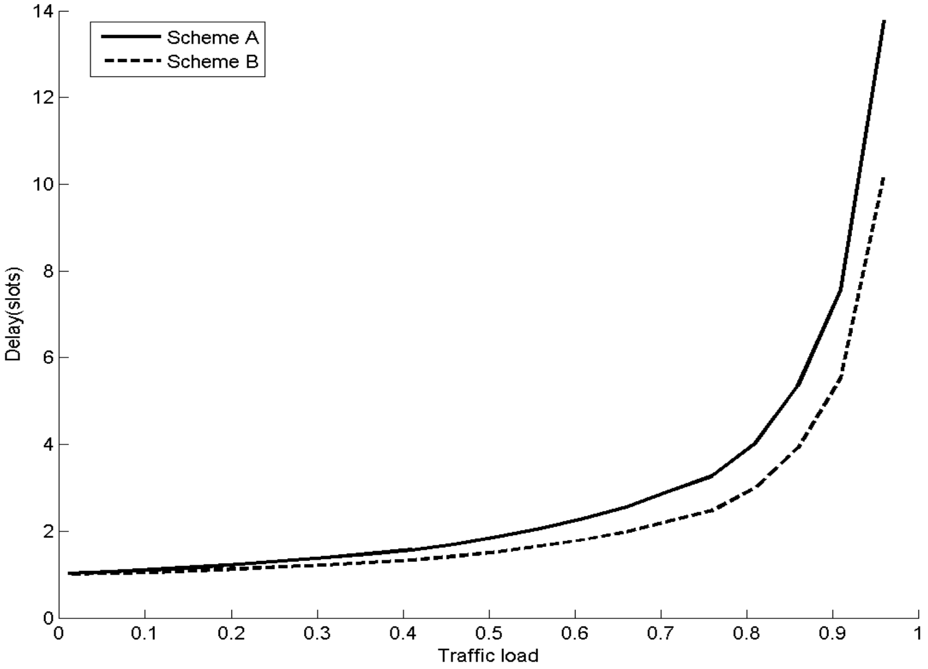
RESULTS AND DISCUSSIONS

In this chapter, simulation results on the performance of the considered schemes are presented and discussed. The considered schemes are programmed and simulated in MATLAB software. For the performance evaluation of the cooperative schemes, two metrics namely delay and throughput has been considered. Consider a network with total users, $J = 32$, and each user is equipped with a buffer of infinite size. The IDs are used to estimate the number of users involved in a collision. The number of OFDM carriers is 64, and only 48 carriers are used to transmit data packets. The OFDM symbol duration is 4 µs and the guard interval is 800 ns. Each packet contains 1000 OFDM blocks, and its duration is 4.8 ms. QPSK modulation is used. The channel matrix is estimated using pilots with 32 OFDM symbols. The SNR is 20 dB. Packets received at the BS with BER higher than $Pe = 0.02$ are considered lost or corrupted.

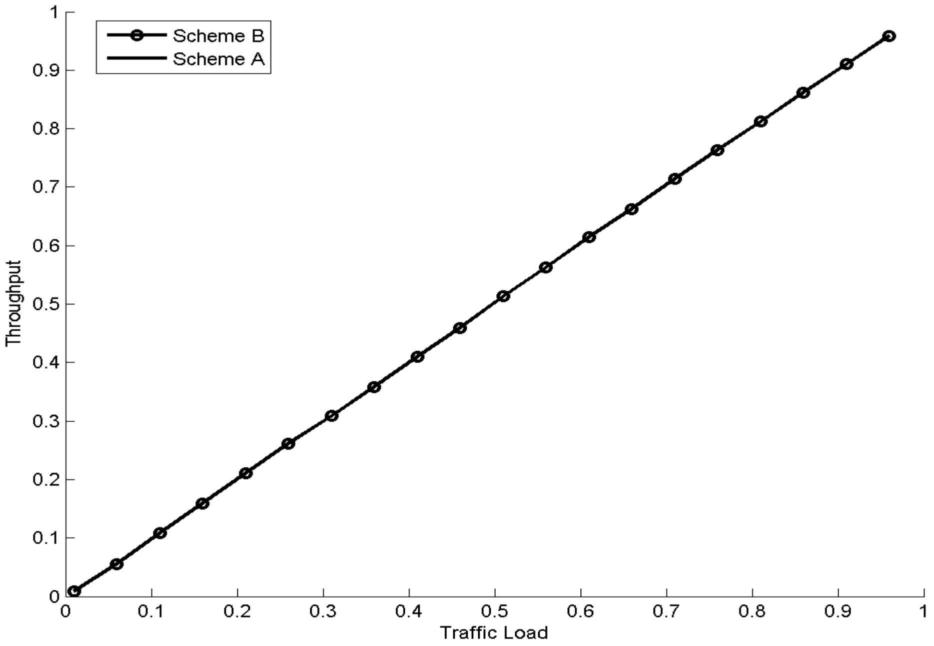
4.1 PERFORMANCE OF SCHEMES A AND B

The throughput is defined as the average number of packets that are successfully transmitted in one time slot, normalized by the number of subchannels M. Each user is fed with a Poisson source with rate λ large packets per slot, so the total traffic load of the system is λJ. The total simulation time is 2000 slots.

In Fig. 4.1 (a), the delay performance of Scheme B, as compared with A is shown. Both schemes exhibit the same throughput as it can be seen in Fig. 4.1 (b)



(a) Delay



(b) Throughput

Fig. 4.1: Delay and Throughput of Schemes A and B

4.2 RANDOM SUBCHANNEL SELECTION SCHEME

Consider a scenario where some users in the network generate bursty traffic. The delay performance as of staircase-like behavior is shown in Fig. 4.2. If there are unused subchannels at the last slot of collision resolution, they are wasted and not be used for transmissions of new packets. Such cases of wasted subchannels do not occur when K/M is an integer.

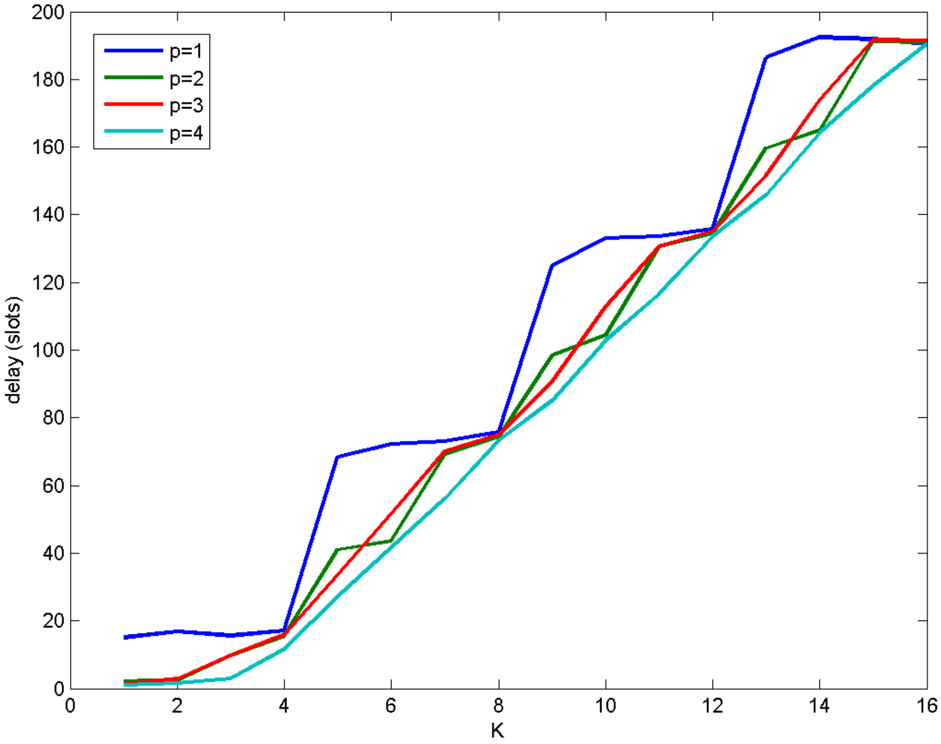


Fig. 4.2: Average Delay for Random Subchannel Selection Scheme

In Fig. 4.2, for K = 4, 8, 12, 16, there are no wasted subchannels, thus delays corresponding to different values of p are almost the same (delay of $p < M$ is slightly longer than $p = M$ due to the random subchannel selection). On the other hand, wasted subchannels do occur when $p < M$ and K/M is not an integer. Thus, as observed for K 6= 4, 8, 12, 16, the delay for $p < M$ is longer than that for $p = M$.

Fig. 4.3 shows the computational complexity for the random subchannel selection scheme for different active users. As expected, under low traffic load (small K), the throughput does not vary significantly between different *p's*. Under high traffic load (large *K*); a smaller *p* can result in higher throughput.

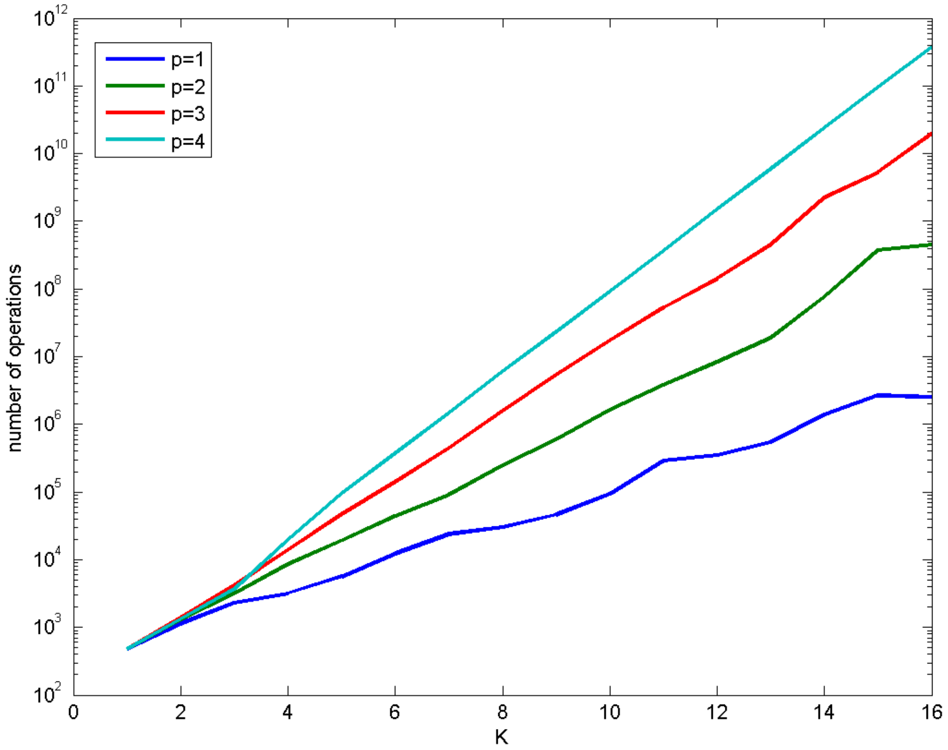


Fig. 4.3: Computational Complexity of Random Subchannel Selection Scheme

4.3 EXPERIMENTAL ANALYSIS OF SCHEME A, SCHEME B AND C

In this thesis, a multichannel extension of cooperative protocol – a cross layer cooperative protocol for collision resolution in data networks was studied. For Scheme A, collision on subchannel C_m involves subchannel C_m only whereas the Scheme B resolves a collision on C_m by using all the available subchannels are28 studied and showed that Scheme B can achieve shorter delay than Scheme A.

Table 4.1: Experimental Analysis of Cooperative Relaying

Cooperative Relaying	For a system consisting 2 SC	3 SC	4 SC	5 SC
Scheme A	3 slots	4 slots	5 slots	6 slots
Scheme B	2.5 slots	5 slots	8.5slots	13 slots
Highest to lowest Allocation Scheme	2.4 slots	4.8slots	8.2slots	9.75slots

For the case of multimedia traffic, two different approaches for subchannel selection were studied. In the first approach the subchannels were selected randomly by each active user. To keep the collision orders properly small, a simple approach to adaptively control the number of transmitted packets for each active user is considered. For resolving collisions at different subchannels, a "highest-to-lowest" scheme is studied such that it further minimizes the average processing time. My collective effort in this thesis is Scheme C where the shared subchannels are used to resolve collision irrespective of the adjacent slot to resolve collision on a particular subchannel. So upon the implication of the hypothetical consideration i.e. Scheme C, it is found that the performance of the system is much improved.

Table 4.2: Experimental Analysis based on Scheme C

After employing the hypothetical consideration	For a system consisting 2 SC	3 SC	4 SC	5 SC
Scheme A	3 slots	4 slots	5 slots	6 slots
Scheme B	2.5 slots	3.66 slots	4.75 slots	5.8 slots
Highest to lowest Allocation Scheme	2.2 slots	3.36slots	4.5slots	4.625 slots

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 SUMMARY

A multichannel extension of cooperative protocol is studied. The two schemes namely Scheme A where a collision occurs in the subchannel Cm only and the second Scheme B which resolves collision by using all available subchannels are studied and showed that Scheme B can achieve shorter delay than Scheme A. For the case of multimedia traffic, two different approaches for subchannel selection are studied. In the first approach the subchannels are selected randomly by each active user with equal probability, which may be suitable for the scenario of heavy traffic without strict delay requirements. To keep the collision orders properly small, a simple approach is considered to adaptively control the number of transmitted packets for each active user. For resolving collisions at different subchannels, a "highest-to-lowest" scheme is considered in a way that minimizes the average processing time.

At the physical layer, the proposed approaches are based on OFDMA, which effectively handles frequency selective fading and convert a frequency selective channel into multiple flat fading subchannels. A Scheme C is proposed where the shared subchannels are used to resolve collision irrespective of the adjacent slot to resolve collision on a particular subchannel. Eventually an experimental analysis of cooperative relaying and so proposed Scheme C is made for the better performance of the system.

5.2 CONCLUSIONS

In this thesis, a multichannel extension of cooperative protocol - a cross-layer cooperative protocol for collision resolution in broadband wireless networks was studied. Two schemes (Schemes A and B) was studied, and showed that Scheme B can achieve shorter delay than Scheme A. For the case of multimedia traffic, two different approaches to subchannel selection were considered. A Scheme C is proposed where the shared subchannels are used to resolve collision irrespective of the adjacent slot to resolve collision on a particular subchannel. At the physical layer, the considered approaches are based on OFDMA, which effectively handles frequency selective channels.

5.3 FUTURE WORK

In this thesis further improvement can be made in the above random subchannel selection for Scheme C by taking in consideration the Quality of Service requirements like BER as a subject of future research. Besides if we consider applying the Scheme C for fixed subchannel selection scheme; with strict delay requirements and diverse Quality of Service requirements, this research work can add further value to wireless security.

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