A HELPER INITIATED DISTRIBUTED COOPERATIVE MEDIUM ACCESS CONTROL PROTOCOL FOR WIRELESS NETWORKS

by

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DEDICATION

THIS THESIS IS DEDICATED

TO

MY BELOVED PARENTS

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List of Abbreviations

MAC	Medium Access Control
DCF	Distributed Coordination Function
QoS	Quality of Service
MIMO	Multiple Input Multiple Output
AP	Access Point
CSMA	Carrier Sense Multiple Access
FHSS	Frequency Hoping Spread Spectrum
DSSS	Direct Sequence Spread Spectrum
CDMA	Code Division Multiple Access
MRC	Maximal Ratio Combining
AF	Amplify and Forward
DF	Decode and Forward
CF	Compress and Forward
CSI	Channel State Information
SNR	Signal to Noise Ratio
SIFS	Short Interframe Space
DIFS	Distributed Interframe Space
RTS	Request To Send
CTS	Clear To Send
ACK	Acknowledgement
T_{SIFS}	SIFS Time
T_{DIFS}	DIFS Time
T_{ACK}	ACK Time
T_{DATA}	Time for a Frame Transmission
T_{CTS}	CTS Time
NAV	Network Allocation Vector
CW	Contention Window Size
RSS	Received Signal Strength
PLCP	Physical Layer Convergence Protocol

CoopTable	Cooperative Table
HCTS	Helper Clear to Send
PHY	Physical Layer
CoopMac	Cooperative MAC

List of Symbols

$x(t)$	channel input at time t
$y(t)$	output of the channel at time t
$h(\tau,t)$	impulse response of the channel at time t
$H(f,t)$	frequency response of the channel at time t
f_c	carrier frequency
$s(t)$	back off stage of a wireless node at time t
$b(t)$	back off counter of a wireless node at time t
p	probability that a transmitted packet suffer collision
τ	probability that a wireless station transmits a frame
CW	contention window size
CW_{min}	minimum contention window size of wireless node
m	maximum number of back of stage of a node
R_{limit}	maximum retry limit
n	number of wireless stations
p_b	probability that the channel is busy
p_s	probability that a successful transmission occurs in a time slot
π	duration of an empty time slot
S	throughput
T_s	time duration of a successful frame transmission
T_c	time duration of a collided frame
L	length of a frame
$E[X]$	average number of time slots
$E[Delay]$	average frame delay
$E[slot]$	expected slot time

p_{drop}	packet drop probability
R_{sh}	data rate from source node to helper node
R_{hd}	data rate from helper node to destination node
R_{sd}	direct data rate between source and destination
T_{PLCP}	time duration of physical layer convergence protocol header
T_{ACK}	time duration of an ACK
T_{DATA}	time duration of a data frame
p_{trans}	probability that at least one station transmits a frame
p_e	channel bit error rate
$L_{payload}$	length of payload in a frame in bits
L_{Header}	length of the header of a frame
$T_{E[P]}$	time duration of average payload
T_{HCTS}	duration of a $HCTS$ frame
T_{RTS}	duration of a RTS frame
T_H	duration of the header of frame
ρ	fading margin of rayleigh channel
f_d	maximum doppler frequency
$T_{ErrorFrame}$	duration of a corrupted frame

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Abstract

Cooperative data transmission is one of the most significant techniques to mitigate fading induced errors in wireless networks. The key idea in cooperative data transmission is that of resource sharing among multiple nodes in a network. This idea enables to design technologies using efficient spectrum utilizations. Although multiple input multiple output system provides a single node to be equipped with multiple antennas, relative higher cost in implementing this system is a barrier. Spatial diversity for wireless transmission requires more than one antenna at the transmitter. However, mobile devices are usually limited by size, so installation of multiple antennas increases the hardware complexity significantly. Due to the omnidirectional nature of wireless signal, a data transmission between a source node and a destination node can be overheard by many other neighbor nodes. By exploiting this characteristic, a number of recent research activities on cooperative Medium Access Control (MAC) have been devised where low data rate stations are assisted by the high data rate stations in forwarding data traffics. Therefore, wireless devices with a single antenna can effectively form a virtual array of antennas by sharing each other's antennas in a multiuser environment. In this thesis a mathematical model is derived for the performance analysis of the legacy IEEE 802.11 DCF MAC using markov chain. This thesis proposes a new distributed cooperative MAC protocol and evaluates the proposed protocol's performances using mathematical modeling. In the proposed protocol a potential relay node initiates itself to participate in the cooperation by calculating supported data transmission rate between source to relay and relay to destination links. Mathematical analysis of the proposed protocol in error prone channel and flat fading Rayleigh environment is presented in this thesis. Performance of the proposed scheme is compared with that of the existing IEEE 802.11 DCF MAC. Numerical results show that the proposed scheme can increase throughput and decrease average frame delay of any IEEE 802.11 Wireless LAN's low data rate station comprehensively.

CHAPTER 1

INTRODUCTION

Cooperative Communication is an effective way to mitigate channel impairments due to fading and interferences in wireless communication system. In cooperative communication, single antenna mobile terminals in a multiple user wireless environment share antennas from other users that form a virtual multiple antenna array system which offers more reliable data transmission with higher spatial diversity gain. In cooperative networks, a single hop data transmission session is replaced with two hop data transmission. Cooperative networking enlarges coverage area and enhances the quality of services (QoS) in wireless communication system. In cooperative communication system, a wireless node does not need to be equipped with multiple antennas as in Multiple Input Multiple Output (MIMO) system. Protocols in all of the higher layers in OSI (Open System Interconnection) reference model may exploit the facilities offered by physical layer cooperative communication for their respective performance enhancement. Although multiple input multiple output (MIMO) system improves the capacity and reliability of the wireless networks through diversity gain, integrating multiple antennas in small mobile devices is a very challenging issue. In literature a number of data link and network layer protocols have been designed by incorporating the benefits of physical layer cooperative communication. Very few researches have been conducted on cooperative MAC layer. IEEE 802.11 DCF MAC needs to be modified to accommodate the facilities provided by physical layer cooperative communication. In designing a cooperative MAC protocol critical questions: while transmitting data, whether MAC mechanism should be cooperative or non-cooperative? If cooperative how much benefits in data transmission can be achieved and what are the overheads the protocol have to deal with effectively. Another critical question is how the source station would know whether cooperative MAC should be triggered. Overheads incurred during a relay station selection for a particular data transmission session should be kept minimized. Cooperative communication enables efficient usages of the limited wireless spectrum. This user cooperation motivates a wireless node to share its power and computation with other neighboring nodes. This phenomenon leads to saving of overall network resources significantly.

1.1 Related Research Works

Research communities are continuously devising new methods to employ spatial diversity in wireless networks with single antenna nodes. Mitigation of channel fading through physical layer cooperation is discussed in [1]. Some unsolved questions regarding both cooperative protocols design and building of cooperative networks are addressed in [2-3]. Several physical layer methods have been studied. Among them, amplify and forward and decode and forward are the two well-known methods [1], [4]. Only a few research studies have focused on cooperative MAC protocol design. Hangguan Shan and others have proposed a cross layer cooperative MAC protocol [2]. A helper is selected from a predetermined cooperative region and the collision probability in selecting a single helper is very high. rDCF (Relay Enable DCF) [5] has exploited the multi rate nature of IEEE 802.11. In this work, mandatory broadcasting of rate information by every wireless station consumes bandwidth. A helper is selected using a triangular hand shake among sender, helper and receiver in a predetermined manner. rPCF protocol [6] enables multi hoping in IEEE 802.11 PCF mode. However, PCF mode has limited applications. Pei Liu has designed a cooperative MAC [7]. In this work a helper is selected by the sender in proactive manner. This technique lacks the addressing of helper selection in distributed fashion within the sender and receiver vicinity. The proposed cooperative MAC of this thesis differs from CoopMac [7] primarily in that, the helper station selection process in our scheme is distributed in nature and a helper selection is initiated by helper node itself. In [8], Xin has designed a Cooperative MAC for multi hop wireless networks in which helper selection is initiated by the receiver only when a data packet is not received correctly. Data transmission from the helper is prone to collision.

S. Bharati [9] has proposed a cooperative Ad hoc MAC for Vehicular Networks. In his work, he has applied a time division multiple access schemes in selecting helper which incurs the disadvantages of TDMA and also has modified the legacy IEEE 802.11 DCF Mac frame format. This scheme is not backward compatible with the legacy IEEE 802.11 DCF MAC. S. Moh *et al.* have proposed a cooperative diversity MAC [10] for ad hoc networks. It has exploited the benefits of coded cooperation through simultaneous transmission from both sender and the helper stations. Zhou *et al.* have designed a cooperative adaptive relay based MAC for vehicular network (ADC-MAC [11]).This protocol has modified the frame structure of IEEE 802.11 DCF MAC. Nature of relay station selection in this protocol is proactive. Therefore, devising an appropriate relay station selection strategy in cooperative MAC design for wireless Networks is not straightforward.

1.2 Motivation

Effective and efficient strategies have to be devised to allocate network resources dynamically through MAC scheduling and routing, so as to trade off the performance benefits against cost, i.e., power, coordination overhead and delay which is the major motivation of the work of this thesis.

Other aspects that have motivated me towards the design of cooperative MAC are as follows

a. Due to adverse effects of shadowing and fading in a infrastructure based Wireless Local Area Network (WLAN), direct link between the Access Point (AP) and the mobile station is not always usable or the channel exhibits low quality signal transmission. This occurs due to the fact that mobile stations do not have line of sight signal propagation with the access point. If an intermediate node is used to forward the data from the source to the destination, data transmission rate of the source station increases. The intermediate node (helper station) may act as a virtual antenna. The MAC layer design must be modified or a separate cooperative MAC may co-exist with the legacy IEEE 802.11 DCF MAC. The source station may opportunistically use one of the MAC protocols to transmit its data.

b. According to IEEE 802.11 DCF MAC, in infrastructure less WLAN (Ad hoc Network), all of the wireless stations get equal access time to wireless medium in sending their data. B. Sadeghi *et al*. have shown that if there are lower data rate stations inside a communication region, they affects the throughput of other stations [12]. As a result, overall throughput of the wireless network is degraded. If those lower rate stations are aided by any of the relay station in forwarding its data frame, throughput gain of the system increases significantly.

c. Moreover, if the lower rate station can increase their data transmission rate through cooperative MAC, those consume less time in sending their data. Thus, capture time of the wireless medium of those lower rate stations decreases. This phenomenon facilitates other stations to get more access time to the medium. Hence, the throughput of the system increases.

1.3 Objectives

User cooperation in wireless networks can bring mutual benefits for all of the wireless nodes in a wireless network. The core objective of this thesis is to design a new helper initiated distributed cooperative medium access control protocol for wireless networks. During the process of designing the proposed protocol, the following basic milestones are the essential objectives of this thesis.

a. Analytical modeling of the legacy IEEE 802.11 DCF MAC with the help of markov process.

b. Formulation of a technique to find out the appropriate helper nodes from multiple potential helper nodes in a wireless network.

c. Analysis of the throughput and end to end frame delay of the proposed protocol in different wireless environments.

d. Performance comparison of the proposed protocol against that of the legacy IEEE 802.11 DCF MAC.

1.4 Adversaries Related to Cooperative MAC Design

a. Overheads in cooperative MAC design affect effective data transmission rate. A negligible amount of overheard must be incorporated for coordination among the wireless nodes to support cooperative data transmission. This overhead signaling decreases the cooperative gain. As the pay load length is always limited to practical applications, this extra overhead becomes more detrimental in those application scenarios. Higher transmission rate is likely to reduce the signal reception quality; hence it may lead to more packet failure. While designing a cooperative MAC, extra protocol overhead, finite payload length, transmission reliability and more importantly unnecessary cooperation must be alleviated.

b. Cooperative communication enlarges the coverage area of the wireless nodes. Hence it also enlarges the interference range of signal transmission. In a multi hop and multi flow network, an enlarged interference area brings collision and packet failure which cause the reduction of average number of concurrent transmissions. Therefore, A cooperative MAC must invoke the tradeoff between spatial reuse and reliability of signal transmission.

c. Extra protocol overhead and overhearing of packet transmission may reduce the effectiveness of the power of wireless nodes. Improper cooperation has to be ignored. Improper cooperation may consume extra battery power.

d. Interferences from neighboring nodes have to be taken into consideration during the design of a cooperative MAC for wireless ad hoc networks or wireless sensor networks. These interferences may mislead communicating pair (sender-relay-destination) in correctly determining the channel state information.

1.5 Organization of Thesis

This thesis consists of six chapters. Brief description of its different chapter is as follows.

Chapter one introduces cooperative communication. Related researches regarding design of cooperative MAC protocol, motivation and different issues in cooperative MAC are presented in this chapter.

Chapter two presents fundamentals of cooperative MAC. Issues related to protocol design for the MAC sub layer of data link layer in OSI reference model and different types of medium access protocols (MAC) are illustrated in this chapter. Different relaying techniques in cooperative cross layer MAC protocol design and modeling of the wireless channel are furnished in this chapter.

Chapter three elucidates the details of legacy IEEE 802.11 DCF MAC and analysis of its throughput, end to end delay, and packet drop probability. A markov chain based analytical model and derivation of equations for throughput, end to end delay and packet drop probability are illustrated in this chapter.

Chapter four describes a new helper initiated distributed cooperative medium access control protocol. Through analysis of different performance metrics of the proposed protocol is presented within this chapter. Performances i.e., throughput, end to end frame delay are derived for flat fading Rayleigh channel.

Chapter five shows the comparisons of different performance metrics between IEEE 802.11 DCF MAC and the proposed protocol.

Chapter six concludes this thesis along with some limitations and future research scopes.

1.6 Summary

In this chapter I discussed related research works of cooperative MAC design. Motivations that allured me to conduct this thesis are succinctly described. Few barriers that must be taken into consideration during the design of a cross layer cooperative MAC are also depicted in this chapter.

CHAPTER 2

FUNDAMENTAL ISSUES OF COOPERATIVE MAC DESIGN

Medium Access Control in Wireless Local Area Networks (WLANs) is one of the significant ways in achieving better throughput for the wireless nodes. In OSI reference model medium access is controlled by the MAC sub layer of the data link layer. This chapter focuses on the Medium access control (MAC) sub layer with the aid of the physical layer. In this chapter i discuss the background related to cooperative MAC design. In Wired Local Area Network, carrier sense multiple access with collision detection (CSMA/CD) mechanism is used as a medium access method. CSMA/CD is not applicable to the Wireless Local Area Networks. In WLANs, IEEE 802.11 DCF MAC is the prominent standard for medium access. In IEEE802.11 DCF MAC mechanism, while a transmitting node sends data other nodes within its transmission region must refrain from sending data at the same time. Time-varying fading and interferences are the two major differences in wireless Media relative to wire line media. Again the distance between the source and receiver pair limits the transmission data rate. Due to fading, interferences and the physical distance of the communicating pairs, the throughput of the communication system is degraded. The more the distance between the sender and receiver, the more the link becomes weaker and supports lesser data rates. To enable the users to transmit data rate with higher gain, researchers are continuously trying to adapt various techniques in providing reliable links between the source and receiver.

Multiple Input Multiple Output (MIMO) has been developed to combat against fading, interferences of the wireless links [15-16]. This technique has predicted linear capacity increases in the number of antennas in rich scattering environments. Space time codes have been developed to exploits the benefits of multiple antennas at the receiver [17-18]. All of the techniques require multiple antennas to be deployed on the wireless nodes. The size of the wireless nodes is becoming smaller in size day by day. Installation of multiple antennas to those small devices becomes more complex. This complexity demotivates the designers to install multiple antennas in small devices. Moreover, hardware complexity of small size devices is not congruent with multiple antennas.

In cooperative networking, each wireless node is equipped with single antenna but every node may act both as a transceiver and a relay. Cooperative diversity is used to mitigate wireless channel affects resulting from slowly-time varying, frequency non-selective multipath fading, large-scale shadowing, and path-loss.

2.1 Adaptive Cooperative Communication

Adaptive communication means transmitting at high rate when the communicating channel is good and at low rates or not at all when the channel is poor and unreliable. The performance gain of adaptive communication comes from exploiting the fluctuations of the fading channel. As compared to the point-to-point setting, the multiuser settings offer more opportunities to exploit. In cooperative communication multiuser diversity has been exploited. In addition to when to transmit, now the question arises as which user to transmit from and again which user to transmit to and the amount of power required to transmit. It contradicts with opportunistic transmission. Opportunistic data transmission exploits the following concepts: at any time in a large network, with high probability there is a user whose channel is near its peak. Cooperative data transmission scenario using relay node is shown in Figure 2.1.

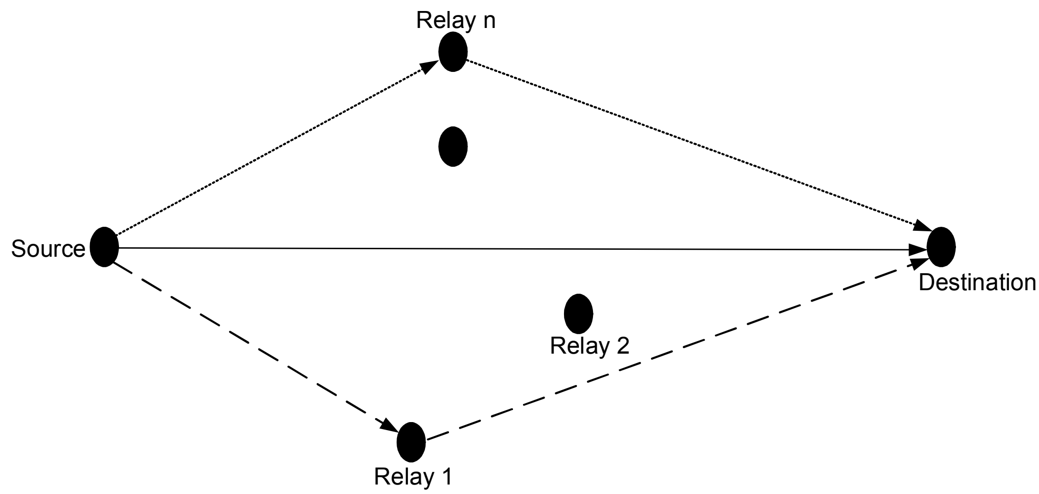


Figure 2.1 Illustration of Cooperative Communication

2.2 Benefits of Cooperative Networking

The benefits of cooperative data transmission increase not only the throughput of the network system but also the other aspects, i.e., spatial diversity, lower delay etc. [13]. In this sub section i briefly discuss several prominent benefits that cooperative network offers.

2.2.1 Higher Throughput and Lower Delay

Physical layer of the OSI reference achieves adaption to different data rates through adaptive modulation and channel coding schemes. MAC sub layer of the data link layer has introduced rate adaptation to combat adverse channel conditions. When a high channel error rate is encountered due to low average signal to interference (SNR), IEEE 802.11 DCF MAC switches to lower data transmission rate to guarantee a certain error free delivery of data packets. If the rate adaption is applied in any data transmission, cooperative communication offers much more benefits by increasing throughput. In Figure 2.1, if the direct transmission rate between the source and destination below 2 Mbps in case of IEEE 802.11 b, data may be transmitted by selecting any of helper stations, i.e., relay 1, relay 2, ….relay n which offers data rate more than 2 Mbps. Again the relay stations (relay 1, relay 2…relay n) in Figure 2.1 enjoy the benefits to lower channel access delay. Hence system throughput is increased.

2.2.2 Higher Spatial Diversity

Single antenna stations in a wireless environment may form dynamic virtual multiple input multiple output antenna array. If the relay nodes in Figure 2.1 overhear the data from the source station and direct channel quality between the source and destination is degraded, any of the relay nodes may forward the data on behalf of the source to the destination. Therefore, transmission failure is reduced through spatial diversity.

2.2.3 Lower Power Consumption

Apparently it may seem that the power of the relay stations is drained up very quickly, if they engage themselves in forwarding others' data packet. In saturated network, high data rate node can get more bits per joule if it is participating in two – hop forwarding schemes. If a station remains idle in the network, it also spends some of its energy. In a network system, if those idle nodes stay online transmitting data for other nodes without any of its own traffic data to send, the bits per joule is increased [7].

2.2.4 Lower Interference and Extended Coverage Region

When the performance metrics such as error rate, throughput etc. are fixed cooperative communication leads to extended coverage region. When the network is deployed in a cellular fashion to reuse the limited bandwidth, interferences among nodes are reduced. If the signal to interference (SIR) ratio is reduced through curtailing the average channel time used by each station to transmit its certain amount of data in cellular network, a more uniform coverage can be achieved. This leads to boost up the network capacity.

2.2.5 Network Condition Adaptability

The choice of relays, traffic conditions, interferences, remaining battery power of nodes, information about the current channel gain, packet loss rate etc. are the major cooperative network conditions that a source node must take into consideration in adapting cooperative data transmission. A relay station for particular cooperative data transmission may be selected dynamically taking any of the above network conditions. To adapt those criteria by nodes in cooperative networks, proper mechanisms have to be incorporated in the higher layer protocols of the OSI reference model. A cross layer approach is more promising in adapting cooperative benefits in cooperative network. I show in this thesis that new signaling methods have to be incorporated for adapting cooperative data transmission in MAC sub layer of the data link layer.

2.3 Modeling the Wireless Channel

A wireless channel can be modeled in general as time varying system described in [14]. The summary can be drawn as follows with the effect of fading in that wireless channel. The received signal can be written as a sum of multiple attenuated and delayed version of the transmitted signal. If we denote the input of the channel at time t by $x(t)$ and the output of the channel by $y(t)$, the attenuation of the path i by $a_i(t)$, and the propagation delay by $\tau_i(t)$, the relationship between the input and output of the channel can be modeled as

$$y(t) = \sum_i a_i(t)x(t - \tau_i(t)) \tag{2.1}$$

Where the summation is over all of different paths from which the receiver receives the signal. Since the channel in (2.1) is linear, it can be described by the response $h(\tau, t)$ at time t to an impulse transmitted at time $t - \tau$. Using $h(\tau, t)$ the channel can be modeled as

$$y(t) = \int_{-\infty}^{\infty} h(\tau, t)x(t - \tau)d\tau \tag{2.2}$$

Therefore, the impulse response for the fading multiple path channels can be modeled as

$$h(\tau, t) = \sum_i a_i(t)\delta(\tau - \tau_i(t)) \tag{2.3}$$

In mobile environment where the transmitter alone, receiver alone or both are mobile, (2.3) is the response of the channel. If both the transmitter and the receiver are stagnant, the attenuations $a_i(t)$ and propagation delays $\tau_i(t)$ do not depend on time t. The channel acts as a linear time invariant (LTI) channel with the following impulse response

$$h(\tau) = \sum_i a_i\delta(\tau - \tau_i(t)) \tag{2.4}$$

For the time variant channel, the time varying frequency response is defined as

$$H(f,t) = \int_{-\infty}^{\infty} h(\tau,t)e^{-j2\pi f\tau}\, d\tau$$

$$= \sum_i a_i(t)\, e^{-j2\pi_i(t)f\tau} \quad (2.5)$$

Therefore, the channel between the sender and the receiver can be thought as a combination of many multipath fading channels as the time-scale at which the channel varies is typically much longer than the delay spread, i.e., the amount of memory of the impulse response at a fixed time.

In most of the wireless data transmissions occurs in pass band of bandwidth W around a center frequency f_c. However, most of the processing, such as coding/decoding, modulation/demodulation, synchronization, etc., is actually done at the baseband. Hence the base band equivalent channel (2.1) is defined as

$$y_b(t) = \sum_i a_i{}^b(t)x_b(t-\tau_i(t)), \quad (2.6)$$

Where $y_b(t)$ and $x_b(t)$ are the base band equivalent input and output of the channel respectively and $a_i{}^b(t) = a_i(t)e^{-j2\pi_i(t)f\tau}$. The baseband equivalent impulse response of the channel

$$h_b(\tau,t) = \sum_i a_i{}^b\delta(\tau-\tau_i(t)). \quad (2.7)$$

Assuming that input $x(t)$ is band limited and applying sampling theorem, the baseband input will be limited to $W/2$ and can be written as

$$x_b(t) = \sum_n x[n]sinc(Wt-n) \quad (2.8)$$

Where $x[n] = x_b(\frac{n}{W})$ and $sinc\ (t)\ = \frac{sin(\pi t)}{\pi t}$ and n is the samples of the signal.

Using (2.7) and (2.8), the baseband equivalent input-output relationship can be written as

$$y_b(t) = \sum_n x[n] \sum_i a_i{}^b(t)sinc(Wt - W\tau_i(t) - n)) \quad (2.9)$$

If $y_b[m] = y_b\left(\frac{m}{W}\right)$, the discrete time output of the channel

$$y_b[m] = \sum_n x[n] \sum_i a_i{}^b(m/W)sinc(m - n - \tau_i(t/W)W)) \quad (2.10)$$

Let, $l = m - n$ and $h_l[m] = \sum_i a_i{}^b(m/W)sinc(l - \tau_i(t/W)W))$, the discrete time input and output relationship of the channel can be written as

$$y_b[m] = \sum_l h_l[m]x[m - l] \quad (2.11)$$

Where, $h_l[m]$ is the l^{th} filter tap of the channel at time m.

If it is assumed that the receiver in wireless communication adds the signal with Additive White Gaussian Noise ($AWGN$) to the received signal. It is assumed that the noise standard zero mean $AWGN$ $w(t)$ is incorporated in this model, (2.1) can be modeled with noise as follows

$$y(t) = \sum_i a_i(t)x(t - \tau_i(t)) + w(t) \quad (2.12)$$

The discrete time equivalent of the channel with noise is

$$y_b[m] = \sum_l h_l[m]x[m - l] + w[m] \quad (2.13)$$

Where $w[m]$ is the low pass filtered noise at the sampling instant $\frac{m}{W}$.

2.4 Fading

In mobile environment, variations in received signal strength over time and frequency are the most significant factors for supported data rate in the wireless network system. These variations are caused due to two types of fading [7].

2.4.1 Large Scale Fading

Large Scale Fading is the result of path loss of signal as a function of distance and shadowing by large objects such as buildings and hills. This occurs as the mobile moves through a distance of the order of the cell size, and is typically frequency independent.

2.4.1.1 Power Decay with Distance and Shadowing

If we consider a fixed antenna radiating into free space and fixed receiver, the electric field and magnetic field remains perpendicular to each other. In response to a sinusoid $cos2\pi ft$, we can express the electric far field as

$$E\big(f,t,(r,\theta,\psi)\big) = \frac{\alpha_s(\theta,\psi,f)cos2\pi f(t-\frac{r}{c})}{r} \tag{2.14}$$

Where, (r,θ,ψ) represents the point u in space at which the electric field is being measured, r is the distance from the transmit antenna to u and where (θ,ψ) represents the vertical and horizontal angles from the antenna to u respectively. The constant c is the speed of light, and $\alpha_s(\theta,\psi,f)$ is the radiation pattern of the sending antenna at frequency f in the direction (θ,ψ). It also contains a scaling factor to account for antenna losses. Here the phase of the field varies with fr/c, corresponding to the delay caused by the radiation traveling at the speed of light. As the distance r increases between the transmitter and the receiver, the electric field decreases as r^{-1}. Therefore, the power of the transmitted signal in per unit area also decreases as r^{-2}.

2.4.1.2 Reflection from a Ground Plane

When the horizontal distance (r) between the transmitter and the receiver become very large enough relative to their vertical displacement, the difference between the direct path length and reflected path length goes to zero as r^{-1} increases with the increase in r. If r is large enough difference between the path length becomes small enough relative to the wave length c/f. Since the sign of the electric field is reversed on the reflected path, two waves start to cancel each other out. The electric wave at the receiver is then attenuated as r^{-2}, and the received power decreases as r^{-4}. The scenario is common in rural areas especially when the base stations are place in road side areas. Hence the supported data rates between the communicating pairs also start to decrease.

2.4.2 Small Scale Fading

Small Scale Fading is experienced due to the constructive and destructive interferences of the multiple signal paths between the transmitter and receiver. This occurs at the spatial scale of the order of the carrier wavelength, and is frequency dependent. Small-scale multipath fading is more relevant to the design of reliable and efficient wireless network systems.

2.4.2.1 Rayleigh Fading and Rician Fading

The simplest probabilistic model for small-scale fading is assumed that there are statistically independent reflected and scattered path with random amplitudes between the sender and receiver. The overall received signal at the receiver is the constituent of various independent small signals. It is reasonable to model the channel filter taps as zero-mean circular complex Gaussian random. In this model, the magnitudes of the signals are Rayleigh distributed. Rayleigh fading is tractable model and used in through put analysis of the network system. Other advantages of Rayleigh fading are that it considers the worst case in analyzing a communication system. Rician fading is another model that assumes that there is a line-of-sight from transmitter to receiver; this model is more suitable for channels in which there is one path with a significant mean that contributes to the overall received signal strength.

2.5 Diversity

In this section I discuss different types of diversities in wireless signal transmission. Because of the broadcast nature of wireless medium, signal transmission may be diversified using three main parameters: time, frequency, space and cooperative diversity. Diversity techniques are used to combat against fading and interferences which may cause the transmitted signal to be lost or corrupted. The time varying nature of the wireless media has also motivated the researchers to find out a way which would send multiple copies of the same message through different independent faded paths. In this thesis I focus mainly on cooperative diversity. Here I discuss those three diversity techniques.

2.5.1 Time Diversity

To mitigate the error burst in time varying channel condition time diversity is used. The error burst in digital data transmission may be occurred due to fading in combination with moving transmitter, moving receiver, obstacles or electromagnetic interferences. In this technique the transmitted message is encoded with sufficiently long codes and the codes are spread over time. Global System for Mobile Communication uses time diversity. In GSM, the whole 25 MHz bandwidth is divided to 125 sub-bands of 200 kHz each. In each sub-band up to 8 users can transmit their signals in 8 time slots and therefore the maximum time diversity order is 8.

2.5.2 Frequency Diversity

This type of diversity is significant in frequency selective fading channels. The signal is transmitted using several frequency channels or spread over a wide ranges of spectrum. Spread spectrum such as Frequency Hoping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum CDMA uses frequency diversity.

2.5.3 Space Diversity

In space diversity the signal is transmitted over several different propagation paths. In wireless transmission, space diversity can be achieved using antenna diversity. Antenna diversity is the technique of using multiple transmitting antennas or multiple receiving antennas. If the receiver receives signals from multiple users, any of the diversity combining techniques such as equal-gain-combining, maximal ratio combining (MRC), switch combining, and selection combining is used.

2.5.4 Cooperative Diversity

Cooperative diversity is the multiple antenna technique which improves the overall capacity of the network systems. In conventional single hop communication system directly transmitted signals are decoded by the receiver and other relayed signals are ignored. In cooperative diversity, the receiver sees the relayed signal as cooperation which contributes in receiving a strong signal. In cooperative diversity each user relays signals for other users toward the destination.

2.5.4.1 Relaying Strategies

A cooperative relaying strategy consists of a source, a destination and a relay node. If the direct data transmission is not successful, the relay node will transmit the overheard message from the source node through different paths to the destination. Since a one hop signal transmission is replaced by two hop transmissions one after another, the relay may adopt some relaying strategies: amplify-and-forward, decode-and-forward, and compress-and-forward [4].

2.5.4.1.1 Amplify and Forward

In this scheme, a relay station amplifies the receive signal from the source and forward the amplified version of the signal to the destination without determining the actual contents of the signal. Amplify and forward (AF) scheme provides spatial diversity to combat against fading. Using capacity estimation of AF, this scheme may provide achievable lower bounds that are known to optimal in some communication scenarios. If signals from multiple users are mixed in the air, AF provides a communication strategy that achieves high throughput with low computational complexity at each relay nodes. The main disadvantage of this scheme is that noise is also amplified with the original signal for retransmission.

2.5.4.1.2 Decode and Forward

In this scheme, the relay first decodes the overheard signal from the source and before retransmitting the relay re-encodes the signal. In decode and forward (DF), the noise is removed before retransmission. If errors occur in the overheard decoded signal within relay station, no cooperation takes place. However, Adaptive DF—in which the source uses either source-relay channel state information (CSI) or feedback from the relay to decide between retransmitting the message and permitting the relay to forward the message does achieve second-order diversity in the high signal-to-noise ratio (SNR) region.

2.5.4.1.3 Compress and Forward

In this technique, the relay station compresses the overheard signal from the source station using any compression technique, i.e., Wyner-Ziv coding and forwards the compressed signal to the destination without decoding the signal. The following

Figure 2.2 shows the difference between DF and Compress and Forward (CF) [19]. This figure shows that DF works better when the relay is close to the source, but CF is Preferred when the relay is close to the destination.

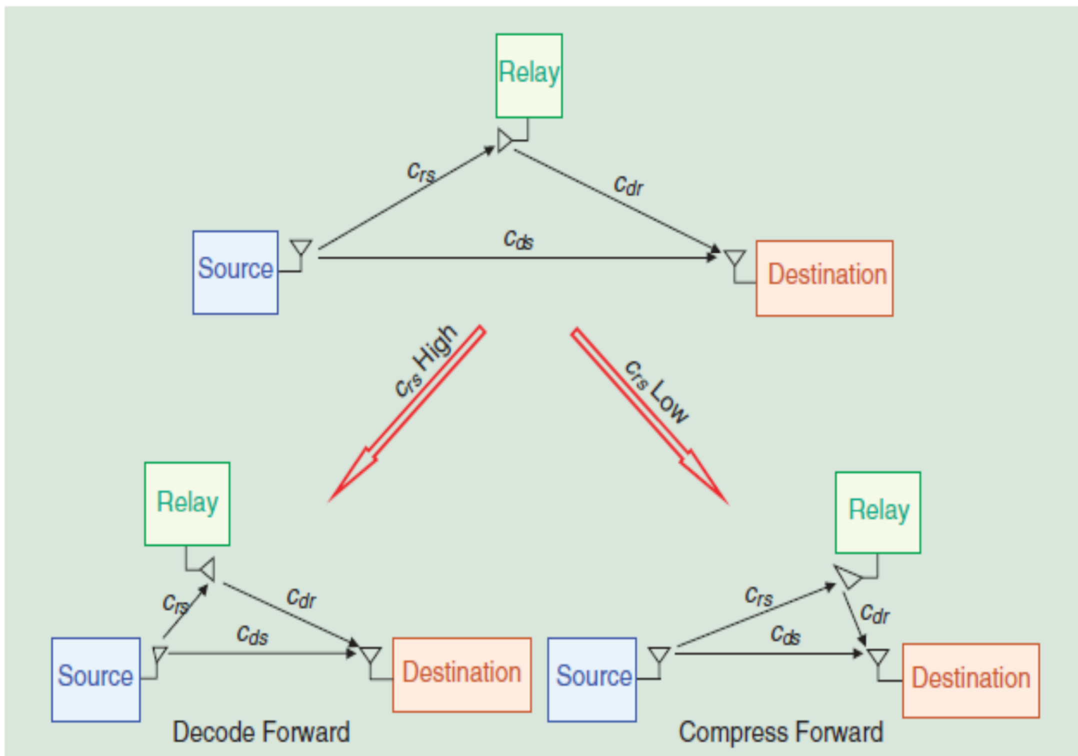


Figure 2.2 Wireless relay channels.

2.5.4.2 Diversity Combining Techniques

There are mainly four types of signal combining techniques in literature. These are equal gain combining, maximal ration combining (MRC), switched combining and selection combining. In case of equal gain combining, the receiver summed up all the versions of the received signals coherently. In case of MRC, the received signal is weighted with respect to SNR and then summed up. In case of switched combining, the receiver switches to another signal if the currently selected signal level drops below a predefined threshold. In selection combining, if there are n number of received signals, the strongest one selected by the receiver and others are ignored.

2.5.4.3 Relay Transmission Topology

Although relay transmission topology in cooperative diversity is dynamic, normally two main transmission topologies are studied. These are serial relay transmission and parallel relay transmission.

2.5.4.3.1 Serial Relay Transmission Topology

In this topology, signals are transmitted from one relay node to another relay node in cascading style. This topology for relay transmission is used for long distance relay data transmission. In this topology, the power gain of the relay transmission is increased. The channels among the neighboring nodes are orthogonal to avoid interferences.

2.5.4.3.2 Parallel Relay Transmission Topology

If serial relay transmission suffers from multipath fading, to increase robustness against multipath fading parallel relay transmission may be used. In this topology signals are propagated through multiple relay paths in the same hop, the destination combines the received signals from multiple paths using combining techniques discussed in section 2.5.4.2. It provides power gain and diversity gain without installing multiple antennas in the relay nodes.

2.6 Cooperation in Different Layers

In this sub section I discuss cooperation in different layers of the OSI reference model. Three layers have been identified so far and the researchers the devising new metrics and methods to deploy cooperation in physical layer, data link layer and network layer.

In physical layer, Amplify and Forward (AF), Decode and Forward (DF) and Compress and Forward (CF) protocols are used broadly in cooperation communication. These techniques have been briefly described in section 2.5.4.1. Adaptive AF and DF are also used in addition to fixed AF and DF to improve the performance capacity of the communication system. In physical layer cooperation, individual signals from the source are re-transmitted by the relay nodes.

The MAC sub layer of the data link layer uses different protocols for providing collision free medium access to the users and for diversity gain. Although CDMA, TDMA and FDMA utilizes codes, time and frequency for the cooperative diversity in the MAC layer, the main drawback of the of those diversity techniques is that cooperation is achieved by the cost of valuable resources, i.e., data rates, time and bandwidth. For long range diversity, spatial diversity can be used. However, spatial diversity is not an opportunistic relaying method [20]. To provide cooperative diversity using CDMA, TDMA and FDMA, the complexities in devising optimal methods are the increasing functions of number of users in the network. Although sub optimal solutions are also provided [21], it comes with extra overhead in the receiver structure which is cost-inefficient in designing cheap wireless devices. The main challenges in cooperative MAC design are to find out the best relay to transmit the overheard packets from the source to the destination. Cooperation in MAC layer requires less overhead than in the physical layer cooperation. There are a number of cooperative MAC protocols have designed, i.e., rDCF[5], CoopMAC[7], CDMAC[10], ADCMAC[11] etc. Some of these protocols send control packets before sending the original data frame to select the relay nodes and some uses fixed relay nodes. Based on the relay selection strategies, A cooperative MAC can be broadly categorized into two classes: proactive cooperative MAC and on demand cooperative MAC. In case of former class, a sender node maintains a table of the list of possible relay nodes, i.e., CoopMAC[7]. In the latter case, sender selects relay nodes during the data transmission or data is transmitted by both the senders and relay node simultaneously, i.e., CDMAC [10]. Another class of Cooperative MAC protocols exploits the advantages of Automatic Repeat Request (ARQ) [22] for achieving cooperative diversity. In this method, relay node that is closer to the destination gets higher priority in retransmitting overheard packets.

Researchers are also devising methods for adapting cooperative routing techniques in the network layer of the OSI reference model. Azgin *et al.* have designed a cooperative routing mechanism base on CMAC [23]. According to this protocol, they have also showed that in addition to achieving gains in throughput, the energy gain is also possible using CMAC. This protocol uses different control messages such route request (RREQ) and route reply (RREP) for exchanging information among neighbors and in finding the best relaying path. By exploiting the Bellman-Ford dynamic programming algorithm in finding the shortest path, Ibrahim et al. have designed an energy efficient cooperative routing protocol [24].

To exploit the benefits of cooperative communications offered by the network and physical layers, cross layer cooperation techniques are being studied. CD MAC [10] is an example of cross layer cooperative MAC protocol. This protocol utilizes physical layer cooperation and space time coding techniques. In this protocol each node monitors its neighbors and finally selects a single relay station from a set of multiple relay stations. As it uses space time coding cooperation, this protocol is more robust to fading.

In network layer, for cooperative routing protocol design, source station requires to find out a suitable route and relay station which is a time consuming task. The source station must resend the data if the first packet is lost. This leads to more delay and requires more overhead and as well as consumes more power. Cooperation in MAC layer is more real times. Protocols in lower layers of the OSI reference model operates in real time. Control overhead in MAC layer cooperation can be reduced by adopting an efficient and effective relay station as well as the consumed power of the network system. As the cooperation in MAC sub layer provides more opportunities, this thesis I have considered designing a cooperative MAC that is backward compatible with IEEE 802.11 DCF MAC.

2.7 MAC layer and Existing Protocols

The following Figure 2.3 states the region of the work in this thesis. This thesis focuses on the MAC sub layer of data link layer in OSI reference model.

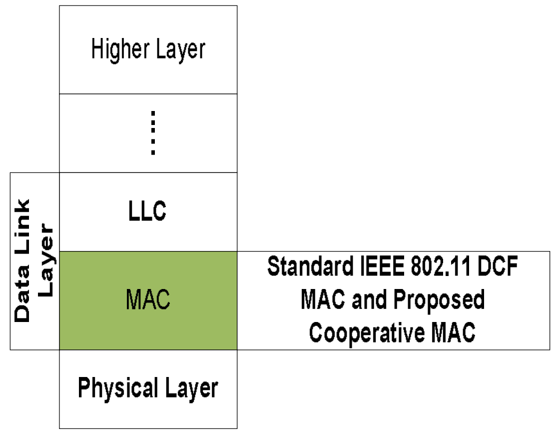


Figure 2.3 OSI reference model, standardization and Implementation area of the proposed Cooperative MAC protocol

2.7.1 Issues in Designing a MAC layer protocol

Access to the shared medium should be controlled in such a way that wireless nodes receive fair share of the available bandwidth. Hence, the bandwidth utilization is efficient. Issues in designing a MAC protocols for WLAN are:

2.7.1.1 Bandwidth Efficiency

Bandwidth available for communication is limited. While designing a MAC protocol, the control overhead must be kept minimal. Bandwidth efficiency can be defined as the ration of the bandwidth used for actual data transmission to the total available bandwidth. A MAC protocol must try to maximize the bandwidth efficiency.

2.7.1.2 Quality of Service (QoS)

Nodes in infrastructure less WLAN may be mobile with time. In mobile environment providing proper quality of service, i.e., throughput, end to end delay etc. is very difficult. A MAC must take the mobility of the wireless medium and nodes into consideration. Services for the real time applications must be addressed properly.

2.7.1.3 Synchronization

Synchronization in access to medium must be maintained among the wireless nodes. Synchronization is very important for bandwidth efficiency. A MAC protocol should not exchange excessive control packets in achieving synchronization.

2.7.1.4 Error Prone Shared Broadcast Channel

A node should be given access to the medium only when its transmission does not affect any ongoing data transmission. Since wireless medium is broadcast in nature, collisions among multiple packets may take place. A MAC protocol should grant a node access to wireless channel in such way that overall collisions are minimized.

2.7.1. 5 Lack of Central Coordination

In Ad hoc network, nodes do not have any central coordinators. Therefore, Access to medium must be handled in distributed manner. This may take some additional control overheads which could be the cause of system throughput degradation.

2.7.1.6 Mobility of Nodes

Nodes in adhoc network are mobile most of the time. If the node mobility is very high, control information among the nodes may be wasted. Thus the throughput of the system would be decreased. A MAC protocol design must take this mobility factor into consideration that the performance of the wireless network system is not significantly affected by node mobility

2.7.2 Multiple Access Techniques in MAC layer

Since the transmission medium in wireless communication is broadcast in nature, a wireless node cannot transmit its data frame haphazardly. Several multiple access techniques have been developed to control the access of the wireless nodes to the medium. Those techniques determine the way in which the node would share the wireless channel. Multiple access techniques in wireless network are based on the orthogonalization of signals. Each signal is represented as a function of time, frequency and code. Hence multiplexing can be performed using one of these parameters. There are three basic multiple access techniques: Time Division Multiple

Access, Frequency Division Multiple Access, Code Division Multiple Access and Space Division Multiple Access. This discussion is the summary of [27].

2.7.3 Classifications of Multiple Access Protocols

Many formal protocols have been design to control the multiple access of the shared medium in a multipoint environment. The following figure shows the classification of such multiple access protocols. Figure 2.4 broadly categorizes the existing MAC protocols.

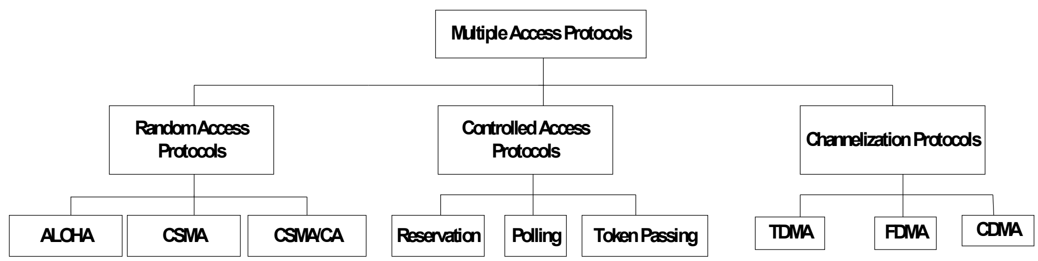


Figure 2.4 Categories of Multiple Access Protocols

2.7.4 Time Division Multiple Access (TDMA)

In Time Division Multiple Access, all the wireless stations share the bandwidth of the channel in time. The time is divided into several time slots. Each station is assigned a specific time slot. During that time slot, the station transmits its data. In dynamic TDMA, time slots can be assigned on demand. Synchronization among multiple stations is the main problem in TDMA. Each station needs to know the beginning of a slot and the location of the slot. To alleviate the synchronization problem, guard time is inserted between two consecutive time slots. This overhead reduces the capacity of the wireless system. The equipment cost in TDMA is less than FDMA. Hence, it widely used in cellular systems.

2.7.5 Frequency Division Multiple Access (FDMA)

In this technique the available bandwidth is divided into multiple frequency sub bands. Each wireless station is assigned a specific band of frequency. Every station sends data through its assigned band all the time. Each station also uses a band pass filter to capture the transmitter frequency. To prevent interferences among the contiguous sub band, two sub bands are separated from each through small guard band.

2.7.6 Code Division Multiple Access (CDMA)

In CDMA, each wireless station uses the whole wireless spectrum while transmitting data. It defers from FDMA because only one channel occupies the entire bandwidth. It defers from TDMA because all stations can send data simultaneously. There is no time sharing. Each station is assigned a specific code. A station sends data using its code. The codes are orthogonal to each other. Hence no interferences occur in simultaneous data transmission by all stations.

2.7.7 Space Division Multiple Access (SDMA)

This technique uses directional transmitters/antennas instead of omnidirectional antennas used TDMA, FDMA or CDMA. Directional antennas can cover angular geographical regions. Therefore, different regions can be served using same frequency channel. This technique mainly used satellite systems. A satellite can reuse the same frequency to cover many different regions of the earth surface.

2.7.8 Classifications of CSMA/CA based MAC protocols

MAC protocols for wireless networks can be classified using various criteria such as initiation approach, time synchronization and reservation approaches. These are: contention based protocols, contention based with reservation mechanisms and contention based with scheduling mechanism.

2.7.8.1 Contention Based Protocols

In this technique, a node does not make any *priori* resource reservation. In this technique whenever a node needs to send a data packet it contends with it neighbor nodes to access the shared channel. Contention based protocols cannot provide required QoS guarantees to real time applications since the wireless stations are not allowed guaranteed regular access to the wireless medium. The following Figure 2.5 shows the available widely used contention based MAC protocols. Contention based protocols are: MACAW(Multiple Access Collision Avoidance for Wireless LANs), FAMA(Floor Acquisition Multiple Access Protocols), BTMA (Busy Tone Multiple

Access Protocols), MACA-BI(Multiple Access Collision Avoidance –By Invitation), MARCH(Medium Access With Reduced Handshake),

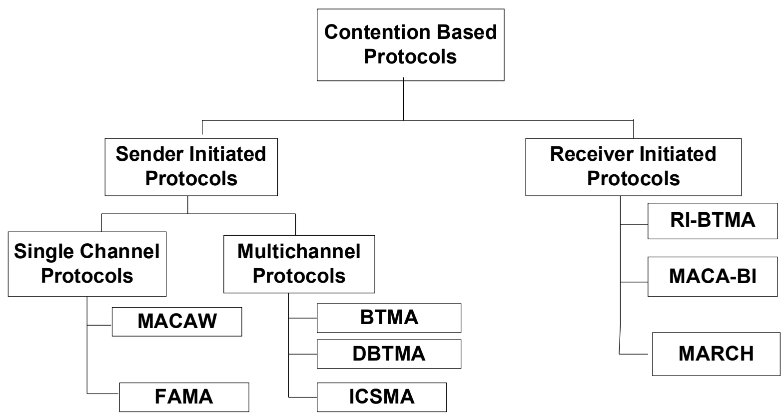


Figure 2.5 Contention Based MAC Protocols

2.7.8.2 Contention Based Protocols with Reservation Mechanisms

To support quality of services in wireless networks for real time traffic applications, MAC protocols must maintain reservation of resources, i.e., bandwidth for a particular data transmission a *priori*. Those protocols can support QoS to time sensitive traffic sessions. These protocols fall in the two categories: Synchronous and Asynchronous protocols. **Synchronous** protocols require time synchronization among all the wireless nodes in the network. The bandwidth for a particular data transmission session must be known by the neighbors of the communicating pair. Although achieving time synchronization is difficult, it does require extra control packets transmission among the nodes. Some of the protocols of this types are: D-PRAMA(Distributed Packet Reservation Multiple Access Protocol), CATA (Collision Avoidance Time Allocation Protocol), HRMA(Hop Reservation Multiple Access Protocol), SRMA/PA(Soft Reservation with Priority Assignment), FPRP(Five Phase Reservation Protocol). In case of Asynchronous protocols, global time synchronization among the nodes is not required. Nodes use only the relative time information in effective bandwidth reservation. Example of such type of protocols is: MACA/PR (MACA with Piggy-Backed Reservation), RTMAC (Real Time Traffic Support for Wireless Ad Hoc Network Protocol). Figure 2.6 depicts categories of contention based with reservation MAC protocols.

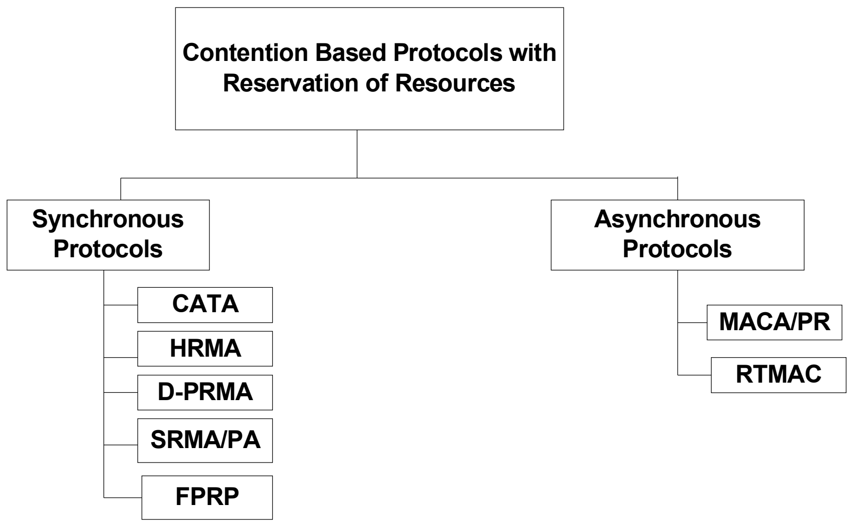


Figure 2.6 Contention Based with Reservation Mechanism MAC Protocols

2.7.8.3 Contention Based Protocol with Scheduling Mechanisms

These types of protocols support both packet scheduling and node scheduling for access to the wireless channel. Node scheduling is achieved in a manner so that all nodes get fair access to the medium and no node starve for bandwidth. Flow based priority is also supported through these protocols. Some protocols also take into consideration the battery characteristics such as remaining batter power in scheduling the node access to the medium. Scheduling decisions takes into consideration various factors, i.e., delay target of a packet, laxities of packets, traffic load at nodes and the remaining battery power at nodes. Examples of these types of protocols are: DPS (Distributed Priority Scheduling and Medium Access in Wireless Networks).DWOP (Distributed Wireless Ordering Protocol), DLPS (Distributed Laxity Based Priority Scheduling Protocol).

2.8 Summary

Channel modeling over small scale and large scale fading is described in this chapter. Different signal relaying techniques such as decode and forward, compress and forward and amplify and forward are depicted. Issues related to MAC protocol design and different existing MAC protocols are also described. Benefits of cross layer cooperative protocols for the higher layers in the OSI reference model has been furnished in this chapter. Different medium access mechanisms which are the sole background of this thesis are also described in this chapter.

CHAPTER 3

EXTENDED ANALYTICAL MODELING OF IEEE 802.11 DCF MAC

DCF (Distributed coordination function) is based on carrier sense multiple access with collision avoidance (CSMA/CA) protocol. It is widely used multiple access mechanism for wireless local area networks. In IEEE 802.11 DCF, shared medium is dedicatedly allocated to the contending stations assigned to two communicating stations. While the medium is assigned to a communication party other stations inside their proximity cannot access or transfer data during that data transmission session. There are two access mechanisms in IEEE 802.11 DCF MAC. Its frame structures are shown in Figure 3.1. In this chapter, analytical modeling and analysis of IEEE 802.11 DCF MAC is described. This analysis and model is used to evaluate the performance of the proposed cooperative MAC.

	Frame Control	Duration	DA	SA	FCS
Octates:	2	2	6	6	4

(a) RTS Frame Format for IEEE 802.11 DCF

	Frame Control	Duration	SA	HA	FCS
Octates:	2	2	6	6	4

(b) HCTS Frame Format for Cooperative MAC

	Frame Control	Duration	DA	FCS
Octates:	2	2	6	4

(c) CTS , ACK frame Format for IEEE 802.11 DCF MAC

DA : Destination MAC Address,
SA : Source MAC Address
HA : Helper Station MAC Address
SC : Sequence Control
FCS : Frame Check Sequence

	Frame Control	Duration/ID	Address1	Address2	Address3	SC	Address4	Pay Load	FCS
Octates:	2	2	6	6	6	2	6	N	4

(d) MAC Header Format of IEEE 802.11 DCF MAC

	Protocol Version	Type	Sub Type	To DS	From DS	More Flag	Retry	Power Mgt	More Data	WEP	Order
Bits :	2	2	4	1	1	1	1	1	1	1	1

(e) Frame Control Format of IEEE 802.11 DCF MAC

Figure 3.1 Frame Structure of IEEE 802.11 DCF MAC

3.1 Basic Access Mechanism

In order to mitigate the collisions within a collision domain, every wireless station using IEEE 802.11 DCF follows random binary exponential back off algorithm (BEB). This randomized algorithm controls wireless stations in accessing the wireless medium. Particularly, the time is slotted. Every station is allowed to transmit at the beginning of a time slot. A slot time is the time required to detect the transmission of a frame from any other station. A station cannot transmit until its back off counter is decremented to zero. The back off counter of a station is decremented while the medium is sensed idle and frozen while it is busy. Back off counter is reactivated again while the station senses that the medium is idle for more than a DIFS time. In order to track its back off counter, every station maintains a contention window (CW). Each station has a maximum retry count which indicates the number of times a frame can be retransmitted due to its transmission failure. The value of CW is chosen between (0, CW-1). Value of CW depends on the number of failure of a frame transmission. At the first time, CW is set to its minimum value, CW_{min}. If a collision during a frame transmission, CW value is doubled. CW has a maximum value which is $CW_{max}=2^k xCW_{min}$, where k is the maximum number of retry limit. If the CW reaches to its maximum, it will remain in its maximum until the CW is reset to CW_{min}. CW is set to its minimum in case of a successful frame transmission or if the maximum retry limit for a frame is reached. If the frame transmission for a station is not successful until the maximum retry limit is reached, the station shall quit and discard that frame transmission. If a station has a frame, it senses the medium for DIFS (Distributed Inter frame Space) time. If it finds the medium idle during that time and its back off counter is zero, it simply sends the frame. CSMA/CA cannot detect a collision. After frame is received correctly in the receiver, the destination station sends an acknowledgement (ACK) of the receipt frame to the sender. The destination station sends ACK after SIFS (Short Intra frame Space time. The length of SIFS is shorter than that of DIFS. If there are more frames queued in the sending stations it must follow the same procedure each time it tries to send a frame.

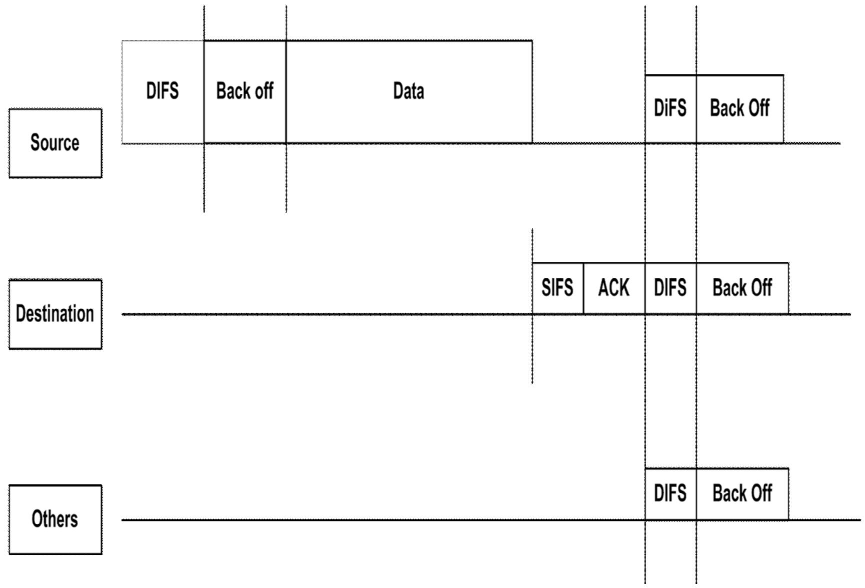


Figure 3.2 IEEE 802.11 Basic Access Mechanisms

Basic access process is shown in Figure 3.2. In IEEE 802.11 DCF basic mechanism, a collision may occur during frame transmission and ACK transmission. In both cases the sending station retransmits the frame.

3.2 IEEE 802.11 RTS-CTS Access Mechanism

Due to the broadcast nature of wireless signal transmission, basic access mechanism has two problems, i.e., hidden station problem and exposed station problem. To deal with the former problem, IEEE 802.11 DCF has employed RTS and CTS control frames. Introduction of these two control frames minimizes the extra time required due to more frequent collisions in heavily loaded wireless transmission system. The frames RTS and CTS carry the information of the length of the packet that will be transmitted by the source station. Other overhearing stations get the information of the length of the transmitted packet. Other stations update their respective network allocation vector (NAV). It contains the information during which the channel will remain busy. Therefore, hidden terminal station can be solved. In this mechanism, after the station finds the medium idle for DIFS time, it sends a RTS frame to the destination station. If the RTS frame is received by the destination correctly, it replies to the source station with a CTS frame after a SIFS time interval. The source after upon receiving a CTS frame from the receiver, it sends the frame spending a SIFS time interval. After the data frame is received by the destination station, an ACK frame is sent to source after SIFS time. The successful transmission of RTS and CTS frames between the two communicating stations keeps the medium reserved for a particular data transmission session.

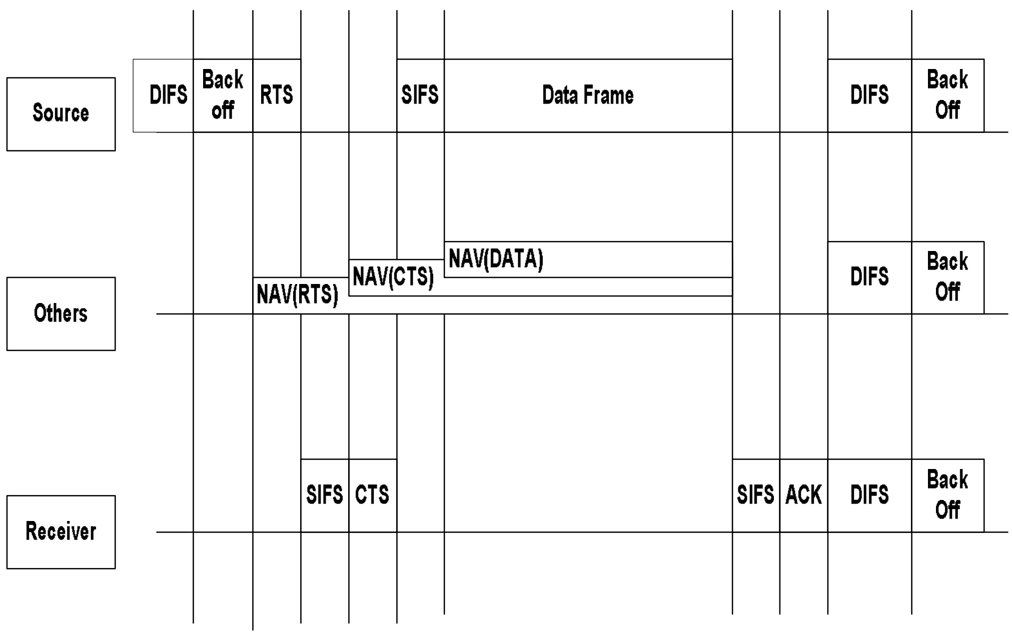


Figure 3.3 IEEE 802.11DCF RTS/CTS Access Mechanism

Control frame time lines of RTS-CTS access mechanism are shown in Figure 3.3. Therefore, the collision time is kept minimized for a long data frame which was imminent in IEEE 802.11 DCF basic access mechanism. The sending station uses a parameter RTS threshold in determining which mechanism it should invoke. RTS threshold is determined by the size of the payload the frame will be carrying. In this mechanism, a collision can only be occurred during RTS frame transmission.

Two problems are related to the IEEE 802.11 DCF MAC access mechanism. These are hidden and exposed station problems.

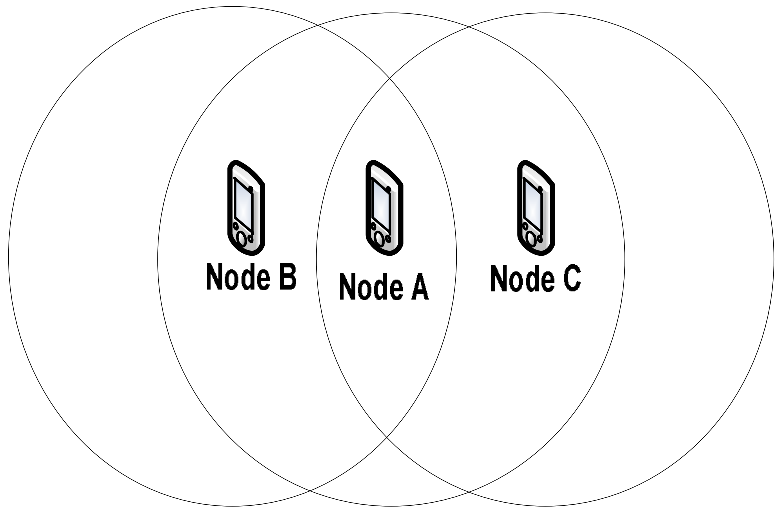


Figure 3.4 Hidden Terminal Problems in IEEE 802.11 DCF MAC and Cooperative MAC

3.3 Hidden Station Problem

In wireless network, a hidden terminal is a wireless station that is out of the range of another wireless nodes or collection of nodes. In Figure 3.4, both node B and node C are not within each other's transmission range. Node B and node C both are within the transmission range of node A. Both node B and node C may try to send data to node A. When node B sends data to node A, node C does not hear the transmission and vice versa. Therefore, if both station B and C transmit at the same time to node A, collisions take place. Throughput of the wireless network system decreases. RTS/CTS mechanism alleviates hidden node problem in wireless network.

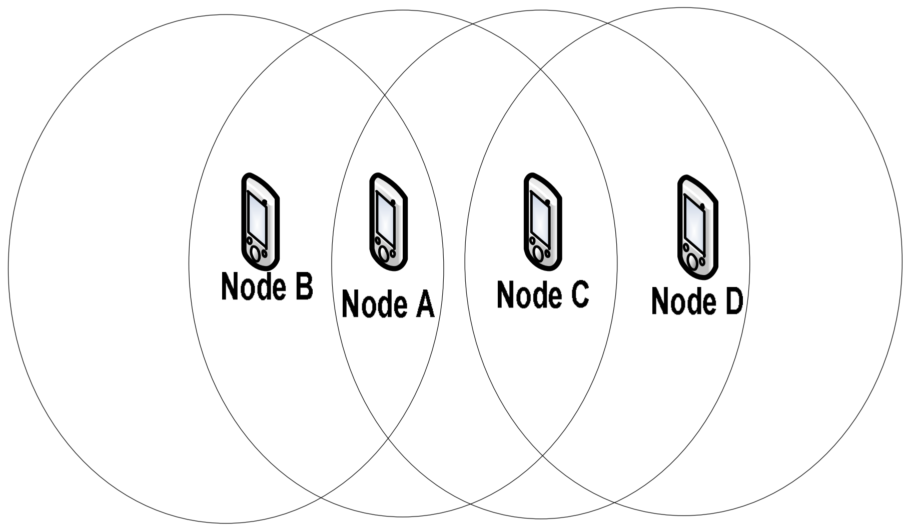


Figure 3.5 Exposed Station Problems in IEEE 802.11 DCF MAC and Cooperative MAC

3.4 Exposed Station Problem

In Figure 3.5, when node A transmits data to node B, node C also overhears this data transmission. If node C has data to transmit to node D, node C refrains from transmitting its data to node D. if node C transmits data to node D, its transmission will collide at node A. Therefore, node A's transmission will be interrupted. Although node C transmission may not collide node B, but it will not transmit due as if the channel is busy. Hence, it is said that transmission from node A to node B exposed to node D. Transmission capacity is decreased.

3.5 Analysis of IEEE 802.11 DCF MAC using Markov Model

IEEE 802.11 DCF MAC perfectly utilizes the contention window size that becomes double every time a collision is occurred of a frame transmission. The analysis carried out in this thesis is similar to [25].

3.5.1 Description of the Model

It is a two dimensional discrete time markov chain. This model is described in Figure 3.6. In this model time (t) represents the slot time. For an example, t and $t+1$ are the two consecutive time slots in IEEE 802.11 DCF MAC. For each state $\{s(t), b(t)\}$, where $s(t)$, represents a stochastic process resembling the back off stages $(0, 1 \ldots . m)$ of a station at time t and $b(t)$, represents a stochastic process resembling the back off counter of station at time t.

In this model, while a station transmits, its data packet collides in each transmission attempt regardless of the number of retry with probability p $(0 <= p <= 1)$. CW_i indicates the contention window size in IEEE 802.11 DCF MAC at stage i $(0 <= i <= m)$ i.e., contention window size of a station depends on the current back off stage of that station at time t. The back off counter of a station is set to CW_{min} if a transmission is successful. If there is a collision in the transmission of a station, that station goes to the next stage with doubling its contention window size. The value of the back off counter $b(t)$, is uniformly chosen in the range of $\{0,1,2, \ldots \ldots CW_i\}$ where

$$CW_i = \begin{cases} 2^i(CW_{min} + 1) \ , \ 0 \le i \le m' \\ 2^{m'}(CW_{min} + 1) \quad , m' < \ i \le m \le R_{limit} \end{cases} \tag{3.1}$$

Where R_{limit} the maximum numbers of retry limit for transmission of a frame and m is the maximum number of back off stages. According to IEEE 802.11 DCF, contention window size becomes double every time a collision occurs until a maximum size is reached. After the contention window size is reached to its maximum due to collisions, it remains fixed to that maximum limit if further collision occurs. So, m being the index of maximum back off size, can take values larger or smaller than m' , where m' represents the stage in which the contention window reaches to its maximum.

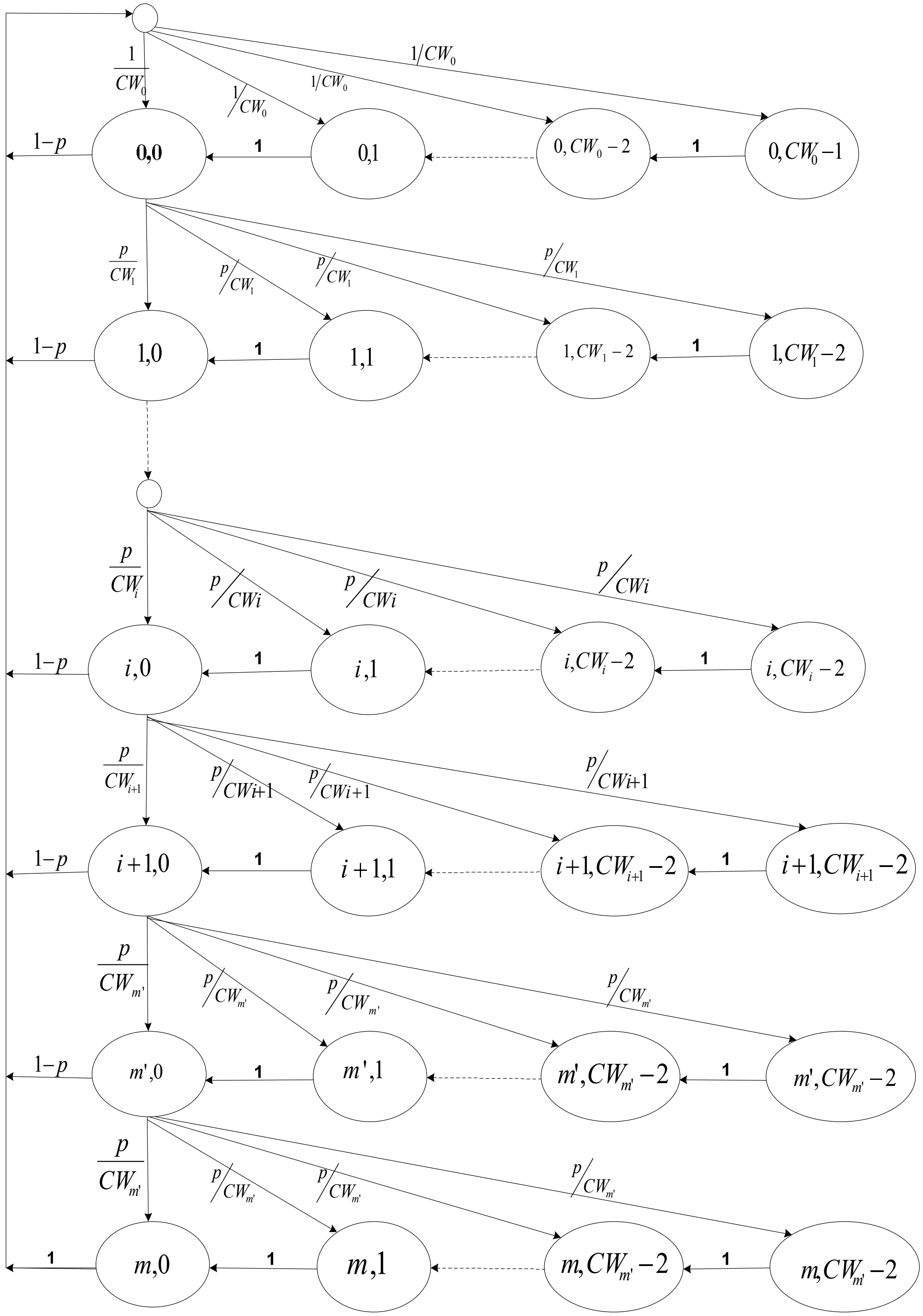


Figure 3.6 Analytical Markov Model for IEEE 802.11 DCF MAC

Let, $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}, i \in [0, m] and\ k \in [0, CW_i - 1]$ be the stationary distribution of the above discrete time markov model. Therefore, meaningful transition probabilities can be written as follows:

$$P[(o,k)|(i,0)] = \frac{1-p}{CW_0}, \qquad 0 \le k \le CW_0, 0 \le i < m$$

$$P[(o,k)|(m,0)] = \frac{1}{CW_0}, \qquad 0 \le k \le CW_0, \quad i = R_{limit}$$

$$P[(i,k)|(i,k+1)] = 1, \qquad 0 \le k \le CW_i, \qquad 0 \le i \le R_{limit}$$

$$P[(i,k)|(i-1,0)] = {}^{p}/_{CW_i}, \qquad 0 \le k \le CW_i, \qquad 0 \le i \le m'$$

$$P[(i,k)|(i-1,0)] = {}^{p}/_{CW_{m'}}, \qquad 0 \le k \le CW_{m'}, \qquad m' < i < R_{limit}$$

A transmission occurs while the back off counter reaches to zero. Thus, we can write from the above Markov model, the probability that a station transmits in a randomly chosen slot time as:

$$\tau = \sum_{i=0}^{m} b_{i,0} \qquad (3.2)$$

As, the above markov model is stationary, therefore, the transition probabilities of the chain can be written for $b_{i,0}$, $b_{m,0}$ $and\ b_{i,k}$ as follows:

$$b_{i,0} = p^i b_{0,0} \qquad for\ 0 \le i < m \qquad (3.3)$$

$$b_{m,0} = p^m b_{0,0} \quad for\ \ i = m$$

As the chain is regular, for each $k \in [0, CW_i]$, we can write

$$b_{i,k} = \frac{CW_i - k}{CW_i} \begin{cases} (1-p).\sum_{s=1}^{m-1} b_{s,0} + b_{m,0} & for\ i = 0 \\ b_{i,0} & for\ 0 < i \le m \end{cases} \qquad (3.4)$$

From (3.3) and (3.4)

$$b_{i,k} = \frac{CW_i - k}{CW_i}\ b_{i,0} \qquad for\ 0 \le i \le m \qquad (3.5)$$

(3.3) and (3.5) expresses all the state transitions in the markov model as the function of $b_{0,0}$ and as the probability of collision p. By applying normalization condition of stationary markov model, we can write

$$\sum_{k=0}^{CW_i-1}\sum_{i=0}^{m} b_{i,k} = 1 \tag{3.6}$$

$$\cong \sum_{k=0}^{CW_i-1}\sum_{i=0}^{m} \frac{CW_i-k}{CW_i}\, b_{i,0} = 1$$

$$\cong \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{CW_i-1} \frac{CW_i-k}{CW_i} = 1$$

$$\cong \sum_{i=0}^{m} b_{i,0}\, \frac{CW_i+\mathbf{1}}{\mathbf{2}} = 1 \tag{3.7}$$

By solving (3.7) with the help of (3.1), we get the value of $b_{0,0}$

For $i \leq m \leq m'$,

$$\sum_{i=0}^{m} b_{i,0}\, \frac{CW_{\boldsymbol{i}}+1}{2} = 1$$

$$\cong \sum_{i=0}^{m} b_{i,0}\, \frac{2^i(CW_{min}+1)+\mathbf{1}}{\mathbf{2}} = 1$$

$$\cong \sum_{\mathrm{i}=0}^{\mathrm{m}} p^i b_{0,0}\, \frac{2^{\mathrm{i}}(\mathrm{CW_{min}}+1)+\mathbf{1}}{\mathbf{2}} = 1$$

$$\cong \frac{b_{0,0}}{2}\left[(CW_{min}+1)\sum_{i=0}^{m}(2p)^i + \sum_{\mathrm{i}=0}^{\mathrm{m}} p^i\right] = 1$$

$$\cong \frac{b_{0,0}}{2}\left[(CW_{min}+1)\frac{1-(2p)^{m+1}}{1-2p} + \frac{1-\mathrm{p}^{\mathrm{m}+1}}{1-\mathrm{p}}\right] = 1$$

Therefore, $$b_{0,0} = \frac{2(1-2p)(1-p)}{(CW_{min}+1)(1-(2p)^{m+1})(1-p)+(1-2p)(1-\mathrm{p}^{\mathrm{m}+1})} \tag{3.8}$$

Accordingly, $for\ m' < i \le m = R_{limit}$

$$\sum_{i=0}^{m} b_{i,0}\ \frac{CW_i + 1}{2} = 1$$

$$\sum_{i=0}^{m'} b_{i,0}\ \frac{2^i(CW_{min} + 1) + 1}{2} + \sum_{i=m'+1}^{m} b_{i,0}\ \frac{2^{m'}(CW_{min} + 1) + 1}{2} = 1$$

Therefore,

$b_{0,0} =$

$$\frac{2(i-2p)(1-p)}{(CW_{min}+1)\left(1-(2p)^{m'+1}\right)(1-p)+(1-2p)(1-\mathrm{p}^{m+1})+(CW_{min}+1).2^{m'}.p^{m'+1}.(1-2p)(1-p^{m-m'})} \quad (3.9)$$

A station transmits when the back off counter reaches to zero. Probability a station transmits in a randomly slot time can be written using $b_{0,0}$ as follows:

$$\tau = \sum_{i=0}^{m} p^i \quad .b_{0,0}$$

$$\tau = \frac{1-p^{m+1}}{1-p} b_{0,0} \quad (3.10)$$

The value of τ can be derived using $b_{0,0}$ for $i \le m \le m'$ and $m' < i \le m = R_{limit}$ using (3.8) and (3.9) respectively.

Transmission probability of station on a time slot depends on the probability of collision p on a time slot. Collision happens whenever more than one station transmits on the same time slot. If a station transmit on a time slot and one of the remaining $(n-1)$ stations transmit on the same time slot, then the sender experience a collision. Therefore, Collision probability p on a randomly selected time slot can be derived as follows:

$$p = 1 - (1 - \tau)^{n-1} \quad (3.11)$$

Where, n is the total number station within a single transmission region.

(3.10) and (3.11) are a nonlinear system. This system can be solved numerically. The solution of the system depends on value of $n, m', and\ R_{limit}$. By setting these parameters appropriately unique solution for p , τ can be found.

3.5.2 Saturated Throughput Analysis

Assume that every station has frames in its queue to transmit. Therefore, there no queuing delays for transmission in this system. Let, p_b be the probability that the channel is busy. The channel remains busy if there is at least one station transmits in any given time slot. Assume that there are n stations which want to gain the channel access in a randomly selected slot time.

$$p_b = 1 - (1 - \tau)^n \quad (3.12)$$

Let, p_s be the probability that a successful transmission occurs in a time slot. A transmission will be successful if a station transmits in given time slot and other stations (n-1) within its transmission region refrain from transmission. However, there must be at least one transmission on going on that time slot. In other words, the channel must be busy in transmitting frames over that time slot. Therefore, it is a condition probability conditioned on p_b. So, the probability that only one station transmit in slot time out of n stations can determine as

$${}^{n}_{1}C\ \tau(1-\tau)^{n-1}$$

$$= n\tau(1-\tau)^{n-1}$$

Therefore, $$p_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (3.13)$$

Duration of a slot time= Fraction of idle time (no transmission) + fraction of time spent in collision+ fraction of time spent in a successful transmission.

Therefore, Throughput S can be derived using the following equation:

$$S = \frac{E[Payload\ in\ bits\ transmitted\ in\ a\ slot\ time]}{E[Duration\ of\ a\ slot\ time]}$$

$$S = \frac{p_b p_s E[L]}{(1-p_b)\pi + p_b p_s T_s + p_b(1-p_s)T_c} \quad (3.14)$$

Here, π , T_c, and T_s are duration of an empty time slot, average time spent in collision in a time slot and medium is sensed busy due to a successful transmission of a frame in a time slot respectively.

Table 3.1 IEEE 802.11b Physical Layer Parameters

MAC Header	224 bits
PHY Header	192 bits
ACK	112 bits +PHY Header
HCTS	112 bits +PHY Header
RTS	160 bits +PHY Header
CTS	112 bits + PHY Header
Channel Basic Data Rate	1 Mbps
Slot Time	20 µs
SIFS	10 µs
DIFS	50 µs

Using the Table 3.1 and (3.14) for IEEE 802.11b WLAN, throughput of IEEE 802.11 DCF MAC is found as the following figures. Figure 3.7 shows the throughput of 1 Mbps stations if the RTS or CTS mechanism is used.

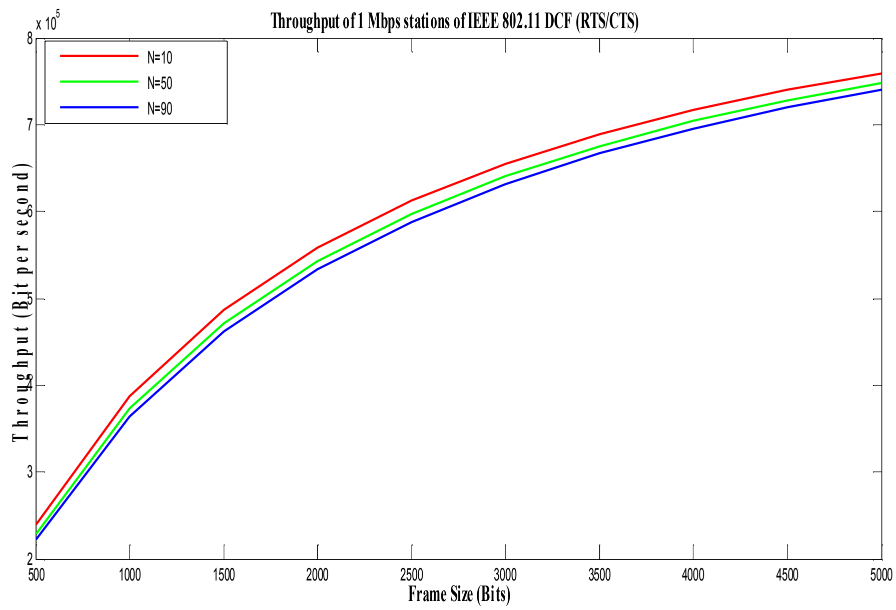


Figure 3.7 IEEE 802.11 DCF MAC Throughput of 1 Mbps stations against different Frame Sizes

Figure 3.7 shows that the throughput increases if the frame size increases. If number of wireless station increases, the relative gain in throughput is also decreases. This figure also shows the throughput for different number of wireless stations, N=10, 50 and 90. Throughput of 2 Mbps stations is shown in Figure 3.8. Throughput of 2 Mbps stations is higher than 1Mbps stations. Stations do not achieve full transmitting capacity due to overhead used in RTS-CTS access mechanism of IEEE 802.11 DCF MAC.

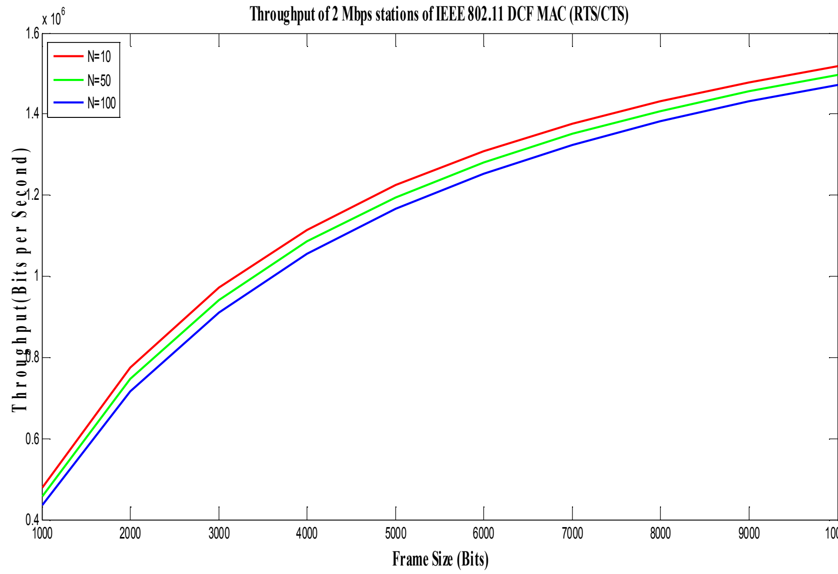


Figure 3.8 IEEE 802.11 DCF MAC Throughput of 2 Mbps stations against different Frame Sizes

3.5.3 Average Frame Delay Analysis

The duration between time when the frame is available at the head of the Line (HOL) of the transmitting station for transmission and the time at which its acknowledgement is received is considered the frame transmission delay. This analysis assumes that all stations have packets queued in its HOL.

Let $E[X]$ denotes the average number of time slots required for a station to transmit a frame successfully.

$$E[X] = \sum_{i=0}^{m-1} p^i . \frac{CW_i + 1}{2} + \frac{p^m (CW_m + 1)}{1 - p}$$

Simplified form of the above equation is,

$$E[X] = \frac{(CW_{min}+1)(1-2p)+pCW_{min}(1-(2p)^m)}{2(1-2p)(1-p)} \quad (3.15)$$

Let, T_{coe} is the average duration while the observed station itself occupies the channel during each unsuccessful retransmission attempt. As an unsuccessful retransmission occurs due to collision only, so we can write $T_{coe} = T_C$. T_C is the average time duration when the medium is sensed busy due to collisions among frames. Average time occupied by the observed station due to unsuccessful retransmissions can be calculated as

$$E[T_{collisionTime}] = \sum_{i=0}^{m-1} p^i .\ T_{coe}$$

$$= \frac{1-p^m}{1-p} . T_{coe} \qquad (3.16)$$

Therefore, Average Frame Delay $E[Delay]$ can be calculated as the following without considering frame dropped probability.

$$E[Delay] = E[X]. E[slot] + E[T_{collisionTime}] \qquad (3.17)$$

Where average length of a slot time, $E[slot] = (1 - p_b)\pi + p_b p_s T_s + p_b(1 - p_s)T_c$

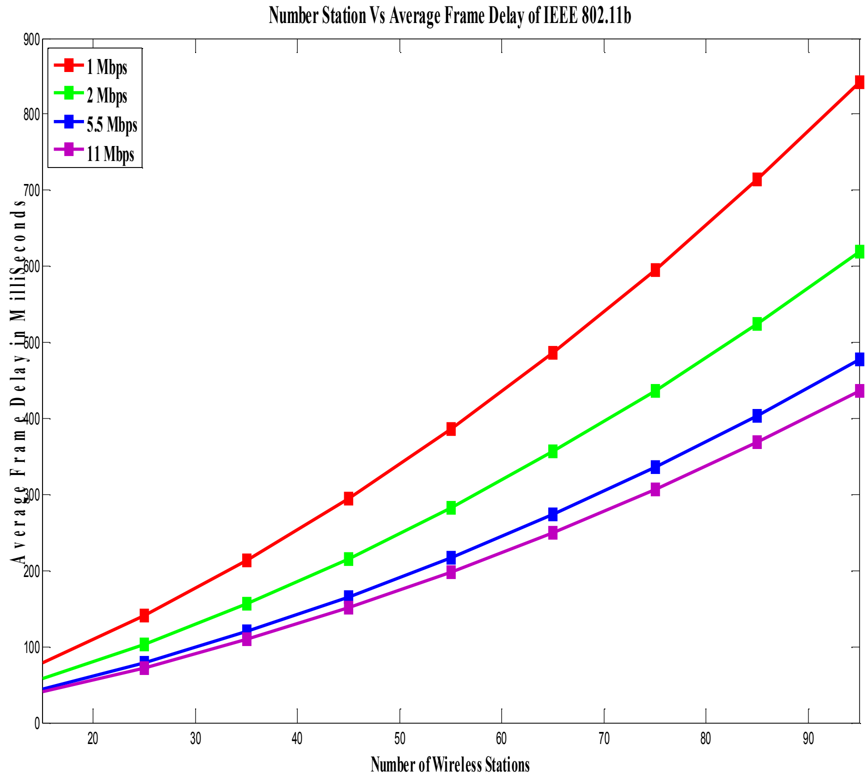


Figure 3.9 Average Frame Delay of IEEE 802.11b WLAN

Average frame delay of IEEE 802.11 b WLAN is shown in Figure 3.9. This outcome is the result of (3.17). Figure 3.9 reveals that average frame delay is increased if the number of wireless station increases while the frame size is kept fixed. In this case frame is 8112 bits. This figure reflects the analysis carried out in 3.5.3.

3.5.4 Packet Drop Probability

Let p_{drop} be the probability that a packet is dropped. Then p_{drop}^{m} is the probability that a packet will finally be dropped after m retransmissions.

In this analysis, packet retransmission is unsuccessful only because of collisions among multiple frames sent in a single time slot. Therefore, Probability that a packet is dropped due to collision after m retransmissions can be written as,

$$p_{drop}^{m} = [1 - (1 - \tau)^{n-1}]^{m} \tag{3.18}$$

Hence, $\frac{p_{drop}^{m}}{1-p_{drop}^{m}}$ represents average number of dropped frame relative to a successful frame transmission.

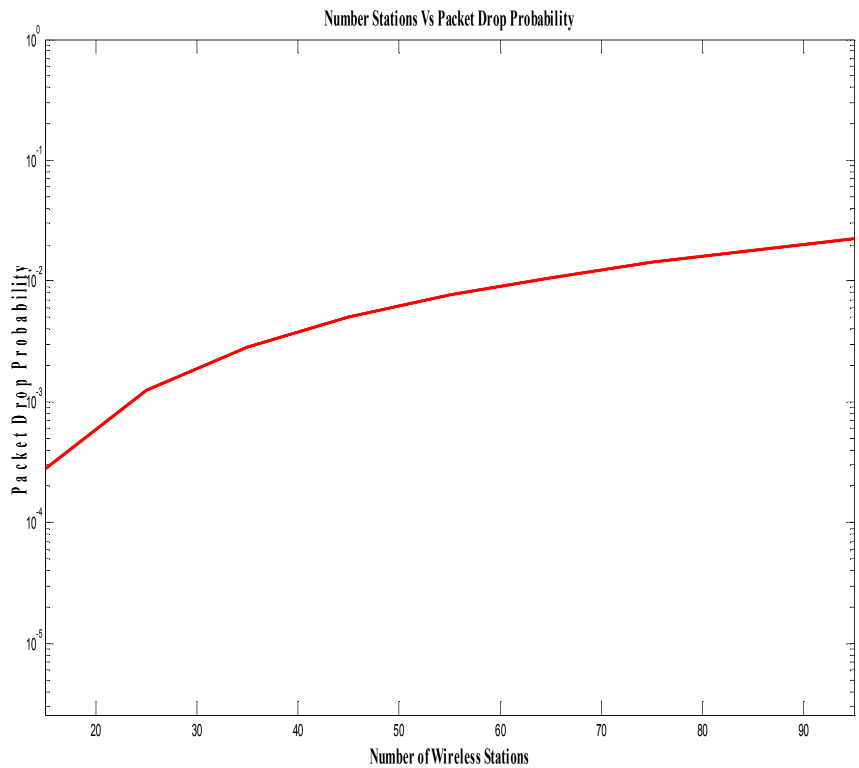


Figure 3.10 Packet Drop Probability of IEEE 802.11 DCF MAC

Figure 3.10 shows that probability that a packet transmission will be failed due to collision. Figure 3.10 is the outcome of (3.18) that uses values of different parameter presented in Table 3.1. The figure reveals that if the number of wireless station increases, probability that a transmitted packet will be dropped is also increased. Above analysis shows that if the number of wireless station is limited to less than 10, the packet dropped probability due to collision is negligible in IEEE 802.11 DCF MAC.

3.6 Summary

Legacy IEEE 802.11 DCF MAC protocol is fully depicted in this chapter. A markovian analytical model is derived and IEEE 802.11 DCF MAC is analyzed using the model. Throughput, end to end frame delay, packet drop probability and collision probability of IEEE 802.11 DCF MAC protocol are analyzed mathematically. Variations of different performance metrics of IEEE 802.11 DCF MAC against number of wireless stations and different frame sizes are shown graphically.

CHAPTER 4

A HELPER INITIATED DISTRIBUTED COOPERATIVE MAC

This chapter presents a cooperative MAC protocol. The protocol “A helper Initiated Distributed Cooperative Medium Access Control for Wireless Networks” is described. Various performance metrics such as throughput, end to end frame delay over error prone channel have been derived. The performance of this protocol is compared with the performances of legacy IEEE 802.11 DCF MAC.

4.1 Problem Formulation

In IEEE 802.11 DCF, all of the wireless stations within a single collision region get equal medium access gain during the saturation time. All wireless station dispose equal amount of time for transmitting their data frames. By exploiting this phenomena researchers are trying to initiate cooperation in the MAC sub layer of the data link layer. Usually stations that reside in the maximum transmission distance from an access point (AP) in wireless LAN transmits data frame using 1 Mbps data rate in IEEE 802.11b.Obviously, those low transmitting stations consume much time to transmit their data comparing to the high transmitting stations that resides within close proximity of the AP. Due to those low transmitting stations, high transmitting stations get much lesser average time to access the medium. Hence, the transmission efficiencies of those high transmitting stations are deteriorated. Therefore, it leaves the system throughput to be degraded. If low transmitting stations are aided by other high rate stations in relaying data frames on behalf of those low transmitting stations to the destination, system’s throughput performance is increases. On average, this facilitates all other stations to get more access time to the medium.

Adaptation of multiple rates by each wireless station plays significant role in designing cooperative MAC exploiting the spatial diversity is shown in Figure 4.1. More importantly, To make cooperative MAC protocol a standard for OSI reference model, an efficient and effective helper station selection algorithm must be devised with low overhead .

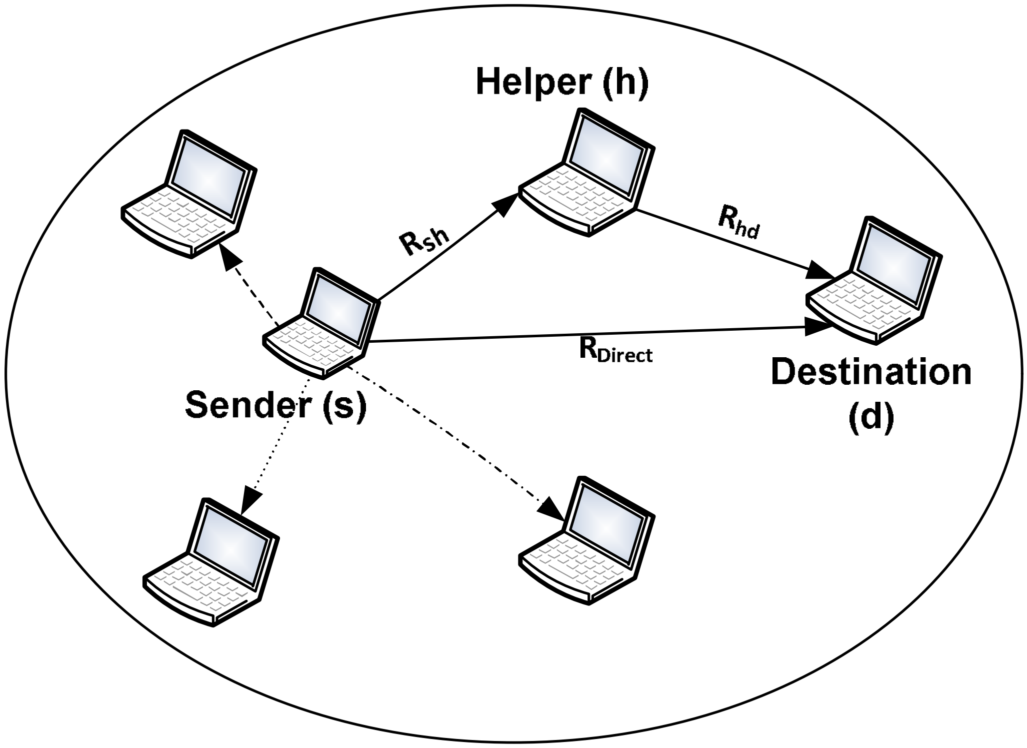


Figure 4.1 Cooperation Scenario

4.2 Cooperation Initiation

In addition to sending and receiving of its own data frame, each wireless station acts as a relay for other stations. In IEEE 802.11 DCF MAC, if a data frame is received by a station, it first examines the destination address field (DA) of the received frame. If the frame is not intended for the station, the station discards the frame by setting its own NAV (Network Allocation Vector) to the value of the duration field tagged inside the received packet header. Stations that hear both RTS and CTS control frames from sender and receiver respectively may act as the potential helper stations. Each potential helper station estimates effective data rate between itself and sender as well as itself and receiver by measuring the Received Signal Strength

(RSS) of the RTS and CTS control frames respectively [26]. Each potential helper station estimates the maximum direct data rate between the source and the destination pair by overhearing the Physical Layer Convergence Protocol Header (PCLP). Intermediate station that have sender- helper (itself), helper-receiver and sender-receiver link data rate information may declare itself as a potential helper stations for a particular data frame transmission session.

4.3 Relay Station Selection and CoopTable Maintenance

Each wireless station maintains a *CoopTable*. In IEEE 802.11, control frames and headers are always modulated at the base rate, i.e., 6 Mbps for IEEE 802.11a and 1 Mbps for IEEE 802.11b wireless networks [4]. Unlike [7] a *CoopTable* in our proposed protocol follows the format like in Table 4.1. Each row of the table keeps track of the updated transmission rate information of sender-helper and helper-receiver links. Each wireless node calculates the overheard RTS and CTS signal strength (RSS) within its proximity. Station which receives RTS and CTS control frame from both sender and receiver respectively assumes itself as a potential relay station for the ensuing data transmission session. Each relay station calculates maximum direct data rate between relay-sender and relay–receiver links through measuring the signal strength of RTS and CTS respectively. In either case, if maximum transmission rate is greater or equal than a threshold (5.5 Mbps for IEEE 802.11 b), it adds the source MAC address of RTS/CTS into its *CoopTable*. It also adds *timestamp* of the last received RTS/CTS frames into its *CoopTable*. If a relay station already has an entry of a neighbor station in its CoopTable from which it has just received an RTS/CTS and supported direct transmission rate is below a threshold, it discards that neighbor from its *CoopTable*. This filtering ensures that only the effective data transmission would take place through this helper keeping the size of the *CoopTable* minimum. Apparently a station considers itself as an effective relay for a particular data transmission session if it finds that [7]

$$\frac{1}{R_{sh}} + \frac{1}{R_{hd}} < \frac{1}{R_{sd}} \qquad (4.1)$$

Where R_{sh} and R_{hd} are data rate for two hop transmission from source to helper and helper to destination respectively. R_{sd} is the direct supported data rate from source to destination. Every intermediate station which hears both RTS and CTS gets the value of R_{sh} and R_{hd} from its $CoopTable$.

A helper station is selected in a distributed manner. If more than one intermediate station satisfies (4.1), each declares itself as the helper. All of the relays transmit HCTS to the sender at the same time. A collision may take place due to multiple HCTS frame transmission. To eradicate this collision, potential helper stations start their back off counter. Station, whose back off counter reaches to zero, senses the medium before sending HCTS. If a potential helper station finds the medium idle for DIFS time, it starts sending HCTS control frame to inform the source and receivers of its presence. All other intermediate stations that intended to be a helper finds the medium busy or their back off counter may not reach to zero. Although they could have been potential helper stations but they refrain from sending HCTS. Therefore, only one station among multiple relay stations becomes a helper station for a particular frame transmission session.

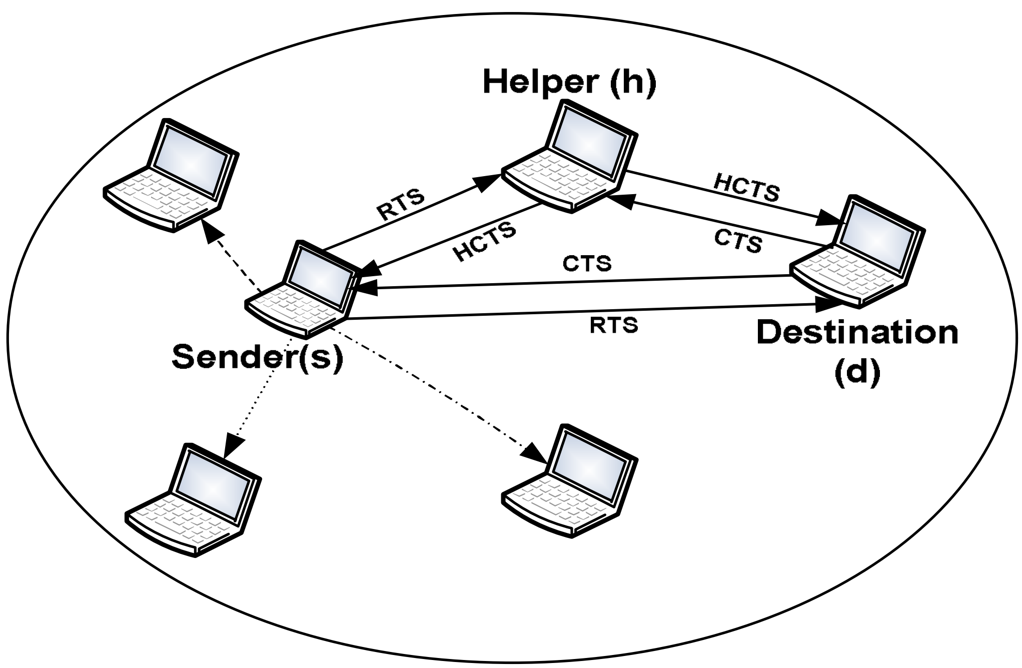


Figure 4.2 Control Frames Exchange in Cooperative MAC

4.4 Data Transmission using a Relay

Control frame hand shaking in this proposed MAC is depicted in Figure 4.2.If a source has a frame to transmit it sends RTS using IEEE 802.11DCF. All other stations within its transmission range overhear this RTS. If the RTS-CTS are not enabled during control frame hand shaking, our proposed cooperative MAC is disabled. This decision is made using RTS threshold. In basic access method, cooperative MAC mechanism is not triggered. In non-cooperative mode sender sends its frame directly to the receiver.

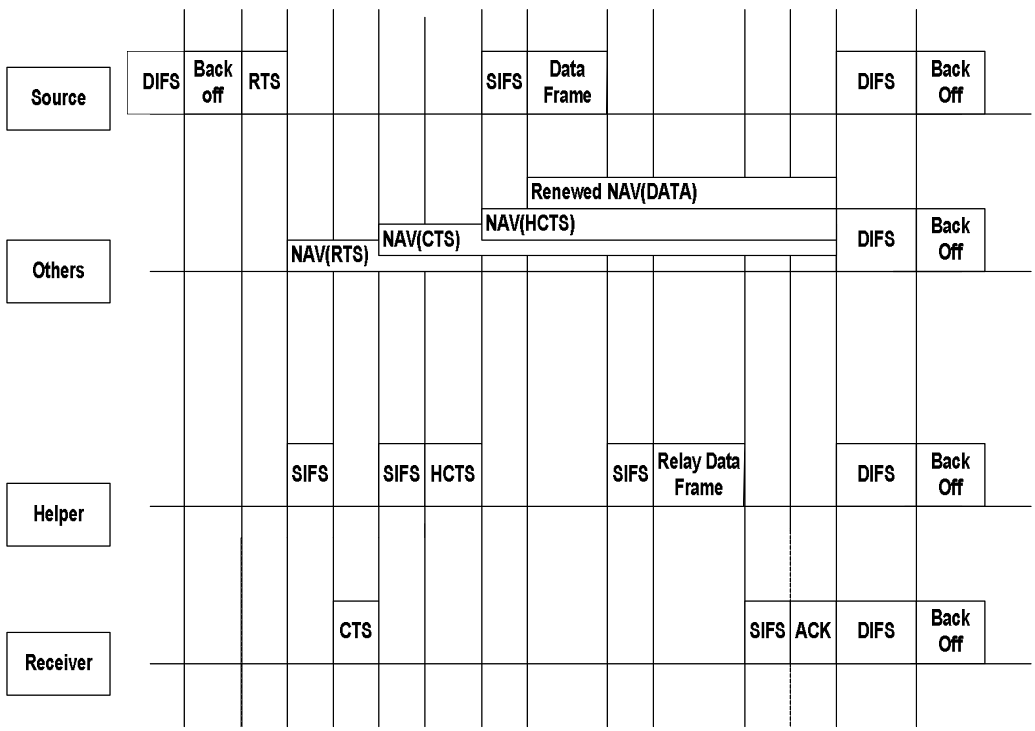
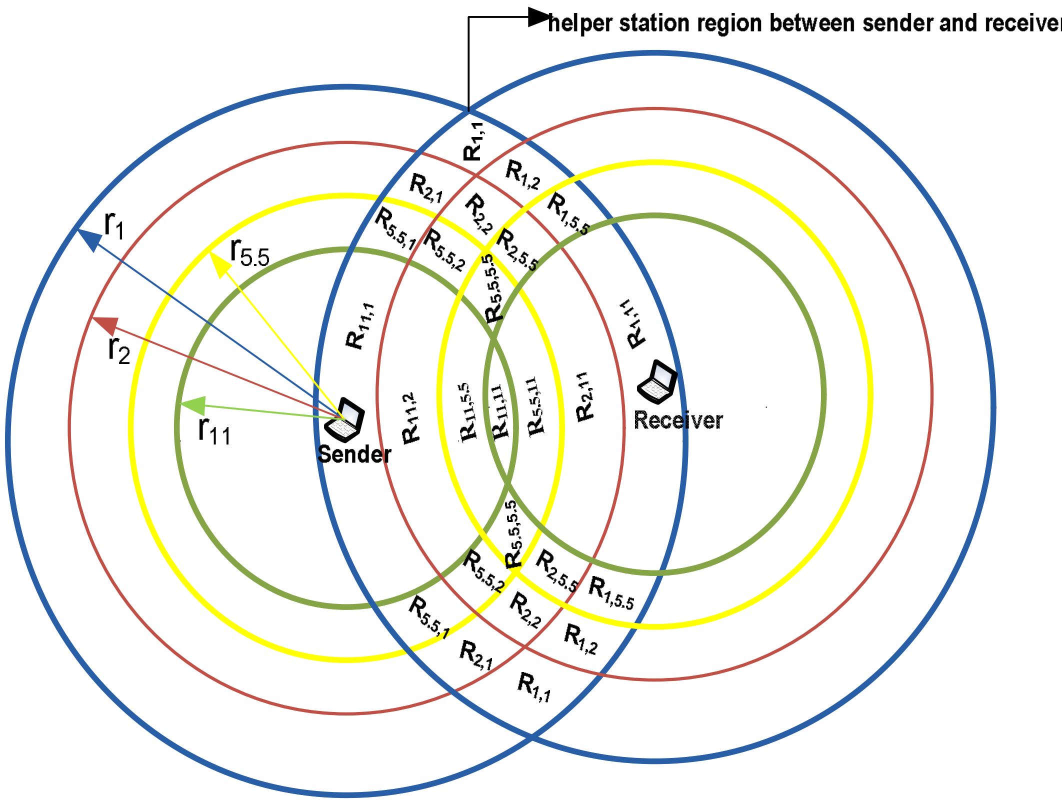


Figure 4.3 Cooperative MAC RTS/CTS/HCTS Mechanism

After sending the RTS frame, the sender will wait for the CTS and HCTS (Helper Clear to Send) frames. Figure 4.3 describes time line of control frames and data frame transmission in our proposed cooperative MAC. If receiver station successfully receives RTS, it sends a CTS frame according to IEEE 802.11 DCF MAC. While the Sender receives the CTS from the receiver, it waits for DIFS time before sending data frame. Potential helper stations also overhear the CTS. If the supported direct data rate between the sender and receiver is 1 or 2 Mbps (IEEE 802.11b), it sends an HCTS frame after SIFS time interval. Upon receiving the HCTS frame, the sender sends data frame to the helper with transmission rate R_{sh} and the relay station forward the data frame to destination with data rate R_{hd}.A cooperation region of a potential helper is shown in Figure 4.4



$R_{X,Y}$ indicates regions of supported X Mbps data rate from sender to helper station and Y Mbps data rate from helper station to receiver.

$r_1, r_2, r_{5.5}, r_{11}$ denotes IEEE 802.11b maximum transmission regions for data rate of 1,2,5.5 and 11 Mbps respectively.

Figure 4.4 Potential helper stations geographical position and their supported two hop data rates (IEEE 802.11b)

Figure 4.4 clearly shows the geographical position of a helper station between the sender and receiver pair. It also shows the supported maximum data rate of the two hop links relative to the geographical position of a helper station. If the sender does not receive any HCTS within SIFS interval time, the sender sends data frame directly to the destination. Specifically a station declares itself as a helper if the following condition is satisfied.

$$\frac{8L}{R_{hs}} + \frac{8L}{R_{hd}} + 2T_{PLCP} + T_{HCTS} + 2T_{SIFS} + T_{DIFS} < \frac{8L}{R_{sd}} \quad (4.2)$$

Where, L is the length of the Data Frame. If this condition is satisfied, the value of duration field (DI) of data frame header gets minimized than that of without cooperation. Correspondingly, NAV value of waiting stations is set to updated lesser value. All stations in the network get more access time to the channel. Duration fields of control frames in IEEE 802.11 DCF MAC along with proposed cooperative MAC are shown in Table 4.2

Table 4.1 CoopTable Format

MAC Address (48 bits)	Data Rate (8 bits)	Time Stamp (8 bits)	RSSI(dBm) (8 bits)
Mac addresses of the adjacent Neighbors	Maximum Data rate	Received time of overheard RTS/CTS frames	RSS Value of the last Received RTS/CTS from the neighbors

Table 4.1 describes the CoopTable each node uses in this proposed protocol. RSSI (Received Signal Strength Indicator) is the average value of received power in (dB) between a Sender-Relay and Relay-Destination links. Time Stamp in Table 4.1 indicates how older an entry in the cooptable. Each node keeps track of all of its neighbor nodes within its transmission range for future usages. This cooptable does not get bigger because each node in the wireless network deletes old neighbor link entries.

Table 4.2 Duration Field of Control Frames and Data frames

Frame type	Duration Value
RTS	$3T_{SIFS} + T_{CTS} + T_{ACK} + T_{DATA}$
CTS	$2T_{SIFS} + T_{ACK} + T_{DATA}$
$HCTS$	$3T_{SIFS} + T_{ACK} + \frac{8L}{R_{hs}} + \frac{8L}{R_{hd}} + 2T_{PLCP}$
$Data\ Frame$	$2T_{SIFS} + T_{ACK} + \frac{8L}{R_{hs}} + \frac{8L}{R_{hd}} + 2T_{PLCP}$

4.5 Analytical Modeling and Performance Evaluation

This section presents the through mathematical analysis of the proposed Cooperative MAC for its performance evaluation.

4.5.1 Throughput Analysis without Mobility

Overlapped area between two circles (Figure 4.4) with radius r_1 and r_2 separated by distance l between them is [7]

$$A_{r_1,r_2}(l) = {r_1}^2 \operatorname{asin}\left(\frac{h}{r_1}\right) + {r_2}^2 \operatorname{asin}\left(\frac{h}{r_2}\right) - hl \tag{4.3}$$

$$\text{Where } l = \frac{1}{2l}\sqrt{2{r_1}^2{r_2}^2 + 2({r_1}^2 + {r_2}^2)l^2 - ({r_1}^4 + {r_2}^4) - l^4}$$

$$\text{and } \quad 0 \le l \le r_1 + r_2$$

For IEEE 802.11 b wireless LAN, let $r_1, r_2, r_5\ and\ r_{11}$ represents the maximum transmission range of a wireless station for its data rate 1Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps respectively. Overlapped regions of the two wireless nodes in IEEE 802.11b WLAN is showed in Figure 4.4. Cooperative data transmission is beneficial for slower wireless stations, i.e., 1 Mbps and 2 Mbps in IEEE 802.11b WLAN. In the next section average throughput of 1 Mbps and 2 Mbps stations in IEEE 802.11b WLAN is derived.

4.5.1.1 Average Throughput of 1 Mbps wireless Stations

Let $P_{r_{x,}r_y}$ denotes the probability that a helper station resides inside the common geographical region between the transmitter and the receiver where r_x , r_y are the transmission ranges of the sender and receivers with $x\ Mbps$ and $y\ Mbps$ data rate respectively to the helper station. Probability that a relay station resides in a region within the transmission range of r_{11} both from sender and receiver, i.e., stations which may act as a helper with supported data rate from the sender to relay station with 11Mbps and relay station to the receiver with data rate 11Mbps is

$$P_{r_{11},r_{11},}(l) = \frac{A_{r_{11},r_{11}}(l)}{A_{r_1,r_1}(l)} \tag{4.4}$$

Accordingly from Figure 4.4,

$$P_{r_5,r_{11}}(l) = \frac{2(A_{r_5,r_{11}}(l) - A_{r_{11},r_{11}}(l))}{A_{r_1,r_1}(l)}$$

$$P_{r_5,r_5}(l) = \frac{A_{r_5,r_5}(l) + A_{r_{11},r_{11}}(l) - 2A_{r_5,r_{11}}(l)}{A_{r_1,r_1}(l)}$$

$$P_{r_2,r_{11}}(l) = \frac{2(A_{r_2,r_{11}}(l) - A_{r_5,r_{11}}(l))}{A_{r_1,r_1}(l)}$$

$$P_{r_5,r_2}(l) = \frac{2(A_{r_2,r_5}(l) + A_{r_5,r_{11}}(l))}{A_{r_1,r_1}(l)} - \frac{2(A_{r_2,r_{11}}(l) + A_{r_5,r_5}(l))}{A_{r_1,r_1}(l)}$$

$$P_{r_2,r_2}(l) = \frac{A_{r_2,r_2}(l) + A_{r_5,r_5}(l) - 2A_{r_2,r_5}(l)}{A_{r_1,r_1}(l)}$$

$$P_{r_{11},r_1}(l) = \frac{2\left(A_{r_{11},r_1}(l) - A_{r_2,r_{11}}(l)\right) + A_{r_{11},r_{11}}(l)}{A_{r_1,r_1}(l)}$$

$$P_{r_5,r_1}(l) = \frac{2(A_{r_5,r_1}(l) + A_{r_{11},r_2}(l))}{A_{r_1,r_1}(l)} - \frac{2(A_{r_{11},r_1}(l) + A_{r_5,r_2}(l))}{A_{r_1,r_1}(l)}$$

$$P_{r_2,r_1}(l) = \frac{2(A_{r_2,r_1}(l) + A_{r_5,r_2}(l))}{A_{r_1,r_1}(l)} - \frac{2(A_{r_5,r_1}(l) + A_{r_2,r_2}(l))}{A_{r_1,r_1}(l)}$$

From the laws of probability, Throughput of a 1 Mbps station in this Cooperative MAC is

$$Throughput_{CoopMAc}^{1Mbps} = P_{r_{11},r_{11}}(l)xS_{11,11} + P_{r_5,r_{11}}(l)xS_{5,11} + P_{r_5,r_5}(l)xS_{5,5} + P_{r_5,r_2}(l)xS_{5,2} + P_{r_2,r_{11}}(l)xS_{2,11} + P_{r_5,r_2}(l)xS_{5,2} + P_{r_2,r_2}(l)xS_{2,2} + P_{r_{11},r_1}(l)xS_{11,1} + P_{r_5,r_1}(l)xS_{5,1} + P_{r_2,r_1}(l)xS_{2,1} + \{1 - (P_{r_{11},r_{11}}(l) + P_{r_5,r_{11}}(l) + P_{r_5,r_5}(l) + P_{r_2,r_{11}}(l) + P_{r_5,r_2}(l) + P_{r_2,r_2}(l) + P_{r_{11},r_1}(l) + P_{r_5,r_1}(l) + P_{r_2,r_1}(l))\}xS_{Basic} \quad (4.5)$$

Here, $S_{x,y}$ means overall data transmission rate in cooperation mode if a helper station supports data rate x Mbps from source to itself and y Mbps from the helper to receiver respectfully. S_{Basic} denotes overall data transmission rate of 1 Mbps stations without cooperation from any of the helper stations.

4.5.1.2 Average throughput of 2 Mbps Wireless Stations

P_{r_x,r_y} for 2 Mbps stations is also derived from Figure 4.4 as follows

$$P_{r_{11},r_{11}}(l) = \frac{A_{r_{11},r_{11}}(l)}{A_{r_1,r_1}(l)}$$

$$P_{r_5,r_{11}}(l) = \frac{2(A_{r_5,r_{11}}(l) - A_{r_{11},r_{11}}(l))}{A_{r_1,r_1}(l)}$$

$$P_{r_5,r_5}(l) = \frac{A_{r_5,r_5}(l) + A_{r_{11},r_{11}}(l) - 2A_{r_5,r_{11}}(l)}{A_{r_1,r_1}(l)} \quad (4.6)$$

$$P_{r_2,r_{11}}(l) = \frac{2(A_{r_2,r_{11}}(l) - A_{r_5,r_{11}}(l))}{A_{r_1,r_1}(l)}$$

$$P_{r_5,r_2}(l) = \frac{2(A_{r_2,r_5}(l) + A_{r_5,r_{11}}(l))}{A_{r_1,r_1}(l)} - \frac{2(A_{r_2,r_{11}}(l) + A_{r_5,r_5}(l))}{A_{r_1,r_1}(l)}$$

Throughput of 2 Mbps stations can be derived according to that of 1Mbps wireless stations derived according to (4.5).

It is assumed that there are n number of stations equally distributed over a region and each station has an equal expected transmission probability with τ in randomly selected time slot. Let, p_{trans} denotes the probability that there is at least one transmission in randomly selected slot time

$$p_{trans} = 1 - (1 - \tau)^n \tag{4.7}$$

Let, p denotes the probability that a collision occurs during a randomly selected slot time. Therefore, the value of τ and p can be found by solving the following nonlinear system.

$$\tau = \frac{2(i-2p)(1-p^{m+1})}{(CW_{min}+1)(1-(2p)^{m+1})(1-p)+(1-2p)(1-\mathrm{p}^{m+1})} \tag{4.8}$$

$$p = 1 - (1 - \tau)^{n-1} \tag{4.9}$$

Where, CW_{min} is minimum contention window size, m denotes the maximum number of retry describe in chapter three.

Table 4.3 System Parameters for MAC and Physical Layer

Packet Payload	8224 bits
MAC Header	224 bits
PHY Header	192 bits
ACK	112 bits +PHY Header
HCTS	112 bits +PHY Header
RTS	160 bits +PHY Header
CTS	112 bits + PHY Header
Channel Basic Data Rate	1 Mbps
Slot Time	20 µs
SIFS	10 µs
DIFS	50 µs
Relay Delay	1 time slot

Let, p_s be the probability that a successful transmission happens that is the probability that a station transmit and other $n-1$ refrain from transmission in that given slot time. Therefore, p_s is a conditional probability conditioned on p_{trans}.

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{p_{trans}} \tag{4.10}$$

Duration of a slot time= Fraction of idle time (no transmission) + fraction of time spent in collision+ fraction of time spent in a successful transmission.

Therefore, Throughput $S_{x,y}$ can be derived using (3.14) as follows

$$S_{x,y} = \frac{E[Payload\ in\ bits\ transmitted\ in\ a\ slot\ time]}{E[Duration\ of\ a\ slot\ time]}$$

$$S_{x,y} = \frac{p_{trans}p_s E[L]}{(1-p_{trans})\pi + p_{trans}p_s T_s + p_{trans}(1-p_s)T_c} \tag{4.11}$$

Here, π , T_c, and T_s is duration of an empty time slot, average time spent in collision in a time slot and medium is sensed busy due to a successful transmission of a frame in a time slot respectively.

If RTS/ CTS access method is employed, T_s and T_c for IEEE 802.11 DCF MAC without cooperation and IEEE 802.11 DCF Cooperative MAC for our proposed helper selection method can be written as follows:

$$T_s^{Without\ CoOperation} = DIFS + T_{RTS} + T_H + 3SIFS + T_{ACK} + +T_{CTS} + T_{E[P]}$$

$$T_C^{Without\ CoOperation} = DIFS + T_{RTS} \tag{4.12}$$

$$T_s^{With\ CoOperation} = 2DIFS + T_{RTS} + 2T_H + 4SIFS + T_{CTS} + T_{HCTS} + \frac{T_{E[P]}}{R_{hs}} + \frac{T_{E[P]}}{R_{hd}}$$

$$T_C^{With\ CoOperation} = DIFS + T_{RTS} + T_{HCTS}$$

Where, T_{RTS} , T_{ACK} , T_{CTS}, T_{HCTS}, $T_{E[P]}$ and T_H are the required transmission time for sending RTS, ACK, CTS, HCTS, Data Frame and Frame Header respectively from sender to receiver.

4.5.2 Throughput Analysis for Error Prone Environment

Throughput in (3.14) considers that frame error is caused due to collisions among the transmitted packets. If the transmission error is considered, the probability that a frame is corrupted due to collision or channel bit error can be written as

$$p = 1 - (1-\tau)^{n-1}(1-p_e)^{L_{payload}+L_{Header}} \tag{4.13}$$

Where p_e is the probability is denotes the channel bit error, $L_{payload}$ denotes length of the frame in bits, L_{Header} denotes the length of the frame header in bits. Now (4.8) and (4.13) are nonlinear system. Numerical solution of (4.8) and (4.13) gives the value of p and τ.

Frame Error rate can be written as

$$FER = 1 - (1-p_e)^{L_{payload}+L_{Header}} \tag{4.14}$$

Probability that a frame is successful given that there is at least one frame transmission in a time slot and no frame error occurred can be written as

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{p_b}(1-FER) \tag{4.15}$$

Probability that a transmitted frame received by the receiver with error can be written as

$$p_{ErrrorFrame} = p_s.FER \tag{4.16}$$

Therefore, Throughput in (3.14) can be re-written for error prone channel as follows

$$S = \frac{p_b p_s E[L]}{(1-p_b)\pi + p_b p_s T_s + p_b(1-p_s)T_c + p_b \cdot p_{ErrrorFrame} \cdot T_{ErrorFrame}} \tag{4.17}$$

Where $T_{ErrorFrame}$ denotes the average time the medium is sensed busy due to corrupted frame transmission.

If RTS/CTS mechanism is employed, $T_{ErrorFrame}$ in error prone channel can be written as

$$T_{ErrorFrame}^{Without\ CoOperation} = DIFS + T_{RTS} + T_H + 3SIFS + T_{ACK} + T_{CTS} + T_{E[P]} \tag{4.18}$$

For the proposed cooperative MAC, $T_{ErrorFrame}$ can be written as

$$T_{ErrorFrame}^{With\ CoOperation} = 2DIFS + T_{RTS} + 2T_H + 4SIFS + T_{ACK} + T_{CTS} + T_{HCTS} + \frac{T_{E[P]}}{R_{hs}} + \frac{T_{E[P]}}{R_{hd}} \tag{4.19}$$

4.5.3 Throughput Analysis with Mobility

McDonald and Znabi [28] have proposed a probabilistic link availability model in mobile environment where all mobile nodes move with constant velocity and constant direction for particular amount of time before changing their directions and speeds. The link availability is defined as the probability that there is an active link between two nodes at time $t + T$ that there is an active link between them at time t. This model is appropriate in this proposed cooperative MAC protocol because while a helper node moves away from the transmission range of the sender and receiver, a new connection must be established by selecting other helper node or the sender will send data directly to the receiver without taking help from any other relay nodes. In this protocol, later is selected due to the mobility of helper stations.

In case of cooperation, let T_s be the time required to transmit a frame from the source station to the destination station with the help of the relay station. During T_s time duration the connection between sender-relay-receiver must be continuous. If the relay station is mobile and leaves sender-receiver vicinity a disconnection shall follow. Therefore, the sender will send data frame to the receiver directly. If a connection is established for particular data transmission session among Sender(S), Relay(R) and Receiver (D) at time t , probability that the link will be continuously available for time T_s can be defined as the following:

$$Pr(T_s) = \Pr[the\ link\ lasts\ for\ time \quad (t + T_s) | the\ link\ is\ available\ at\ time\ \ t] \tag{4.20}$$

If wireless stations remain static, according to our cooperative MAC cooperative data transmission will be successful for the whole time duration T_s. Let, wireless stations' mobility patterns are independent of each other and the random duration during which their speed and direction remain unchanged is exponentially distributed with mean $\frac{1}{\lambda}$. We assume that wireless station are moving with constant speed and as the exponential distribution is 'memory less'. Therefore,

$$\Pr(T_s) = [1 - E(T_s)]^2 = e^{-2T_s\lambda} \tag{4.21}$$

Throughput for mobile environment is calculated using throughput result found in section 4.5.1.1 and 4.5.1.2 for 1Mbps and 2Mbps transmission stations.

4.5.4 Throughput Analysis over Rayleigh Fading Channel

We assume that mobile wireless channel is flat fading Rayleigh channel. In particular time duration, the channel remains in fading states or in inter fading state. Two states are determined by the receiver by evaluating a certain threshold value of the received signal power level. A transmitted frame is successfully received if and only if the whole frame is transmitted during inter-fading states. If any part of the frame falls into the fading state, the frame is received with error. In Rayleigh fading margin is defined as $\rho = \frac{R_{thresold}}{R_{rms}}$ where $R_{thresold}$ is the required received power level and R_{rms} is the root mean square signal level. Fading duration and inter fading duration is exponentially distribute for $\rho < -10dB$.

Let T_{frame} is the time required to transmit a whole frame to the destination. The frame error rate in flat fading Rayleigh channel is given in [29]

$$FER = 1 - \frac{T_i}{T_i + T_f} P(t_i > T_{frame}) \tag{4.22}$$

Here, t_i and t_f inter-fading and fading duration respectively of the channel . T_i and T_f denotes average inter-fading and fading duration respectively. Since t_i and t_f are exponentially distributed.

$$\text{Therefore,} \quad P\left(t_i > T_{frame}\right) = e^{-\frac{T_{frame}}{T_i}} \tag{4.23}$$

For Rayleigh fading channel, average fading duration is given by

$$T_f = \frac{e^{\rho^2} - 1}{\rho f_d \sqrt{2\pi}} \tag{4.24}$$

Where f_d is the maximum Doppler frequency and it is calculated from $\frac{v}{\lambda}$. v is the velocity of the mobile nodes and λ is the wave length.

In Rayleigh fading channel, $T_i + T_f$ is equal to the inverse of the level crossing rate (LCR).

$$LCR = \sqrt{2\pi}\, f_d\, \rho e^{-\rho^2} \tag{4.25}$$

From the above discussion it is shown that Frame Error Rate (FER) is dependent on fading margin, maximum Doppler frequency and frame transmission duration. Since fading margin and Doppler frequency are not dynamically controllable. Only controllable parameter is the frame transmission duration. Therefore, Frame Error Rate (FER) is dependent on frame transmission duration.

If FER is considered, the probability that a transmitted frame is successful can be rewritten as

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{p_{trans}}\,(1 - FER) \tag{4.26}$$

Therefore, Throughput S of (3.14) can be re written as follows

$$S = \frac{p_{trans} p_S E[L]}{(1-p_{trans})\pi + p_{trans} p_S T_s + p_{trans}(1-p_s)T_c + p_{trans}.FER.T_{ErrorFrame}} \tag{4.27}$$

Here $T_{ErrorFrame}$ is the time consumed by an erroneous frame.

If legacy RTS/CTS mechanism is employed, $T_{ErrorFrame}$ is

$$T_{ErrFrame} = DIFS + T_{RTS} + T_H + 3SIFS + T_{ACK} + T_{CTS} + T_{E[P]}$$

In proposed Cooperative MAC,

$$T_{ErrFrame} = 2DIFS + T_{RTS} + 2T_H + 4SIFS + T_{ACK} + T_{CTS} + T_{HCTS} + \frac{T_{E[P]}}{R_{hs}} + \frac{T_{E[P]}}{R_{hd}}$$

4.5.5 Average Frame Delay Analysis

The duration between time when the frame is available at the head of the Line (HOL) of the transmitting station for transmission and the time at which its acknowledgement is received is considered the frame transmission delay. This analysis assumes that all stations have packets queued in its HOL.

Let $E[X]$ denotes the average number of time slots required for a station to transmit a frame successfully.

$$E[X] = \sum_{i=0}^{m-1} p^i . \frac{CW_i + 1}{2} + \frac{p^m (CW_m + 1)}{1 - p}$$

Simplified form of the above equation is,

$$E[X] = \frac{(CW_{min} + 1)(1 - 2p) + pCW_{min}(1 - (2p)^m)}{2(1 - 2p)(1 - p)}$$

Let, T_{coe} is the average duration while the observed station itself occupies the channel during each unsuccessful retransmission attempt. As an unsuccessful retransmission occurs due to collision only, so we can write $T_{coe} = T_C$. T_C is the average time duration when the medium is sensed busy due to collisions among frames. Average time occupied by the observed station due to unsuccessful retransmissions can be calculated as,

$$E[T_{collisionTime}] = \sum_{i=0}^{m-1} p^i .\ T_{coe}$$

$$= \frac{1-p^m}{1-p} . T_{coe}$$

Therefore, Average Frame Delay $E[Delay]$ can be calculated as the following without considering frame dropped probability,

$$E[Delay] = E[X]. E[slot] + E[T_{collisionTime}] \qquad (4.28)$$

Where average length of a slot time,

$$E[slot] = (1 - p_b)\pi + p_b p_s T_s + p_b (1 - p_s) T_c$$

Where,

$$T_s^{Without\ CoOperation} = DIFS + T_{RTS} + T_H + 3SIFS + T_{ACK} + +T_{CTS} + T_{E[P]}$$

$$T_C^{Without\ CoOperation} = DIFS + T_{RTS}$$

$$T_s^{With\ CoOperation} = 2DIFS + T_{RTS} + 2T_H + 4SIFS + T_{CTS} + T_{HCTS} + \frac{T_{E[P]}}{R_{hs}} + \frac{T_{E[P]}}{R_{hd}}$$

$$T_C^{With\ CoOperation} = DIFS + T_{RTS} + T_{HCTS}$$

4.6 Summary

In this chapter, a helper initiated distributed cooperative medium access control protocol for a wireless network is furnished. The proposed protocol is analyzed using the model derived in chapter 3. Throughput of the proposed protocol is derived in error prone channel and flat fading Rayleigh channel. Parameters and the different assumptions used for the performance analysis of the protocol are lucidly described in this chapter.

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, I discuss the results of the analysis carried out in chapter four. I used system parameters of IEEE 802.11b DSSS presented in Table 3.1 for the analysis of the proposed Cooperative MAC. This analysis shows how proposed cooperative MAC and IEEE 802.11 MAC throughput differs with the changes in frame sizes and number of stations.

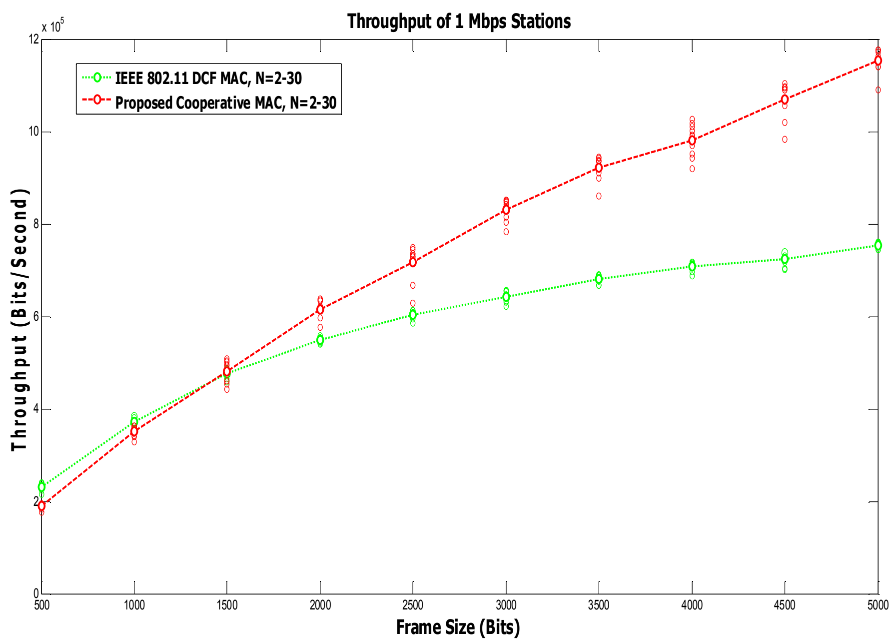


Figure 5.1 Throughput versus Frame Size for 1 Mbps station with different number of stations in a WLAN (N=2-30)

Figure 5.1 shows that throughput of 1 Mbps stations increases with the increase in frame size. If number of nodes in a WLAN varies from 2 to 30, the approximate threshold payload size from which our proposed cooperative MAC performs better than legacy IEEE 802.11 DCF MAC is 1500 bytes. Figure 5.1 is drawn with (4.5) and parameters used are described in Table 3.1. Figure 5.1 depicts that if number of stations varies, probability that a station transmits is also varies. Therefore, the throughput of 1 Mbps stations varies. It is due to extra overhead $2SIFS + T_{HCTS}$

incurred for helper node selection. If the frame size increases, throughput efficiency of 1 Mbps stations increases dramatically with our proposed mechanism with respect to IEEE 802.11 DCF MAC.

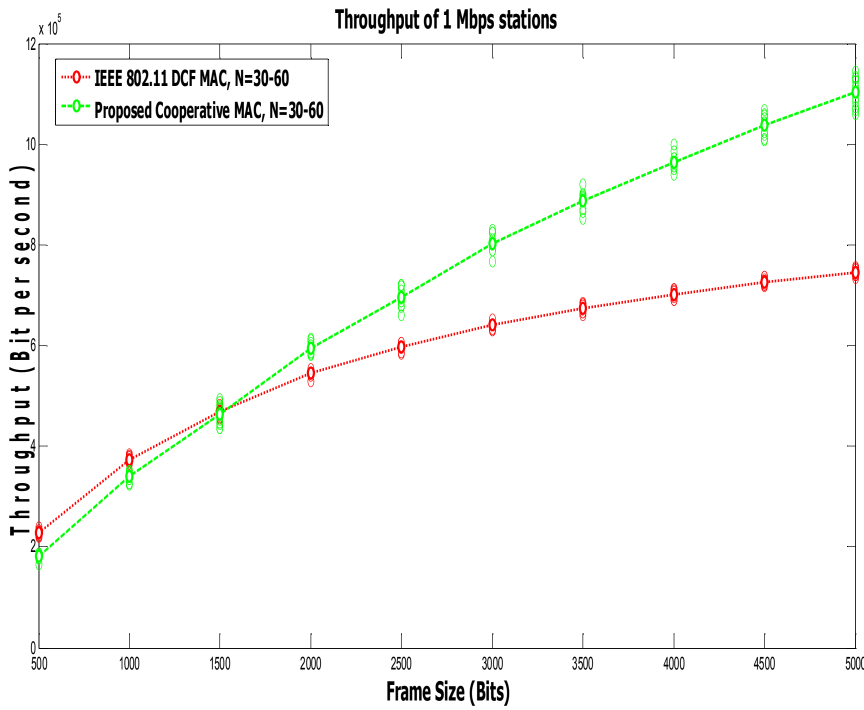


Figure 5.2 Throughput versus Frame Size for 1 Mbps station with different number of stations in a WLAN (N=30-60)

Figure 5.2 reveals that if the number of stations (N) in a WLAN varies within 30 to 60 stations, the threshold payload size also increases for our proposed cooperative MAC. This occurred due to the fact that if number of stations increases, each station gets less access time to the medium and collision increases among the frames in a single collision domain. Figure 5.3 (next page) depicts that 2 Mbps stations achieve more throughput than IEEE 802.11 DCF MAC with higher frame size threshold. Figure 5.3 is the outcome of the same equation as that of Figure 5.1 and Figure 5.2. It happened due to the fact that overhead incurred during helper selection is more costly for 2 Mbps stations than 1 Mbps stations. In both cases (1 Mbps and 2 Mbps), slower stations are highly benefited if our proposed cooperative MAC is applied.

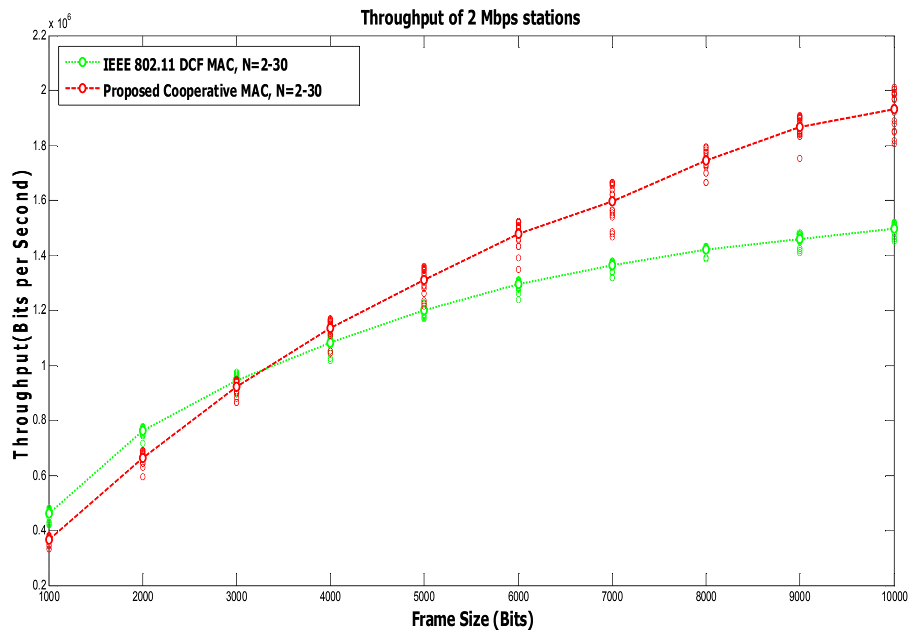


Figure 5.3 Throughput versus Frame Size for 2 Mbps station with different number of stations in a WLAN (N=2-30)

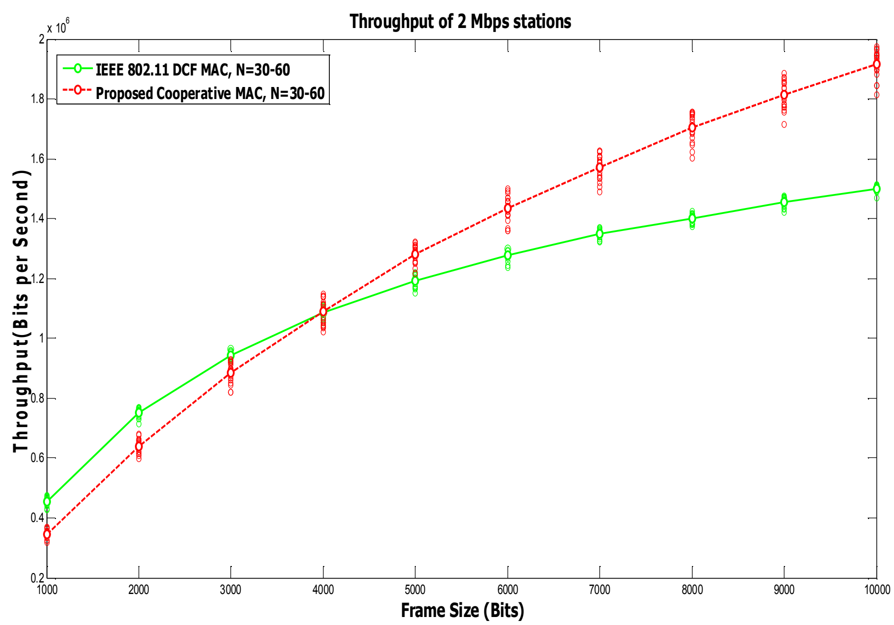


Figure 5.4 Throughput versus Frame Size for 2 Mbps station with different number of stations in a WLAN (N=2-30)

Figure 5.4 illustrates the throughput comparison of the proposed MAC and legacy 802.11 DCF MAC if the number of nodes (N) in a WLAN varies within 30-60. The more nodes, the more threshold size for cooperation benefits from the proposed protocol.

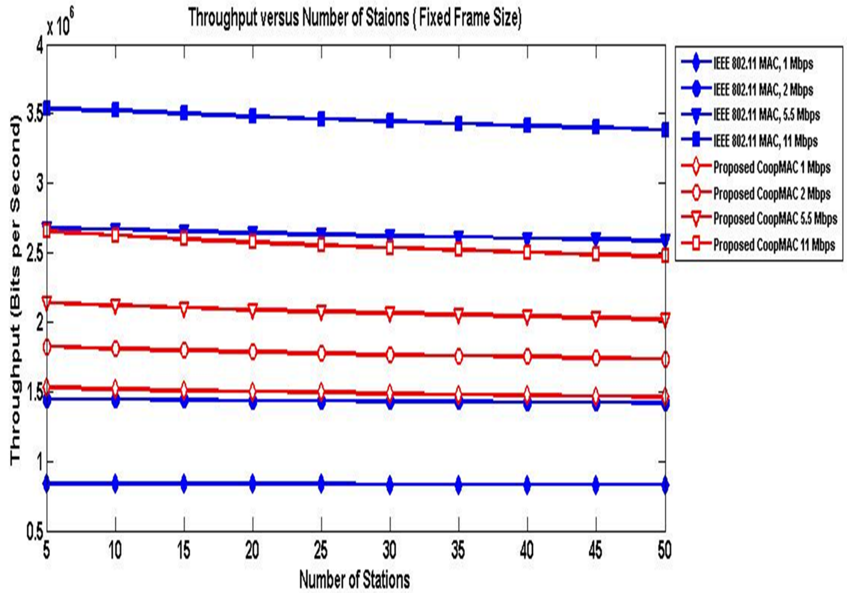


Figure 5.5 Throughputs of IEEE 802.11b WLAN Stations

In Figure 5.5, variations in throughput achievement for different data rate stations are shown with the increase in number of wireless stations for a fixed frame size of 8224 bits. It reveals that cooperative MAC is not beneficial for stations with data rates 5.5 Mbps and 11 Mbps. Higher transmitting stations do not need cooperation from the lower stations. According to (4.5), if 5.5 Mbps stations initiates cooperative transmission, it is less likely that two hop transmission will be beneficial than direct transmission. The same reason is applicable for 11 Mbps stations. Higher transmitting stations suffer from overhead requirements to initiate cooperative transmission. Another observation is that the more the frame size is the better the throughput gain for lower transmitting stations. Average time to successfully transmit a frame is decreased in our proposed cooperative MAC than that of IEEE 802.11 DCF MAC is shown in Figure 5.6. Average frame delay comparison is plotted from (4.28) and system parameters described in Table 4.3.

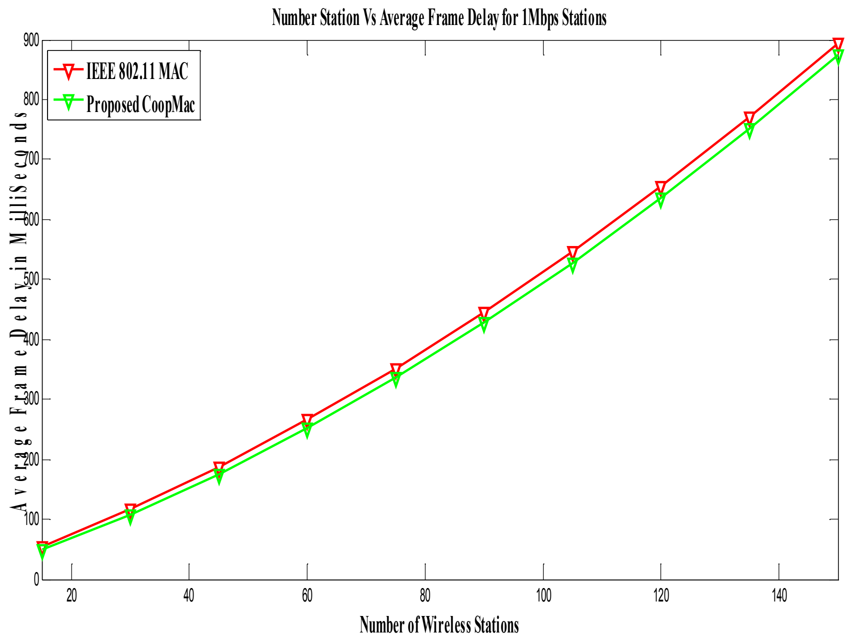


Figure 5.6 Comparison of average frame delay of IEEE 802.11 DCF MAC and proposed cooperative MAC

Figure 5.6 illustrates that if the number of nodes increases in a WLAN, the required time to transmit a frame successfully also increases. Our proposed MAC performs better than that of legacy IEEE 802.11 DCF MAC by decreasing the time required to transmit a frame successfully from the source to receiver.

To analyze the performance of the proposed protocol in mobile environment, probabilistic link availability model (4.21) is used. Figure 5.7 and Figure 5.8 describes throughput of 1 Mbps and 2 Mbps wireless stations respectively with mobility. With the increase in mobility of the wireless stations, 1 Mbps station still achieves higher throughput gain than 2 Mbps stations in both IEEE 802.11 DCF MAC and our proposed cooperative MAC. In mobile environment the proposed scheme performs better than legacy IEEE 802.11 DCF MAC. Increase in mobility also increases link failures. Figure 5.8 shows that 2 Mbps stations get benefits from our proposed cooperative MAC after a threshold payload size. This threshold payload size varies with variations in mobility of the wireless nodes.

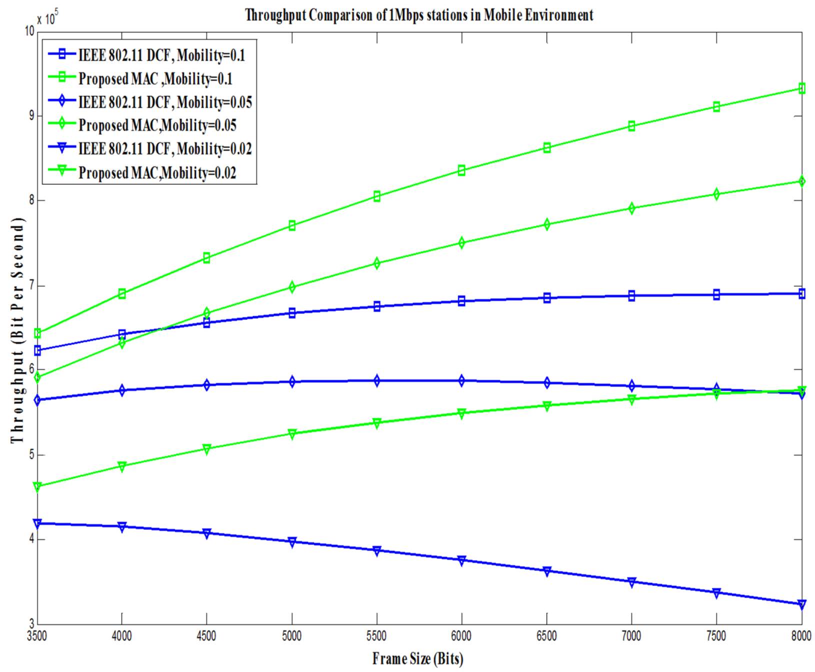


Figure 5.7 Throughput comparisons of 1 Mbps stations with mobility.

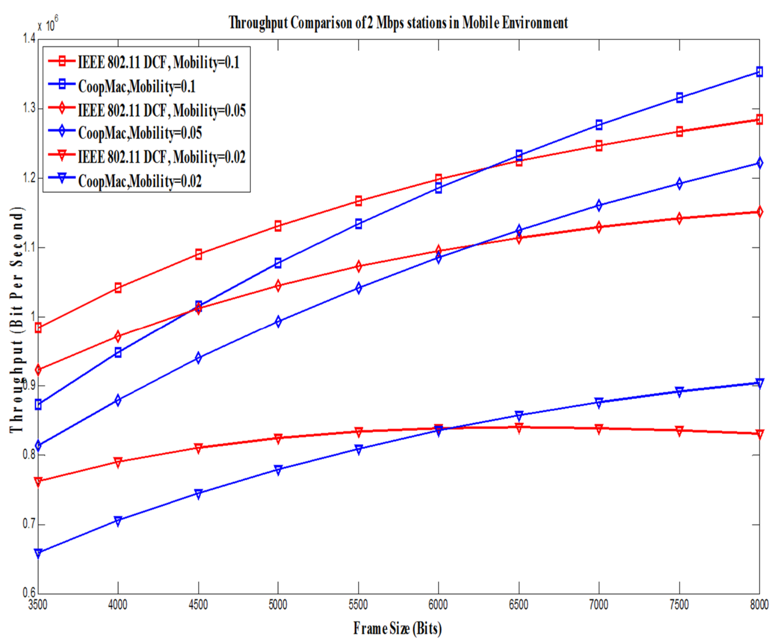


Figure 5.8 Throughput comparison of 2 Mbps station with mobility.

Figure 5.7 states that after a threshold of frame size 3500 bits, 1 Mbps stations perform better than legacy IEEE 802.11. The threshold for 2 Mbps is higher than that of 1 Mbps station.

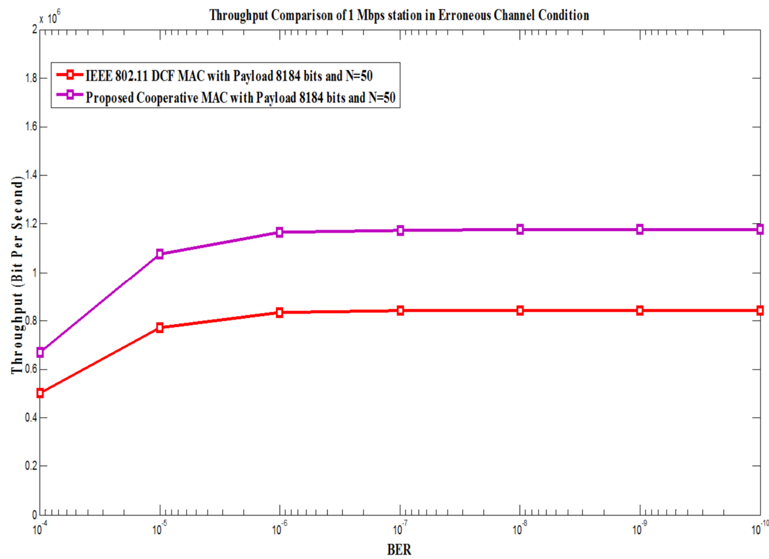


Figure 5.9 Throughput comparison of 1 Mbps station with erroneous channel

Throughput of the 1 and 2 mbps stations with considering error prone channel are shown in Figure 5.9 and Figure 5.10 respectively. The analysis presented in section 4.5.2 is used to plot those figures along with system parameters in Table 4.3. As the received power at the destination station decreases with distance of signal has travelled, bit error rate (BER) is increases. If the transmit power remain constant that, due less distance from the sender relay received power is higher than that of the receiver. BER would be lower for sender to relay and relay to receiver links than that of direct data transmission link.If the direct transmission (source–destination) has the BER at the destination 10^{-5} , we consider in our analysis that average BER for sender to relay and relay to destination links is little less than 10^{-5} with payload size of 8184 bits and 50 wireless stations.

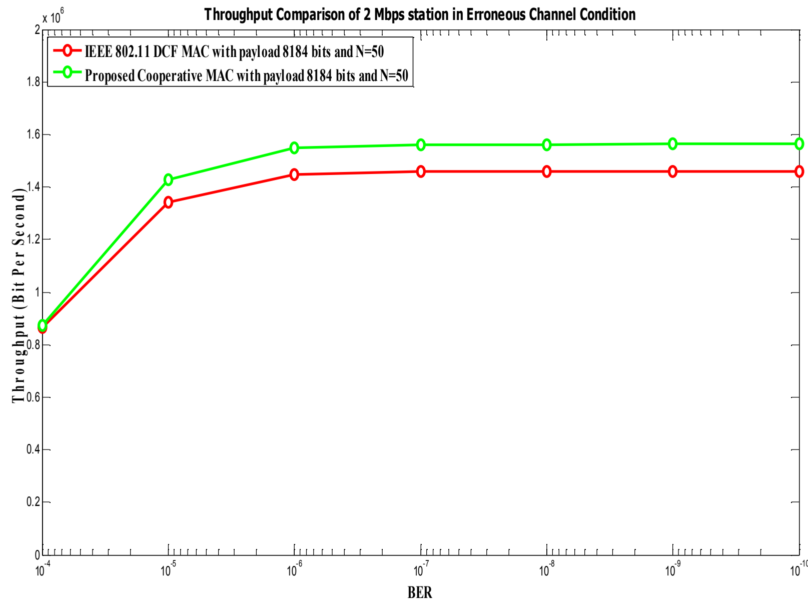


Figure 5.10 Throughput comparison of 2 Mbps station with erroneous channel

Figure 5.11 and Figure 5.12 show throughput of the proposed protocol over Rayleigh fading channel. These figures are the results of the analysis carried out at section 4.5.4. System parameters of Table 4.3 are used. Throughput performance of the proposed scheme is compared against legacy system in Rayleigh fading channel. In both cases fading margin of the plots are -20dB. Velocities of mobile nodes are kept in 72 Km/h. If the velocity increases the throughput decreases. Throughput performance also depends on fading margin. If fading margin is greater than -10dB, the received signal is not acceptable. In Rayleigh fading channel 1 Mbps stations, if cooperative MAC is use, gains higher throughput than 2 Mbps station in the same environment.

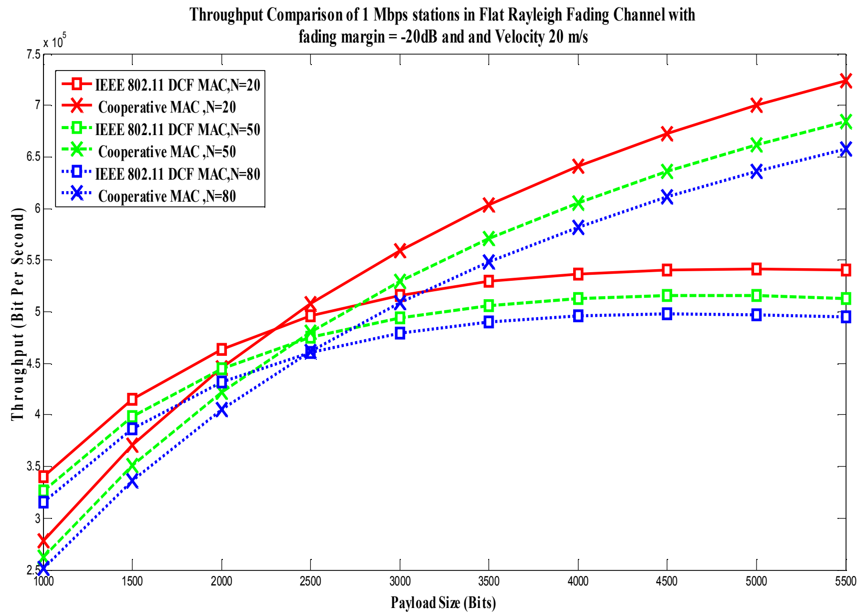


Figure 5.11 Throughput with different number of stations (N) in flat Rayleigh fading channel

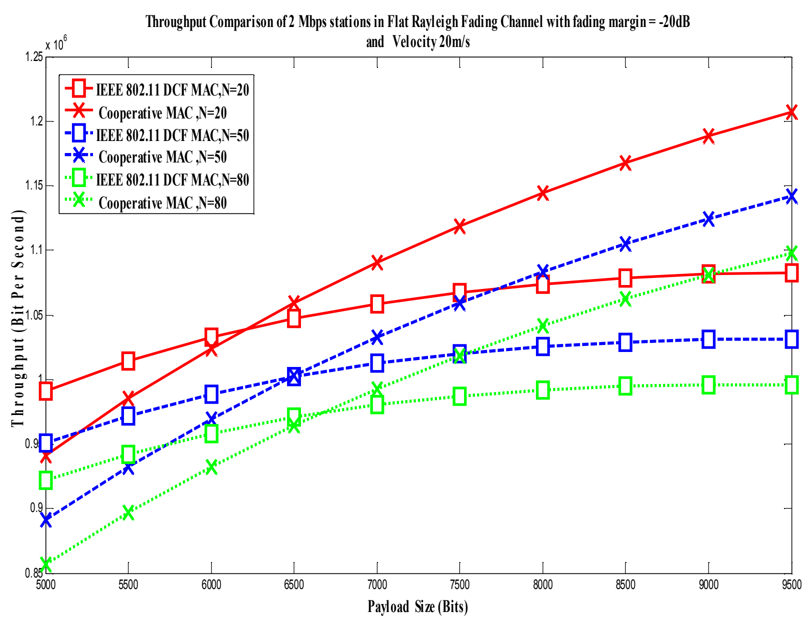


Figure 5.12 Throughput with different number of stations (N) in flat Rayleigh fading channel

5.1 Summary

We have discussed the analysis carried out in chapter four. Throughput and end end frame delay of the proposed protocol is compared against those of the legacy IEEE 802.11 DCF MAC. The analysis shows that the proposed protocol performs better by increasing the throughput and decreasing the end to end frame delay in wireless networks.

CHAPTER 6

CONCLUSION

6.1 Conclusion

In this thesis different performance metrics of IEEE 802.11 DCF MAC are analyzed and a relay initiated cooperative MAC protocol is designed. Relay selection process is the corner stone in designing a cooperative MAC protocol. To facilitate the wireless stations to gain more access to wireless medium proposed protocol has minimized the overhead time in helper selection process. The slower rate stations speed up their transmissions through cooperation from helper nodes. Numerical analysis shows that lower rate stations gain more throughput efficiency than the higher rate stations. For higher rate stations, initiating a cooperative transmission reduces their throughput than that of IEEE 802.11 DCF MAC. Higher rate stations need not initiate cooperative transmission. In this thesis the proposed protocol has also been analyzed and compared against legacy IEEE 802.11 DCF MAC in the case of mobility scenarios of the wireless environment. Analytical results show that in both cases slower stations get more throughput gain in our proposed cooperative MAC scheme. In chapter three, the analytical model used to analyze the throughput and end to end delay of IEEE 802.11 DCF mac assumed that the channel is noise free. A helper node among the common geographical regions of the sender-receiver pair triggers itself in case of beneficial cooperation. Hence, our proposed protocol does not allow wireless stations to indulge in unnecessary cooperation. According to the analysis and mathematical model beneficial cooperation in data transmission gives the lower transmitting stations more throughput gain than that of legacy MAC protocols.

Analysis of IEEE 802.11 DCF MAC shows that throughput of the WLAN varies for different frame size. If the frame size increases, RTC-CTS access mechanism exhibits more throughput gain than that of basic access mechanism of the IEEE 802.11 DCF MAC. This happens due to the fact that larger frame is prone to more collision. Larger frames are affected by the interferences more easily. Hence data packet loss due to both interference and collision increases. This phenomenon decreases the throughput of the wireless local area network.

A promising feature of IEEE 802.11 DCF MAC in WLAN is that, in saturated scenarios, all wireless stations are given equal access time to wireless medium. This also led to less throughput gain if there are some lower rate stations within a transmission range of an access point. Lower rate stations consumes more time giving other higher transmitting stations less medium access time. Hence, the overall throughput of the WLAN is decreased. This thesis shows that if lower rate stations are helped by the other relay stations, their transmission time decreases substantially giving other stations more access to wireless medium. Hence, overall throughput of the WLAN increases. Throughput of the proposed protocol has also analyzed in case of error prone channels and flat fading Rayleigh channel. In both cases, fading margin, velocity of the wireless nodes and average fading duration are not controllable in practical wireless environment. The only parameter that can be controlled is the duration of the frame transmission. If the benefits of physical layer cooperative communication are exploited to the higher layer of the OSI reference mode, frame transmission time can be reduced. This reduction in frame transmission makes the data transmission less vulnerable to fading induced errors. Analytical modeling of the proposed protocol shows that its throughput increases and end to end frame delay decreases than those of the legacy IEEE 802.11 DCF MAC in Rayleigh fading channels.

6.2 Recommendation for Future Works

To effectively and efficiently exploit the benefits of physical layer cooperative data transmission in the upper layer of the OSI reference model, viable protocols for those layers have to be design. Therefore, it requires cross layer protocols in every upper layers of the OSI reference model. In future, my motivation is to design a cross layer cooperative routing protocol for wireless networks. The idea presented in thesis would be used as a building block for network layer cooperative protocols design.

This protocol has some limitations. Firstly, if there are more than one potential helper stations between the source and destination pair, this thesis relies on average power of the RTS and CTS but these controls frames are also vulnerable to interferences. Interferences from external sources or other transmission channel may affect the correct measurements of the average power. This incorrect measurement may mislead the helper stations to determine the exact data rate between source-helper and helper-destination pairs.

Secondly, if relay stations are used on behalf of the source stations, the frame may be visible to other users (intruders). This may violate the privacy parameter of message security of the data transmission. Therefore, security mechanism should be derived so that intermediate relay nodes cannot hamper privacy and integrity metrics of the transmitted frames.

Thirdly, if there are no potential helper stations between the source-destination pair, there is an extra overhead of SIFS time which may decrease the throughput. A mechanism should be derived so that extra overheads incurred due to cooperation may not largely affect the relay time required in forwarding the frames.

In future, extensive comparisons of both simulation and analytical model of the proposed cooperative MAC protocol will be investigated. A test bed analysis of the proposed scheme will be carried out. The benefits offered by this proposed MAC protocol could be exploited in designing of cooperative network and transport layer protocols.

References

[1] Laneman, J.N., "Cooperative diversity: models, algorithms, and architectures," Cooperation in wireless networks: principles and applications, chapter 1, Springer, Berlin, Germany, 2006.

[2] Shan, H., Cheng, H.T. and Zhuang, W., “Cross layer cooperative MAC protocol in distributed wireless networks,” IEEE Transaction on wireless communications, vol. 10, no. 8, pp. 2603-2615, Aug. 2011.

[3] Sheng, Z., Ding, Z. and Leung, K.K., " Cooperative wireless networks: from radio to network protocol designs," IEEE Communication magazine: advances in cooperative wireless networking, vol. 49, no. 5, pp. 64-69, May 2011.

[4] Nosratinia, A., Hunter, T.E. and Hedayat, A., “Cooperative communication in wireless networks,” IEEE Communication magazine, vol. 42, no. 10, pp. 74-80, Oct. 2004.

[5] Zhu, H. and Cao, G., “rDCF: A relay enabled medium access control protocol for wireless ad hoc networks,” IEEE Transactions on Mobile Computing, vol. 5, no. 9, pp. 1201-1213, Sep. 2006.

[6] Zhu, H. and Cao, G., “On improving the performance of IEEE 802.11 with relay-enable PCF,” Journal of mobile networks and applications, vol. 9, pp. 423-434, Aug. 2004.

[7] Liu, P., Tao, Z. and Panwar, S.S., “A cooperative MAC protocol for wireless local area networks,” IEEE Journal on selected areas in communications, vol. 25, no. 2, pp. 340-353, Feb. 2007.

[8] He, X., Li, F.Y., “Cooperative medium access control in wireless networks: the two hop case,” in Proceedings of IEEE wireless and mobile computing, networking and communications, vol. 1, pp. 13-18, 2009.

[9] Bharati, S. and Zhuang, W., “ Performance analysis of cooperative adhoc MAC for vehicular networks,” IEEE Globecom wireless networking symposium , pp. 5482 - 5487 , 3-7 Dec. 2012, California, USA.

[10] Moh, S., Yu, C., “A cooperative diversity based robust mac protocol in wireless ad hoc networks,” IEEE Transactions on parallel and distributed systems, vol. 22, no. 3, pp. 353-363, March 2011.

[11] Zhou, T., Sharif, H., Hempel, M., Mahasukhon, P., Wang, W., and Ma, T., “A novel adaptive distributed cooperative relaying mac protocol for vehicular networks,” IEEE Journal on selected areas in communication, vol. 29, no. 1, pp. 72-82, Jan. 2011.

[12] Sadeghi, B., Kanodia, V., Sabharwal, A. and Knightly, E., " Opportunistic media access for multi rate ad hoc network," in Proceeding of 8th international conference on mobile computing and networking, pp. 24-34, 23-28 Sep. 2002, Atlanta, USA.

[13] Liu, P., Tao, Z., Lin, Z., Erkip. E. and Panwar. S., "Cooperative wireless communication: a cross layer approach," IEEE Wireless communications, vol. 13, no. 4, pp. 84-92, Aug 2006.

[14] Tse, D.N.C. and Viswanath, P., "Fundamentals of wireless communications," Cambridge University Press, 2005.

[15] Telatar, E.,"Capacity of multi-antenna Gaussian channels," European transaction on telecommunications, vol. 10, no. 6, pp. 585-95, Dec 1999.

[16] Foschini, G. J. and Gans, M., "On the limit of wireless communication in fading environment when using multiple antennas," Journal of wireless personal communications, vol. 6, pp. 311-335, Mar. 1998.

[17] Foschini, G.J., Golden, G.D., Valenzuela, R.A. and Wolniansky, P.W., "Simplified processing for high spectral efficiency wireless communication employing multi-element arrays," IEEE Journal on selected areas in communication, vol. 17, no. 11, pp. 1841-1852, Nov. 1999.

[18] Alamouti, S., "A simple transmit diversity scheme for wireless communications," IEEE Journal on selected areas in communication, vol. 16, no. 8, pp. 1451-58, Oct. 1998.

[19] Stankovic, V., Madsen, A.H. and Xiong, Z., "Cooperative Diversity for Wireless Ad Hoc Networks," IEEE signals processing magazine, vol. 23, pp. 37-49, Sep. 2006.

[20] Bletsas, A., Shin, H. and Win, M., "Cooperative communications with outage optimal opportunistic relaying," IEEE transactions on wireless communications, vol. 6, no. 9, pp. 3450-3460, Sep. 2007.

[21] Sendonaris, A., Erkip, E. and Aazhang, B.,"User cooperation diversity - part II: Implementation aspects and performance analysis," IEEE Transactions on communications, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[22] Lin, S., Costello, D.J. and Miller, M. J., "Automatic-repeat-request error control schemes," IEEE communication magazine, vol. 22, no. 12, pp. 5-17, Dec.1984.

[23] Azgin, A., Altunbasak, Y. and Alregib, G., "Cooperative MAC and routing protocols for wireless ad hoc networks," in Proceedings of IEEE global telecom-communications conference (globecom), vol. 5, Dec. 2005, St. Louis, USA.

[24] Ibrahim, A.S., Han, Z. and Liu, K.J.R., "Distributed energy-efficient cooperative routing in wireless networks," IEEE Transactions on wireless communications, vol. 7, no. 10, pp. 3930–3941, Oct. 2008.

[25] Bianchi, G., “Performance analysis of the IEEE 802.11 distributed coordination function,” IEEE Journal of selected areas of communication, vol. 18, no. 3, pp. 535-547, Mar. 2000.

[26] Pavon, J.D.P. and Choi, S., “Link adaptation strategy for IEEE 802.11 wlan via received signal strength measurement,” in Proceedings of IEEE ICC 2003, vol. 2, pp. 1108-1113, 11-15 May 2003, Anchorage, Alaska.

[27] Murthy, C.S.R. and Monoj, B.S., “Ad hoc wireless network: architectures and protocols,” chapter 1.6, 6.2, 6.4, Prentice Hall PTR, Englewood Cliffs, 2004.

[28] McDonald, A.B. and Znabi, T.F., “A path availability model for wireless ad hoc Networks,” in Proceedings of IEEE wireless communication and networking conference (wcnc), vol. 1, pp. 35-40, Sep. 1999, New Orleans, USA.

[29] Yong, Xi., Bo, W.J. and Wen, Z.Z., “Throughput analysis of IEEE 802.11 DCF over correlated fading channel in manet,” IEEE wireless communication, networking and mobile computing, vol. 2, pp. 694-697, 23-26 Sep. 2005