AN EFFICIENT COOPERATIVE MAC PROTOCOL FOR ENHANCING QoS OF IEEE 802.11e EDCA

By

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Dedication

THIS THESIS IS DEDICATED

TO

MY PARENTS AND MY SISTERS

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List of Abbreviations

IEEE	Institute of Electrical and Electronics Engineers
WLAN	Wireless Local Area Network
MAC	Media Access Control
PHY	Physical Layer
DCF	Distributed Coordination Function
PCF	Point Coordination Function
HCF	Hybrid Coordination Function
EDCA	Enhanced Distributed Channel Access
HCCA	HCF Controlled Channel Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
RTS	Ready To Send
RTS	Clear To Send
RTH	Ready To Help
HTS	Helper Ready To Send
ACK	Acknowledgement
ERTS	Enhanced RTS
ECTS	Enhanced CTS
IFS	Inter Frame Space
DIFS	DCF IFS
SIFS	Short IFS
PIFS	PCF IFS
AIFS	Arbitrary IFS
BEB	Binary Exponential Backoff
AC	Access Class
TXOP	Transmission Opportunity

List of symbols

T_{DATA}	Duration of Sending a Data Frame
T_{ERTS}	Duration of Sending a ERTS Frame
T_{ECTS}	Duration of Sending a ECTS Frame
T_{ACK}	Duration of Sending a Acknowledgement Frame
T_{RTH}	Duration of Sending a RTH Frame
T_e	Duration of a Time Slot
$b_{i,j,k}$	State Distribution for $j \geq 0$
$b_{i,sat,0}$	State Under Saturation
$\boldsymbol{i}$	AC Number
$\boldsymbol{j}$	Retransmission Counter
$\boldsymbol{k}$	Current Backoff Value
n_i	Number of Nodes in the *ith* AC
N_c	Number of ACs
$W_{i,0}$	Minimum Contention Window Size in the *ith* AC
$p_{i,c}$	Probability of Collision in the *ith* AC
$p_{i,s}$	Probability of Successful Transmission in the *ith* AC
$p_{i,b}$	Probability of Busy Medium
τ_i	Probability that a Station Transmits in the *ith* AC
P_S	Probability of Successful Transmission in Any AC
ρ_i	Probability of Saturation in Any AC
$S_{th,i}$	Throughput in the *ith* AC
δ	Propagation Delay
D_i	Overall Service Delay in the *ith* AC
X_i	Average Number of Slot Times in the *ith* AC

Acknowledgment

All praises are for the almighty for giving me the strength, without which I could not afford to attempt this research work.

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Abstract

Cost effectiveness and easiness in deployment make IEEE 802.11 Wireless Local Area Network (WLAN) one of the most widely deployed wireless technologies now-a-days. To cope up with the thriving necessity of Quality of Service (QoS) required by modern multimedia applications, IEEE 802.11 Working Group proposes an enhanced version of the 802.11, also known as 802.11e. The access mechanism of 802.11e, referred to as Enhanced Distributed Channel Access (EDCA), assigns different types of data traffic with different priorities based on the QoS requirements of the traffic. For each priority, it uses a different set of medium access parameters to introduce QoS support. Differentiating channel access probability based on only traffic priority can ensure QoS statistically in enhanced distributed channel access (EDCA) of IEEE 802.11e. However, it may seriously affect the overall performance in the presence of degraded channel conditions, specially for the distant stations far away from the access point (AP). To overcome this limitation, cooperative communication is getting very popular in wireless communication where sender station transmits data via a helper node to alleviate the adverse effect of low data rate due to bad channel condition. Most of the cooperative MAC protocols are based on DCF mode and concentrate on finding an optimal helper on the basis of data rate only. In this research work, an effective channel access scheme is proposed which exploits the benefit of cooperative communication in order to mitigate the adverse effect of bad channel condition while maintaining deterministically prioritized channel access for high priority traffic. Unlike EDCA, the proposed scheme chooses a prospective helper to assist the sender in transmission whenever a distant station with degraded channel condition wins the channel contention. The major difference with the state of the art cooperative MAC protocols is that it selects an optimal helper node which has data of equal or higher as well as supports significantly high data rate for cooperative transmission. Analytical results show that proposed protocol outperforms the existing protocols in terms of throughput and delay performance.

Chapter 1

Introduction

1.1 Motivation

The popularity of wireless technology during the last decades led to a great progress in the field of telecommunications. The expansion of electronic devices such as laptops, smart phones, tablets with social media, different VoIP application software, etc reinforces the need of multimedia services.

The IEEE 802.11 standard defines multiple physical layers (PHYs) and a common medium access control (MAC) layer for wireless local area networking. The most popular standard used for wireless communication is IEEE 802.11, which designs a medium access control (MAC) protocol for sharing the wireless medium among different wireless node [1]. This standard defines a MAC sublayer called Distributed Coordination Function (DCF). DCF uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism to access the wireless medium for data transfer. CSMA/CA is based on the principle 'listen before talk' to avoid collisions. With CSMA/CA, if the station detects that the medium is busy, it defers its transmission for a random period and continues to sense the medium to when going idle again. Collisions are avoided by using three strategies: the inter frame space (IFS), the contention window and acknowledgements [2].

But it cannot satisfy the increasing demand for real time application support. However multimedia applications require some quality of service support such as error rates, bit rate, throughput, transmission delay, availability, jitter, etc. To support multimedia applications with Quality of Service (QoS) requirements in the IEEE 802.11 MAC protocol, the IEEE 802.11e has been standardized [3]. The distributed access mechanism of IEEE 802.11e is called Enhanced Distributed Channel Access

(EDCA), and supports QoS by introducing service differentiation. Different types of traffic are assigned with different priorities based on their QoS requirements, and service differentiation is introduced by using a different set of medium access parameters for each priority.

Some cooperative MAC protocols propose in [4–8] to increase the network performances in terms of throughput and delay. Cooperative communications are based on the concept that transmitting with a partner or helper station. When the direct link between sender and receiver is too poor to communicate, then the sender searches for a helper to assist in its transmission. There are two phases of cooperative communication, i.e., from sender to helper phase and from helper to sender phase.

According to the Binary Exponential Backoff (BEB) algorithm used in WLAN, a low priority or low link rate station can win contention process and thus, can occupy the channel for long times. This will degrade the network performance by introducing access delay. The introduction of service differentiation in IEEE 802.11e partially mitigates this problem by allowing high priority stations to access first. To resolve this problem, a new EDCA based cooperative MAC protocol for wireless networks is proposed in this thesis work.

1.2 Related Work

To provide QoS at MAC layer, several studies adopt EDCA for wireless communication. EDCA offers traffic differentiation to provide QoS guarantee in the MAC layer [3]. Many studies provide QoS by providing priority to the traffics by offering them different QoS parameters. Some DCF based work also use priority scheme to support QoS. To reduce the overhead, and improve the performance of the network, the ECC-MAC protocol [9] extends the CoopMAC protocol by using only the concept of TXOP and Block ACK parameters of IEEE 802.11e EDCA, but optimal helper selection and QoS enhancement are not in the consideration of their work. There is no priority based Access Classes (AC) and their EDCA parameter consideration. It can select a helper like [5] with little modification in RTS/CTS frame format and send data packets to the helper one by one instead of a single data packet to the relay for cooperative communication. After receiving the data packets from the helper, the destination then sends a Block ACK to acknowledge the reception of all data packets

to reduce the overhead. To ensure QoS guarantee in DCF mode QoS-Guaranteed MAC (QC-MAC) protocol [10] is proposed, where each sender sends busy tone or senses the channel according to the binary digits of its virtual ID. After this highest priority sender wins the contention and then it adopts the cooperation process for data transmission and piggybacks also. In this protocol, service differentiation of helper node is not taken into account. In some research works, EDCA is modified by using busy tones to prioritize the traffic and access the channel with high priority properly. To provide guaranteed channel access to multimedia applications a simple scheme called DPCA protocol [11] is proposed. This proposed protocol provides deterministically prioritized channel access for high-priority ACs and avoid collisions caused by low-priority ACs. This protocol does not consider the unfairness issue at the low priority ACs. In the literatures [5–7][12], researchers concentrate to use cooperative communications in their research work to enhance the performance of the network. In DC-MAC protocol [13], the authors concentrate on the retransmission process of collided packets by using cooperation. In this protocol, they consider two queues at each station and there is a partner queue for each traffic class to support cooperative retransmission. This protocol is only used for retransmission process but the QoS enhancement of the network is not applicable for this protocol. Some recent papers based on EDCA mechanism has been studied in [14–18]. For contention resolution, several studies based on busy tone are proposed in [12, 19–24]. Several studies on cooperation [4–8][12] have been studied to find out the selection of optimal helper. For implementing a Markov Chain model to mathematically analyze the research work, several literatures based on mathematical model has been studied [25–27]. EDCA related research works are also analyzed to seek knowledge about mathematical analyze the research work [20][28–39]. The earlier cooperative MAC protocols for EDCA do not take into account the hidden helper node problems for protocol design. In this research work, the proposed protocol uses here busy tone techniques to contend among helpers and also consider the hidden helper node problems into account. Because, in the hidden terminal environment, hidden stations cannot sense the other stations' busy tones so that lower priority stations cannot sense the presence of higher priority stations.

To resolve these problems, an efficient cooperative MAC protocol for IEEE 802.11e

EDCA is proposed in this research work. The main concentration of this research work is to ensure QoS at the MAC layer with cooperation for EDCA. The novel idea of this research work is to propose a protocol to find out a helper node in the basis of priority class and link rate. The proposed cooperative protocol for EDCA outperforms the standard EDCA by choosing an optimal helper for cooperation that enhances QoS and network performance.

1.3 Research Objectives

- To develop a Cooperative MAC protocol for IEEE 802.11e.
- To mitigate the hidden helper node problem by using busy tone based helper selection.
- To select an optimal helper in the basis of traffic priority and data rate.
- To compare the performance of the proposed protocol with existing cooperative MAC protocols.

1.4 Outline of Methodology

- A new cooperative MAC protocol for EDCA is propossed considering both link rate and traffic class priority for helper selection process.
- A new helper selection process is proposed which exploits the benefit of cooperative communication in order to mitigate the adverse effect of bad channel condition while maintaining deterministically prioritized channel access for high priority traffic. Eventually by exchanging sequence of busy tones and a special frame, it selects an optimal helper which has data with equal or higher priority as well as supports significantly higher data rate for cooperative transmission.
- The optimal helper assists the sender for transmission and also piggybacks its own data if there enough time remains in the Transmission Opportunity (TXOP) will also be investigated through analytical analysis.
- An analytical model of the new cooperative MAC protocol for EDCA will be developed on the MATLAB simulation framework.

- Finally, the performance of the proposed protocol in terms of 'network throughput', 'transmission probability' and 'end to end delay' will be investigated and compared with the existing protocols.

1.5 Organization of Thesis

This thesis consists of five chapters.

Chapter 1 introduces the IEEE 802.11 standard of WLAN and also IEEE 802.11e standard that is the concentration of this research work. Related research works regarding cooperative network also discussed. After that, objectives and methodology also presented in this chapter.

Chapter 2 of this thesis work covers a detail overview of IEEE 802.11 standard of WLAN and also IEEE 802.11e standard. Cooperative communication is also discussed in this chapter.

Chapter 3 presents an EDCA based cooperative MAC protocol to enhance the QoS of the wireless network. A new helper selection process and contention resolution process are discussed in details. A Markov chain model for the proposed protocol is analyzed in this chapter.

Chapter 4 investigates the performance between proposed techniques and existing methods in terms of performance parameters such as throughput, transmission probability and end to end delay etc.

Chapter 5 concludes the thesis and recommendations for future work is also available in this chapter.

1.6 Summary

This chapter introduces a very brief introduction of WLAN with its background. A little glance of IEEE 802.11e standard is included here. Some related work of IEEE 802.11 and IEEE 802.11e using cooperative MAC also discussed in this chapter. Methodology of the research work is also discussed here to get a clear overview of the research work.

Chapter 2

An Overview of Wireless Local Area Networks

2.1 Introduction

In this chapter, an ultimate overview is given to Wireless Local Area Networks (WLANs). This chapter gives the detailed overview about IEEE 802.11 standards as well as the overview of Cooperative communication in wireless network.

2.2 Introduction of IEEE 802.11

Institute of Electrical and Electronics Engineers (IEEE) released the 802.11Wireless Local Area Network (WLAN) standard [1] in 1997 which defines Media Access Control (MAC) and Physical (PHY) layer specification for Wireless LANs. There are different physical layer specifications to support with the maximum data transmission rate up to 2 Mbps. The technology continued evolving with the new physical layer specifications to enrich the data rate for WLAN. In 1999, IEEE introduced two enhanced physical layer specifications 802.11b [40] and 802.11a [41] with data transmission rates of up to 11 and 54 Mbps respectively. 802.11b is also based on Direct Sequence Spread Spectrum (DSSS) and operates in the 2.4 GHz band, and, 802.11a is based on Orthogonal Frequency Division Multiplexing (OFDM) and operates in the 5 GHz band.

In 2003, IEEE released 802.11g [42] that extended 802.11b physical layer to support data transmission rates of up to 54 Mbps in the 2.4 GHz band. IEEE 802.11 has gained huge popularity due to its cost effectiveness and easy deployment features. Today, IEEE 802.11 hot-spots are available at offices, campuses, airports, hotels, public transport stations, and residential places, making it one of the most widely deployed wireless network technologies in the world.

IEEE 802.11 defines two different architectures, Basic Service Set (BSS) and Independent BSS (IBSS). In a BSS, numbers of wireless stations are associated to an Access Point (AP). All communications take place through the AP. In an IBSS, stations can be connected together via a Distributed System (DS) to form an extended network, called Extended Service Set (ESS).

IEEE 802.11 MAC defines two different access mechanisms, the mandatory Distributed Coordination Function (DCF) which provides distributed channel access based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), and the optional Point Coordination Function (PCF) which provides centrally controlled channel access through polling [1].

2.2.1 Distributed Coordination Function (DCF)

DCF is the basic access mechanism of 802.11 and is based on Carrier Sense Multiple Access (CSMA). CSMA works as listen-before-talk, i.e., before transmitting a frame, the station senses the medium (carrier sensing). If the medium is found idle at least for DCF Inter-Frame Space (DIFS) time period, the station starts transmission, and other stations wait until medium becomes idle again for at least DIFS time period. As the destination station successfully receives a frame, it acknowledges by sending back an ACK frame after Short Inter-Frame Space (SIFS) time period. Figure 2.1 illustrates the mechanism. SIFS is the shortest of the three Inter-Frame Spaces (IFS)

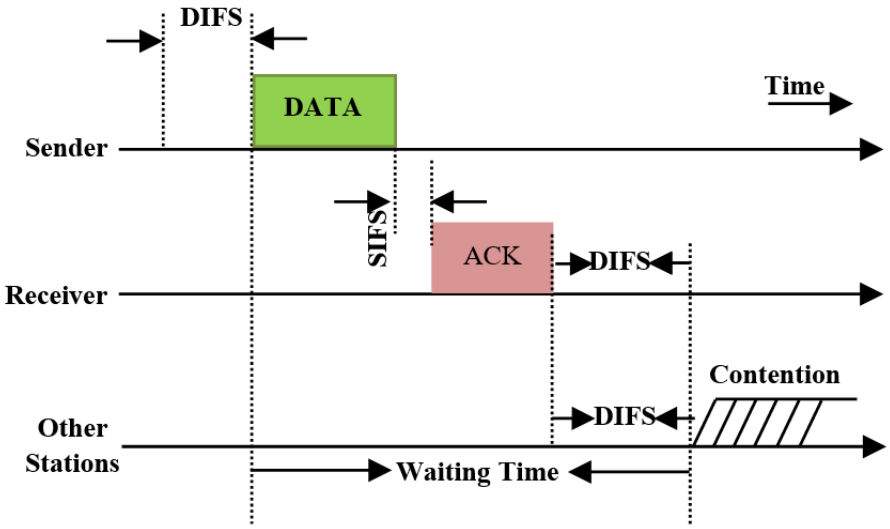


Figure 2.1: DCF Basic Access Mechanism

defined in IEEE 802.11 [1] to control the access to the medium. IFS relationships can be seen in Figure 2.2. Subsequent frame transmissions are separated by these inter-frame spaces depending on the priority of the frame exchange sequence, i.e., higher the priority of the frame exchange sequence, shorter is the inter-frame space used between the frames. The SIFS between the data and ACK frames, as seen in Figure 2.1, therefore prevents other stations to transmit at the same time the receiver transmits the ACK frame and thereby resulting in transmission failure; this is because other stations have to wait for the DIFS time prior to start transmission which is longer than SIFS. Thus, in this way, a station transmitting the ACK frame is given priority over the stations trying to transmit data frames. The second shortest inter-frame space, PCF Inter-Frame Space (PIFS), is used by AP in the PCF, the optional access mechanism of IEEE 802.11, in which PC/AP centrally controls the access to the medium by polling individual stations. In PCF, PC/AP is given priority over ordinary stations such that it has to wait PIFS instead of longer DIFS prior to transmitting a frame. The values of inter-frame spaces are dependent on the underlying Physical layer (PHY) and are defined in relation to a slot time. Slot time is derived from propagation delay, transmitter delay, and other PHY dependent parameters [1]. PIFS consists of a SIFS plus one slot time and DIFS consists of a SIFS plus two slot times. Two types of carrier sensing are used to determine whether the medium is idle or busy. With Physical Carrier Sensing, the wireless channel is sensed itself at the Physical layer. On the other hand, virtual carrier sensing is used at the MAC layer, such that as a station receives a frame that is not directed to it. Virtual carrier sensing examines the duration field in the frame header, which

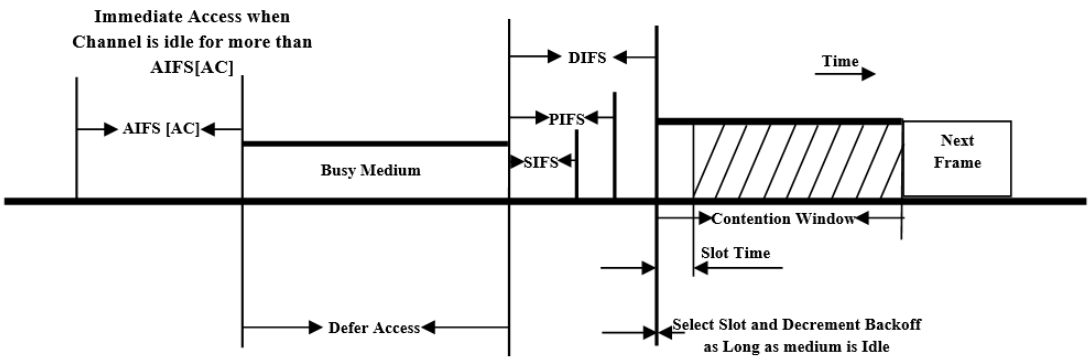


Figure 2.2: Medium access and IFS relationships

specifies the time required to transmit the frame and to receive the ACK frame in response. According to this time stations defer to access the medium for that particular period. The process is described in more detail in Section 2.2.3.

2.2.1.1 Collision Avoidance and Backoff Process

The above scenario may lead to collisions if two or more stations sense the medium idle and try to transmit at the same time. In order to avoid such collisions, a station has to wait an additional time period prior to transmitting if the medium is sensed busy in the DIFS period, or, if the medium was busy just before the station started waiting the DIFS period. In these situations, the station defers access until the medium becomes idle, and chooses a random backoff value, which specifies the time period, measured in time slots. The station also has to wait in addition to the DIFS after the medium becomes idle. This additional random delay in form of backoff helps to avoid collisions, otherwise all stations would try to transmit as soon as medium becomes idle for the DIFS period. This mechanism is called Collision Avoidance (CA), and thus the whole access mechanism is referred to as CSMA/CA.

While a new station need not to choose a new backoff value, instead it can resume its paused backoff timer to start a fresh contention. Thus, in this way a station that attempted first and thus waited longer is given advantage over a station that attempted after it, because it only has to wait for its remaining backoff time.

The random backoff value is uniformly chosen from the interval [0, CW], called the Contention Window (CW). At the first transmission attempt, CW is set to the minimum CW size (CWmin). After each unsuccessful transmission, CW is increased exponentially using the equation (2 x (CW + 1) - 1) until it reaches the maximum Contention Window size (CWmax). The values of CWmin and CWmax are uniformly chosen from the range 31 and 1023 respectively [1], in which case the CW size increases in the form of 31, 63, 127, 255, 511 and 1023. For this reason, the mechanism is also referred to as exponential backoff. An unsuccessful transmission (in other words, a collision) is determined if the sender station does not receive ACK frame within a specified ACK timeout period. After the ACK timeout period, the station assumes that a collision has occurred and enters into the backoff period again after waiting for medium to be idle for DIFS, such that the new backoff value is

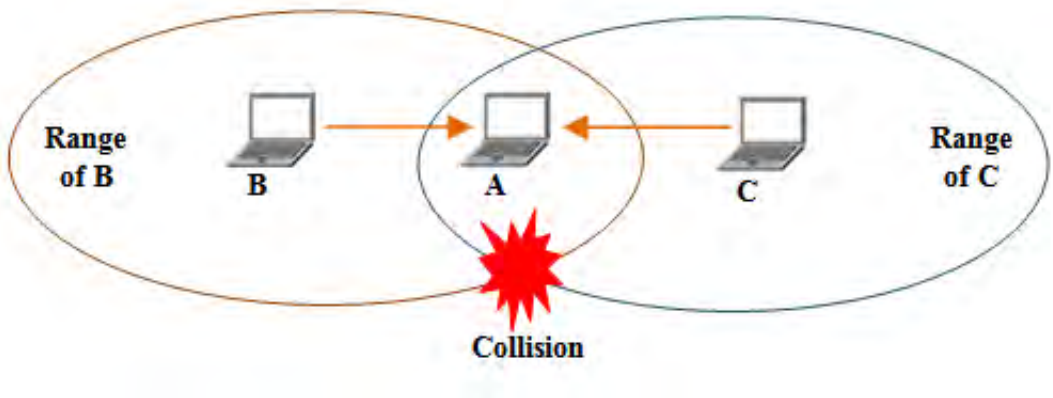


Figure 2.3: Hidden Node Problem

chosen from the doubled CW. With the doubled CWsize, the probability of a bigger random backoff value is higher, which reduces the probability of the stations colliding again.

DCF specifies a retransmit limit (also referred to as retry limit), i.e., the number of times a frame can be retransmitted. If an unsuccessful transmission is determined after reaching the retransmit limit, the frame is dropped. The CW size is reset to CWmin after each successful transmission.

2.2.1.2 Hidden Node Problem

Due to the wireless and mobility features in IEEE 802.11 every station in the WLAN unable to communicate directly with every other station or to know the where-about of every other station. This is the reason why there exists a hidden node problem. An example explains this best (see figure 2.3[2]) in the range of station B, every station can hear any signal transmitted by station B and also it is true for station C. But, station B and C are not in range of each other. Station A, however, is in the area covered by both B and C; as a result, station A can hear any signal transmitted B or C. Let station B has data to send to station A and at the same time, station C also has data to send to station A. However, station C is out of B's range and transmissions from B cannot reach C. Station C also sends it data to A, which results in a collision at A because A is receiving data from both B and C. In this case, it can be said that the stations B and C are hidden from each other with respect to A. Hidden stations can reduce the capacity of the network because of the probability of

collision.

To deal with this problem in the wireless media, IEEE 802.11 has introduced two additional frames in the MAC frame exchange protocol, called Ready To Send (RTS) and Clear To Send (CTS). These two frames are further discussed in the next section.

- **The RTS/CTS mechanism-** An additional mechanism, RTS/CTS is defined to solve the hidden terminal problem found in the wireless network that uses CSMA. With RTS/CTS, the sender and receiver perform a handshake mechanism by exchanging RTS and CTS control frames. The procedure is shown in Figure 2.4. After waiting the DIFS time, prior to transmit the data frame, the sender sends a RTS frame to the receiver, and the receiver responds with a CTS frame after waiting for a SIFS time. The CTS frame indicates that the handshake is successful and ensures that the medium has been reserved for the particular sender and receiver for the transmission.

  RTS/CTS use Virtual Carrier Sensing, such that the RTS and CTS frames include the duration of the complete frame exchange sequence, inclusive of SIFS and ACK. All stations within the receiving range around the sender and

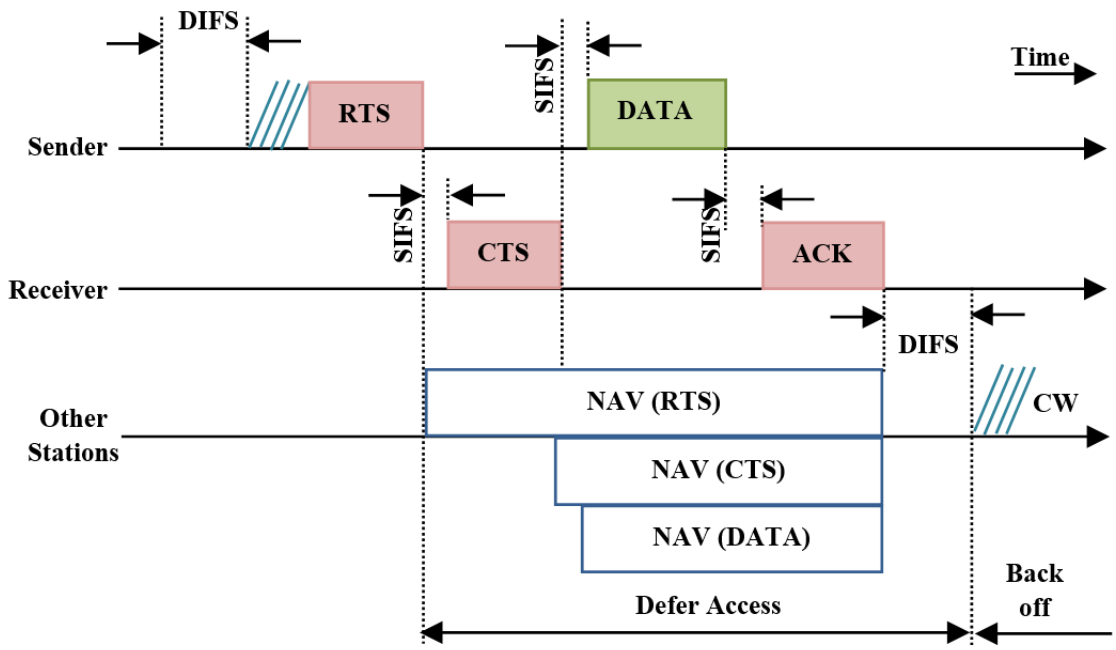


Figure 2.4: Illustration of the RTS/CTS mechanism

receiver set their Network Allocation Vector (NAV) after receiving the RTS and CTS frames, and thus are informed that they have to wait until the current transmission finishes. Here, an important thing to note is that the sets of stations receiving RTS and CTS frames can be different. NAV is a timer and is decremented in the similar way the backoff timer is decremented. The station is allowed to transmit after its NAV reaches to zero. Collisions can only occur at the beginning when the RTS frame is transmitted, as two or more stations may start transmitting, either RTS or data frames, at the same time. Such collisions are determined if the sender does not receive the CTS frame within a specified CTS timeout period. In that case, the sender transmits the RTS frame again. As the size of the RTS frame is significantly smaller compared to that of data frame, the RTS/CTS mechanism provides a mean of fast recovery from collisions as the sender becomes aware of failure and may retransmit more quickly compared to the case when long data frame is transmitted and failure is determined after ACK timeout. As seen in Figure 2.4, again the SIFS intervals between RTS, CTS and data frames prevent other stations to transmit and thereby interrupting the transmission. RTS/CTS mechanism shall be used for large data frames. Using it for small data frames may result in significant overhead causing inefficient capacity utilization and higher delays.

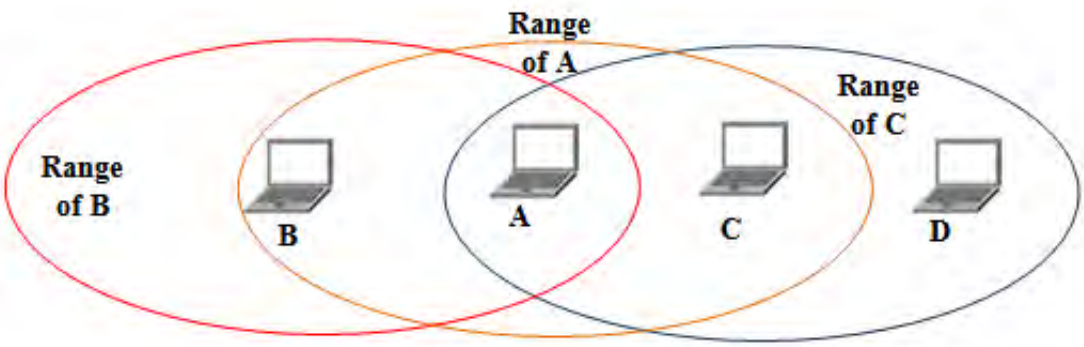


Figure 2.5: Illustration of Exposed Node Problem

2.2.1.3 Exposed Node Problem

The exposed station problem is inverse of the hidden node problem. In this problem, a station refrains from using a channel when the channel is, in fact, available. In figure 2.5, station A is transmitting to station B. Station C has some data to send to station D, which can be sent without interfering with the transmission from A to B. However, station C is exposed to transmission from A; it hears what A is sending and thus refrains from sending. In other words, C is too conservative and wastes the capacity of the channel.

The RTS/CTS mechanism also solves exposed node problem. But it may not help in some situations [2], for example, station C hears RTS from A, but does not hear CTS from station B. Station C, after hearing the RTS from A, can wait for a time so that the CTS from B reaches A; it then sends an RTS to D to show that it needs to communicate with D. Both stations B and A may hear this RTS, but station A is in the sending state, not the receiving state. Station B, however, responds with a CTS. The problem is here. If station A has started sending its data, station C cannot hear the CTS from station D because of the collision; it cannot send its data to D. It remains exposed until A finishes sending its data.

2.2.2 Point Coordination Function (PCF)

To support applications that require near real-time service, the IEEE 802.11 standard includes the point coordination function. The PCF has not been widely implemented and is an optional part of the standard, though stations that implement only the DCF will interoperate with point coordinators [1]. The PCF is built over the DCF, and both operate simultaneously.

This centrally controlled access mechanism uses a poll and response protocol to eliminate the possibility of contention for the medium. A point coordinator (PC) controls the PCF and is always located in the AP, thus access to the medium is restricted by the PC. Stations associated with this AP can only transmit data when they are polled by the PC. Although access is under control of the PC, all frames must be acknowledged.

In PCF, time is divided into super frames. A super frame includes a contention period (CP), where DCF is used, and a contention-free period (CFP), where PCF is

used. A super frame starts with a beacon management frame transmitted by the PC.

2.2.3 Frame Format

The IEEE 802.11 protocol defines three different classes of frames: data, control and management frames. Data frames are used for sending data between stations, the control frames are used to deal with handshaking before sending data and acknowledgments; the management frame is used for beacon frames, association, disassociation, authentication, deauthentication, and for distribution of different kinds of parameters. Each of these frames has a header with a variety of fields used within the MAC sub layer.

The MAC of the IEEE 802.11 names the data frames as MAC service data units (MSDUs). The MAC accepts these MSDUs from layers higher up in the protocol stack, e.g. the network layer, for the meaning of reliable sending of those MSDUs to the network layer in another station. The MAC adds headers and trailer to create a MAC protocol data unit (MPDU). With these headers and trailer, the MAC can pass the MPDU to the physical layer for sending over the wireless medium to the other station. The header and trailer information, in combination with the information received as the MSDU, is referred to as the MAC frame. Figure 2.6 shows the frame format of IEEE 802.11.

2.3 Introduction of IEEE 802.11E

IEEE is currently working on a new standard, called IEEE 802.11e [3], which is an enhanced version of the legacy 802.11 MAC, in order to support quality of service (QoS). IEEE 802.11e is in standardization process and the final draft has been released. IEEE 802.11e supports quality of service by introducing service differentiation to

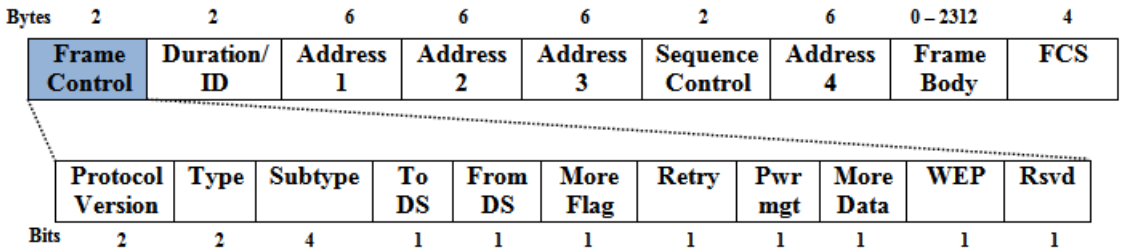


Figure 2.6: IEEE 802.11 Frame Format

give priority among contending stations. All types of data traffic are not treated equally as done by the legacy IEEE 802.11 standard, instead, 802.11e supports service differentiation by assigning data traffic with different priorities based on their QoS requirements. Furthermore, four different Access Categories (AC) have been defined each for data traffic of a different priority. Access to the medium is then granted based on the priorities of data traffic, such that each frame with a particular priority is mapped to an Access Category, and service differentiation is realized by using a different set of contention parameters to contend for the medium for each AC.

In IEEE 802.11e, the AP and stations that provides QoS services are referred to as QoS Access Point (QAP) and QoS Station (QSTA) respectively, and the BSS they are operating in is called QoS Basic Service Set (QBSS). IEEE 802.11e introduces a new coordination function, called Hybrid Coordination Function (HCF), to provide QoS support. Subsequent sections describe HCF together with the detailed description of its service differentiation mechanism.

2.3.1 Hybrid Coordination Function (HCF)

IEEE 802.11e defines a new coordination function called Hybrid Coordination Function (HCF). HCF is a centralized coordination function that combines the aspects of DCF and PCF with enhanced QoS mechanisms to provide service differentiation. HCF provides both distributed and centrally controlled channel access mechanisms similar to DCF and PCF in the original standard. The distributed, contention based channel access mechanism of HCF is called Enhanced Distributed Channel Access (EDCA), and the centrally controlled, contention-free channel access mechanism is called HCF Controlled Channel Access (HCCA).

IEEE 802.11e introduces Transmission Opportunity (TXOP), defined as the time period during which a QSTA has the right to transmit. In other words, in 802.11e when a station gets access to the medium, it is said to be granted the TXOP. TXOP is characterized by a starting time and a maximum duration, called TXOP Limit. As a QSTA gets the TXOP, it can then start transmitting frames such that the transmission duration does not exceed the TXOP limit. TXOP Limit is specified by the QAP.

The next section describes EDCA, the distributed access mechanism of HCF.

The detailed functionality of the centrally controlled access mechanism HCCA is beyond the scope of this report as the focus of this research work on EDCA access mechanism.

2.3.1.1 Enhanced Distributed Channel Access (EDCA)

This is the prioritized carrier sense multiple access with collision avoidance (CSMA/CA) access mechanism used by QSTAs in a QoS basic service set (QBSS). This access mechanism is also used by the QAP and operates concurrently with the hybrid coordination function (HCF) controlled channel access (HCCA). The EDCA provides differentiated, distributed access to the medium using different priorities for different types of data traffic. The detailed description of the components and operation of EDCA is presented next.

- **Access Categories (ACs):** EDCA defines four Access Categories (ACs) for different types of data traffic, and service differentiation is introduced such that for each AC, a different set of parameters is used to contend for the medium. These parameters are referred to as EDCA parameters and are

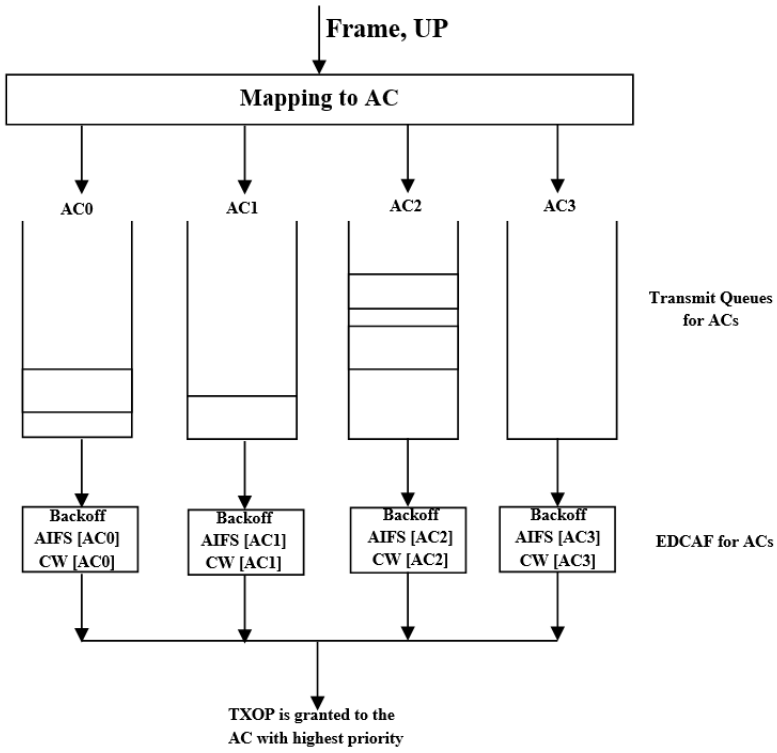


Figure 2.7: Internal contention in EDCA

Table 2.1: User Priority to Access Category mapping

Priority	**User Priority**	**Access Catagory (AC)**	**Designation**
Lowest	1	AC_BK	Background
.	2	AC_BK	Background
.	0	AC_BE	Best Effort
.	3	AC_BE	Best Effort
.	4	AC_VI	Video
.	5	AC_VI	Video
.	6	AC_VO	Voice
Highest	7	AC_VO	Voice

described in the next subsection. Frames from different types of data traffic are mapped into different ACs depending on the QoS requirements of the traffic the frames belong to. The four Access Categories are named AC_BK, AC_BE, AC_VI and AC_VO for Background, Best Effort, Video and Voice data traffic respectively. Here AC_BK has the lowest and AC_VO has the highest priority as shown in Table 2.1. Each frame from the higher layer arrives at the MAC layer along with a priority value. This priority value is referred to as User Priority (UP) and assigned according to the type of traffic the frame belongs to. There are eight different priority values ranging from 0 to 7 [3].

At the MAC layer, a frame with a particular UP is further mapped to an AC. ACs are derived from the UPs as illustrated in Table 2.1.

- **Enhanced Distributed Channel Access Function (EDCAF):** Every station maintains four transmit queues one for each AC, and four independent Enhanced Distributed Channel Access Functions (EDCAF), one for each queue, as illustrated in Figure 2.7. EDCAF is an enhanced version of DCF, and contends for the medium on the same principles of CSMA/CA and backoff, but based on the parameters specific to the AC. Next section discusses these

EDCA parameters.

- **EDCA Parameters:** An EDCAF contends for medium based on the following parameters associated to an AC:

  - **AIFS:** The time period the medium is sensed idle before the transmission or backoff is started. The minimum time period for which the medium must be sensed idle before an EDCAF. Station may start transmission or backoff is not the fixed value as DIFS, but is a variable value, AIFS, that depends on the AC for which the EDCAF is contending for. AIFS is derived from the following equation:

$$AIFS = AIFSN \times aSlotTime + aSIFSTime \tag{2.1}$$

  where aSlotTime is the slot time, aSIFSTime is the SIFS time period and Arbitration Inter-Frame Space Number (AIFSN) is used to determine the length of the AIFS. AIFSN specifies the number of time slots in addition to the SIFS time period the AIFS consists of. Different AIFSN values are used for different ACs such that the high priority ACs use smaller values compared to the low priority ACs. The minimum possible value of AIFSN is 2. As a DIFS is equal to 2 x aSlotTime + aSIFSTime, it shows that the minimum length of AIFS is same as of DIFS. For QAP operating in HCCA, the minimum possible value of AIFSN is 1, which makes it equal to PIFS as PIFS is 1 x aSlotTime + aSIFSTime. The default AIFSN values for all four ACs can be seen in Table 2.2. The smaller AIFSN value for a higher priority AC explains that the corresponding

Table 2.2: Default EDCA parameter Values

Access Category (AC)	**AIFSN**	CW_{min}	CW_{max}	**TXOP Limit**
AC_VO	2	((AC_min+1)/4)-1	((AC_min+1)/2)-1	1.504ms
AC_VI	2	((AC_min+1)/2)-1	AC_min	3.008ms
AC_BE	3	AC_min	AC_max	0
AC_BG	7	AC_min	AC_max	0

EDCAF has to wait shorter time period before it can start transmission or counting down its backoff timer compared to the EDCAF for a low priority AC. In this way, the higher priority ACs are guaranteed greater share of the bandwidth. Moreover, smaller AIFS lengths ensure that the higher priority ACs will not suffer from long delays, which are very critical for the delay sensitive traffics. The lower priority ACs may suffer from longer delays because of the larger AIFS durations they have to wait, but since these ACs are designed for delay-tolerant traffics, certain amount of delays do not degrade their performance beyond an acceptable limit.

– **CWmin and CWmax:** Size of Contention Window (CW) used for backoff. The minimum and maximum CW size limits are not fixed as it is in DCF, but are variable depending on the AC. The higher priority ACs has smaller CWmin and CWmax values compared to lower priority ACs. The default values of CWmin and CWmax parameters for each of the four ACs are presented in Table 2.2. A smaller CW for an AC will cause the corresponding EDCAF to choose smaller random backoff values, and thereby waiting shorter time period in addition to AIFS as the medium becomes idle. It gives such an AC priority over the AC with a larger CW, which results in larger backoff values and thereby longer delays.

  As seen in Table 2.2, for the commonly used Physical layer DSSS, the CWmin values for lower priority ACs, AC_BE and AC_BK, are same

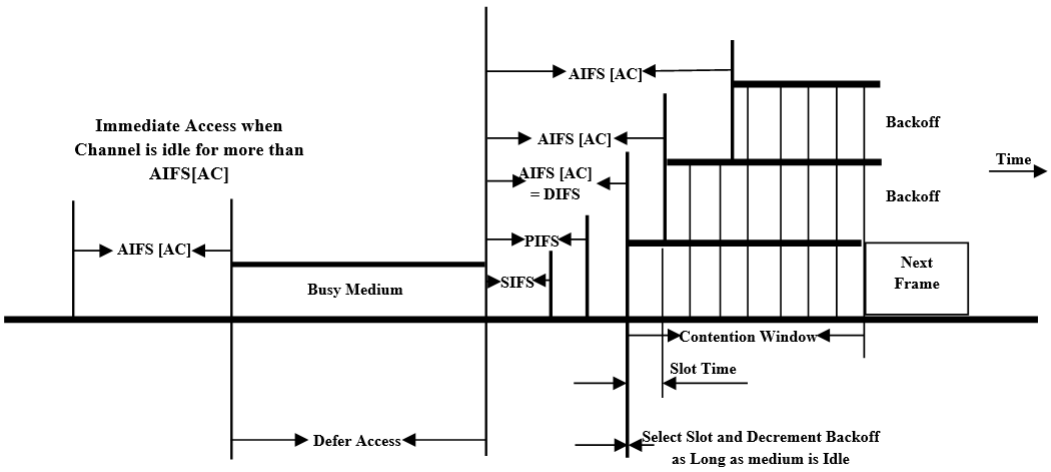


Figure 2.8: Prioritization based on AIFS

as it is for the legacy 802.11 DCF, but these values for higher priority ACs, AC_VO and AC_VI, are as small as one half or quarter of those of the lower priority ACs. This results in smaller backoff values for the high priority ACs and thereby shorter medium access delays. The negative aspect of small CW sizes for higher priority ACs is that they suffer from higher number of collisions. The reason is, as described in Section 2.2.1.1, that the probability of choosing the same backoff values or counting the backoff timers to zero at the same time increases with the decreasing size of CW. CWmax values for high priority ACs are also set such that they are equal or less than the CWmin values for the lower priority ACs, i.e., CWs are non-overlapping. This shows that after doubling the CW size in case of an unsuccessful transmission, i.e., collision, its size still remains smaller than the CWmin size of lower priority ACs. Furthermore, it also indicates that while a low priority AC has to double its CW size after each unsuccessful transmission, until it reaches the CWmax, and with higher probability, has to choose a bigger backoff value for each retransmission. The CW size of a high priority AC becomes constant after fewer retransmissions, allowing it to consistently choose smaller backoff values and thereby winning access to the medium. In this way, high priority ACs is given consistent and greater share of the bandwidth in the situations when the network has become congested. On the other hand, this may severely degrade the performance of the low priority ACs since they might not be able to decrement their backoff timers because of the smaller post backoff durations of the higher priority ACs. The situation is further explained with an example later in this section. As it can be seen in Table 2.2, the default values for CWmin and CWmax for both AC_BE and AC_BK are same, but priority is given to AC_BE over AC_BK by assigning it a much smaller AIFSN, i.e., 3 compared to 7, indicating that AC_BK has to wait four additional slots prior to starting transmission or backoff procedure. It also shows that AC_BK suffers from much high delays compared to the other ACs.

– **Transmission Opportunity (TXOP):** The maximum duration of the

transmission after the medium is acquired.

As described above, TXOP is the time duration an EDCAF may transmit after winning access to the medium. TXOP is characterized by a maximum duration, called TXOP Limit. As an EDCAF gets the TXOP, it can then start transmitting frames such that the transmission duration does not exceed the TXOP Limit. The transmission duration covers the whole frame exchange sequence, including the intermediate SIFS periods and ACKs, and the RTS and CTS frames if RTS/CTS mechanism is used. Table 2.2 shows the default TXOP limits for different ACs. A non zero value of TXOP Limit indicates that the EDCAF may transmit multiple frames in a TXOP, provided that the transmission duration does not exceed the TXOP Limit and the frames belong to the same AC. This is then referred to as Contention Free Bursting (CFB). The consecutive frame transmissions in a TXOP are then separated by SIFS time periods instead of AIFS plus the post backoff periods. It is important to note that the multiple frame transmission is granted to EDCAF (or AC) and not to the station, i.e., it is only allowed for the transmission of frames of the same AC as of the frame for which the TXOP was obtained.

If RTS/CTS mechanism is used with CFB, then the RTS CTS frames handshake is done only once, before the first frame, instead of for every frame in the CFB.

The TXOP Limit of zero indicates that CFB is disabled, and thus only one frame, in addition to RTS/CTS if enabled, can be transmitted in a TXOP. In that case, if there is a risk that the transmission duration of the first frame may exceed the TXOP limit, then the frame should be fragmented.

As it can be seen in Table 2.2, the default values of TXOP limits for the low priority ACs, AC_BK and AC_BE, are zero, indicating that CFB is disabled for these ACs. For high priority ACs, CFB allows to seize the medium for certain amount of time periods, which results in significantly reduced delay. However, too large TXOP limits for high priority ACs may result in higher delays for the low priority ACs. Thus,

service differentiation is introduced through TXOP limits by allowing higher priority ACs to gain continuous access to the medium for longer time periods compared to the lower priority ACs.

In the case when CFB is enabled, the virtual carrier sensing is applied such that the Duration field in frame header is set to the remaining duration of the whole TXOP and thus all stations receiving the frame set their NAVs for the duration of whole TXOP instead of that of one frame, i.e., first frame in TXOP, plus the intermediate SIFS times and ACK.

2.3.1.2 Architecture and Important Frame Formats

Together with HCF and its two access mechanisms EDCA and HCCA, IEEE 802.11e also includes the two coordination functions from the original 802.11, DCF and PCF, in order to provide backward compatibility. Figure 2.9 illustrates the architecture of 802.11e MAC.

For backward compatibility, a QSTA can also operate in a non-QoS BSS (nQBSS) by associating itself to a non-QoS AP (nQAP), in case a QAP is not available. On the other hand, a non-QoS STA (nQSTA) may also associate with a QAP in a QBSS, such that it operates just like an ordinary STA in 802.11 and the transmissions from QAP to nQSTA do not use frame formats specific for QoS services.

The centrally controlled, contention-free channel access mechanism of HCF, i.e., HCCA, uses a centralized coordinator called Hybrid Controller (HC), which is collocated in QAP. HC operates concurrently with the EDCA just like in the legacy 802.11, i.e., a Contention Free Period (CFP) is followed by a Contention Period (CP), such that the EDCA operates in CP while HC operates both in CP and CFP. This is in contrast with legacy 802.11 where PC can only operate in CFP. It indicates that HC is capable of polling QSTAs both in CP and CFP, and explains why it is referred to as Hybrid Controller. The QoS subfield in Frame Control field of MAC header indicates whether the station is acting as a QSTA or an nQSTA. The field is set to 1 if the station is QSTAs, and 0 otherwise. Figure 2.10 shows the QoS subfield in the MAC header. At MAC layer, each frame is assigned a priority in the form of a Traffic Identifier (TID). TID field in the newly added QoS Control field in the MAC header contains this TID value. UP of the frame is then determined based on

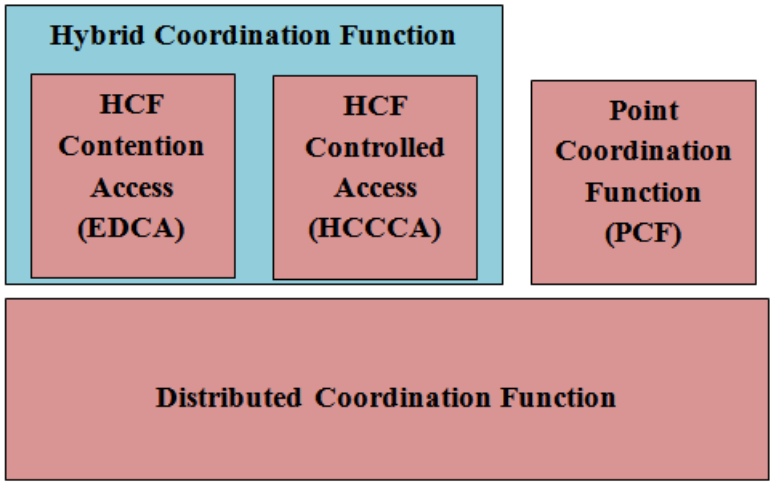


Figure 2.9: IEEE 802.11e MAC architecture

this TID value, such that when QAP receives a frame from a QSTA, it gets the UP value from TID field, ranging from 0 to 7. Figure 2.11 illustrates the QoS Control and TID fields in the MAC header.

The priority value in TID field is supported only if the station has its QoS subfield in the Frame Control field set to 1, i.e., the station is associated with a QAP and thus working as a QSTA. If no QAP is available and a QSTA is associated with an ordinary AP, i.e., nQAP, then the QSTA is functioning just like an ordinary STA, which is indicated by setting the QoS subfield to 0. In that case, the TID value is meaningless and all frames from the station are treated as frames with priority of contention, indicating that they shall be transmitted without any priority, as it is done in the DCF. Similarly, if an ordinary station, i.e., STA or nQSTA, is associated

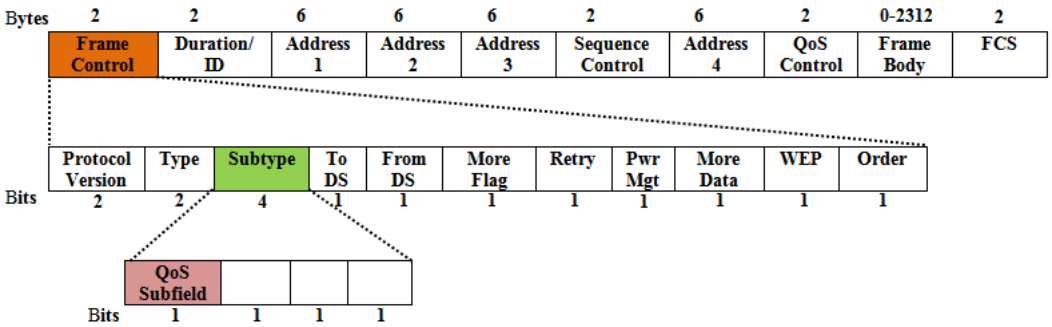


Figure 2.10: MAC data frame header and QoS subfield

with a QAP, all frames from the station are treated as frames with priority of 0. The Queue size field in QoS Control field of the frame header, as seen in Figure 2.11, specifies the total number of frames of the particular priority/TID the station have in its AC transmit queue, excluding the current frame.

TXOP are obtained both in EDCA and HCCA, such that the former is referred to as EDCA TXOP, and the later is referred to as HCCA TXOP or Polled TXOP. An EDCA TXOP is obtained as soon as a QSTA wins access to the medium while operating in EDCA. A HCCA TXOP is granted by the HC while operating in HCCA, such that the HC polls individual stations to grant HCCA TXOPs based on their requirements. A QSTA can specify the intention to transmit multiple frames in a TXOP by setting the Duration/ID field in the frame header, such that it also includes the time required to transmit the additional frames. While operating in HCCA, a QSTA can request the TXOP of particular duration by setting the TXOP duration requested subfield of QoS Control field shown in Figure 2.11. The TID field in that case indicates the AC for which the TXOP is being requested. The HC/QAP may then assign a TXOP of the size requested or of a smaller size.

2.3.1.3 HCF Controlled Channel Access (HCCA)

HCCA uses a Hybrid Coordinator (HC) to centrally manage the medium access to provide parameterized QoS. The intent of this coordination function is to increase efficiency by reducing the contention on the medium, with a polled-based mechanism. Parameterized QoS refers to the capability of providing QoS flows from applications with specific QoS parameters for the benefit of having tighter control of latency and scheduling [3].

The HC has a highest medium access priority over all QSTAs because it has

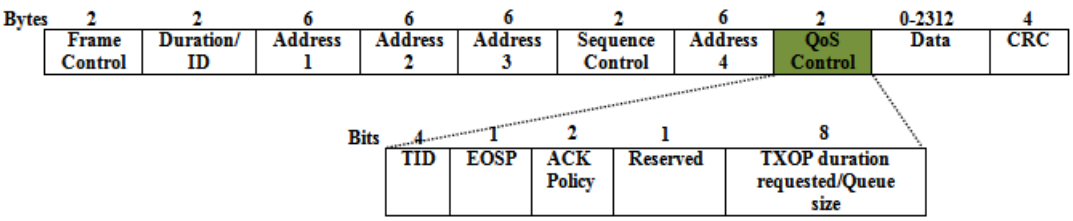


Figure 2.11: TID field in QoS Control field

the shortest waiting time of all contending QSTAs. The HC assigns TXOP under consideration of the current QoS requirements in the BSS. The difference between a HC and the legacy PC is that the HC can control the medium in both the CFP and the CP. A nearly continuous sequence of frame exchange can be maintained with short, fixed delays between frames, under the control of the HC.

The HC is responsible for controlling the allocation of time on the medium through the use of polled TXOPs. The traffic-flow requirements of the QSTAs are specified using Traffic Specifications (TSPEC), and describe requirements such as data rate, delay, packet size and service interval. TSPECs are requested by the QSTA, and the QAP may grant or deny a TSPEC. The IEEE 802.11e specifies the use of TSPECs for negotiating admission control for both EDCA and HCCA [3].

Different priority classes in HCCA are implemented by the so-called Traffic Stream (TS) operation. TSs are a set of MSDUs transmitted with the same traffic characteristics and QoS requirements as defined in the TSPEC element during the creation of a traffic stream performed by QSTAs.

The TSPEC describes the TS characteristics such as the data rate, MSDU size, service interval, delay bound and the service start time. QSTAs requesting TXOPs indicate to which TS the TXOP shall belong to. If there are no TS fulfilling the traffic flow's QoS requirements available, new TS can be created by the requesting QSTA. Every QSTA can support up to eight TSs from the HC to itself and eight in the opposite direction. After the HC has received all the TXOP requests, it schedules their assignment according to a scheduling algorithm. The IEEE 802.11e standard does not specify a mandatory scheduling algorithm but proposes a simple scheduler based on the mean data rate, nominal MSDU size and maximum service interval or delay bound information provided in the TSPEC.

There have some research works concentrating on HCCA mechanism [43–46]. In those research works, different scheduling algorithms are proposed to enhance the quality of the networks using HCCA mechanism.

2.4 An Overview of Cooperative Network

Technology development during the last decades led to a great progress in the field of telecommunications in general and more particularly in wireless communication.

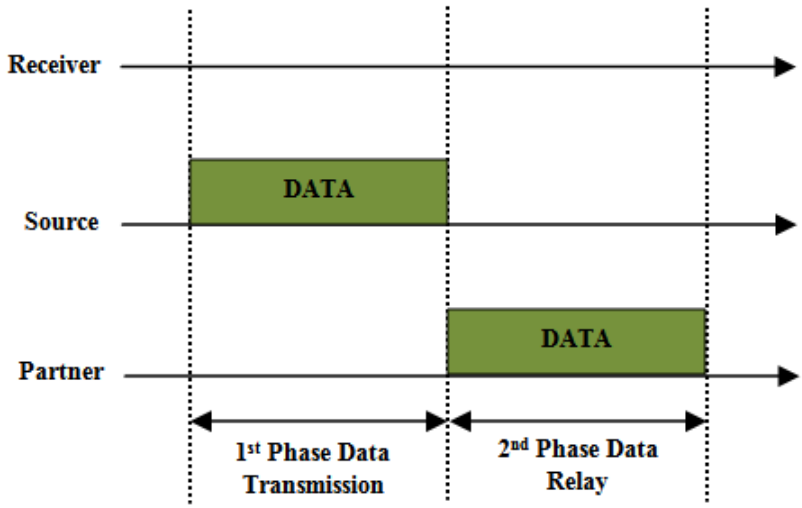


Figure 2.12: Basics of Cooperation

In contrast with wired communication, the medium in wireless communication suffers from external disturbances that challenge the data transmission reliability. Mobile networks and the demand for ubiquitous connectivity add to the challenge of providing reliable communication. Researchers have put in many efforts to provide communication systems able to overcome these issues and to satisfy the users demand.

Cooperative communication has been one of the methods proposed so far to address these challenges [4–7][47]. There are at least three terminals in the cooperative network, namely the source, the relay and the destination. While the communication occurs between the source and the destination, the relay terminal assists the source in its transmission by relaying its data to the destination.

Diversity has also been explored to mitigate the channel impairments. The mobile radio channel suffers from fading, meaning that mobile users may experience variations in signal attenuation during a transmission. Diversity related studies has been investigated in [8][48, 49]. Some busy tone based cooperative MAC also been proposed in [12, 13] to chose helper and mitigate the hidden node problems. The fundamental idea behind cooperation is that each user has a partner also known as relay or helper. Each of the two partners is responsible for transmitting not only their own data, but also the data of their partner, which they can overhear. Cooperation attempts to create spatial diversity through the use of the partner's antenna. There are two phases in a cooperative transmission as illustrated in Figure

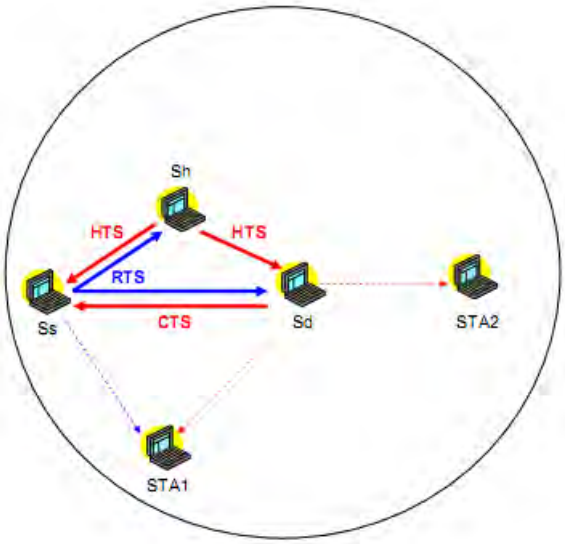


Figure 2.13: Exchange of control packets for Cooperative MAC

2.12 [50]. During the first phase, the source transmits its data which are received by the destination and overheard by the partner. The partner relays the received data to the destination [50].

The CoopMac protocol is proposed in [4, 5]. Two versions of the protocol are proposed: CoopMac I [4] and CoopMac II [5]. In CoopMac I, the RTS conveys the helper's ID and the expected data rates. A Helper ready To Send (HTS) is used by the helper to inform the source if it can maintain the expected data rates. The packet is transmitted cooperatively if it can be delivered faster in two hops (source-helper-destination) rather than through the direct link. To avoid the RTS modification and the use of HTS, CoopMac II [5] proposes to convey the helper's ID in the fourth address field of the data frame. It reduces the overhead incurred by CoopMac I but is more vulnerable to the channel changes since the chosen helper cannot confirm its availability to cooperate. The basic idea of this protocol is shown in Figure 2.13 [4].

When a transmission from a station (denoted by S_h) is overheard, a CoopMAC station S_s estimates the channel condition (e.g. path loss) between the sender of that packet and itself by measuring the received signal strength. Since all stations use the same frequency band for transmission and reception, the channel between any two stations is assumed to be symmetric. By checking the threshold value, which is pre-calculated and guarantees a certain bit error rate for each modulation scheme,

the station S_h can find the corresponding data rate between S_h and S_s, denoted by R_{sh}. When station S_s overhears a data packet transmission between a pair of other stations (from S_h to S_d), it will identify the data rate used for this transmission from the Physical Layer Convergence Procedure (PLCP) header. This rate will be referred to as R_{hd} [5].

When a source station S_s has data of length L octets to send, it checks each entry in the CoopTable to decide whether to transmit through a particular helper. The transmission time for such a two hop transmission is $8L/R_{sh}$ $+8L/R_{hd}$, ignoring the overhead. The helper through which the minimum transmission time can be achieved will be chosen as the candidate helper. If multiple stations have the same value, the protocol chooses the one with the most recent Time value. As in the existing standard, the mode selection is based on a configurable RTS threshold. If the packet length is over this threshold, the RTS/CTS mode is chosen. If transmission through the chosen helper is more time efficient than a direct transmission, the protocol will start a cooperative transmission. For the RTS/CTS mode, the condition for a cooperative transmission can be expressed as

$$\frac{8L}{R_{sh}} + \frac{8L}{R_{hd}} + T_{PLCP} + T_{HTS} + 2T_{SIFS} < \frac{8L}{R_{direct}} \tag{2.2}$$

where R_{direct} is the sustainable data rate for a direct transmission from station S_s to the destination station S_d and T_{PLCP}, T_{HTS} and T_{SIFS} are the additional time associated with a helper aided transmission for the physical layer overhead, HTS and SIFS, respectively. The HTS is a new message introduced to facilitate the cooperation, and will be explained in the following protocol description. For the base mode, where the data packets are not preceded by RTS/CTS, the condition would be

$$\frac{8L}{R_{sh}} + \frac{8L}{R_{hd}} + T_{PLCP} + T_{SIFS} < \frac{8L}{R_{direct}} \tag{2.3}$$

If the condition is not satisfied for any of the entries in the CoopTable, the data frame is transmitted directly to S_d.

In [9], the authors proposed a novel cooperative MAC protocol for QoS enhancement in WLANs based on the IEEE 802.11e EDCA MAC protocol. It is called EDCA based Cooperative Communication MAC (ECC-MAC). In the proposed protocol, a node can transmit multiple data packets consecutively until the duration

of transmission exceeds the specific TXOP time period. By using the Block ACK procedure, a receiver acknowledges a block of received data packets.

Like [5] each node maintains a table, referred to as the ECTable (EDCA Cooperative Table). A node overhears transmissions of packets such as RTS, CTS, DATA, and ACK by other nodes, and then updates its ECTable. The ECTable contains 5 fields. Data in the first field is MAC address of a helper node. In the time field, time of the last packet received from the helper node is recorded. In the transmission rate fields, transmission rates between source node S and helper node H, and between helper node H and destination node D are stored, respectively. In the last field, channel credit (CH) of the helper node is stored. The channel credit tracks the channel status of the particular helper node. This value is used to calculate the block ACK size, which is the number of data packets to be transmitted and to be acknowledged by a single block ACK.

Although the proposed ECC-MAC protocol has the similar procedure of exchanging packets to that of the CoopMAC [9] protocol, it uses a different method in transmitting data packets.

2.5 Summary

This chapter gives an overview on IEEE 802.11 channel access mechanism frame formats and RTS/CTS mechanism, IEEE 802.11e Wireless LANs, and its access mechanisms and channel differentiation to ensure priority of different Access Classes (ACs) and Cooperative communication basics.

Chapter 3

Proposed MAC Protocol for Enhancing QoS of IEEE 802.11e EDCA

3.1 Introduction

The term Quality of Service (QoS) means the quality of a network in terms of throughput, packet loss, delay, jitter and bandwidth utilization of data traffic over a network. When any kind of traffic in the network delivers in time and utilizes the network bandwidth properly, then the network can be said that it is capable of fulfilling QoS. QoS requirements vary from application to application and can be classified in three dimensions: bandwidth, delay, and data loss [51].

Bandwidth is one of the most important parameter to define QoS which refers to

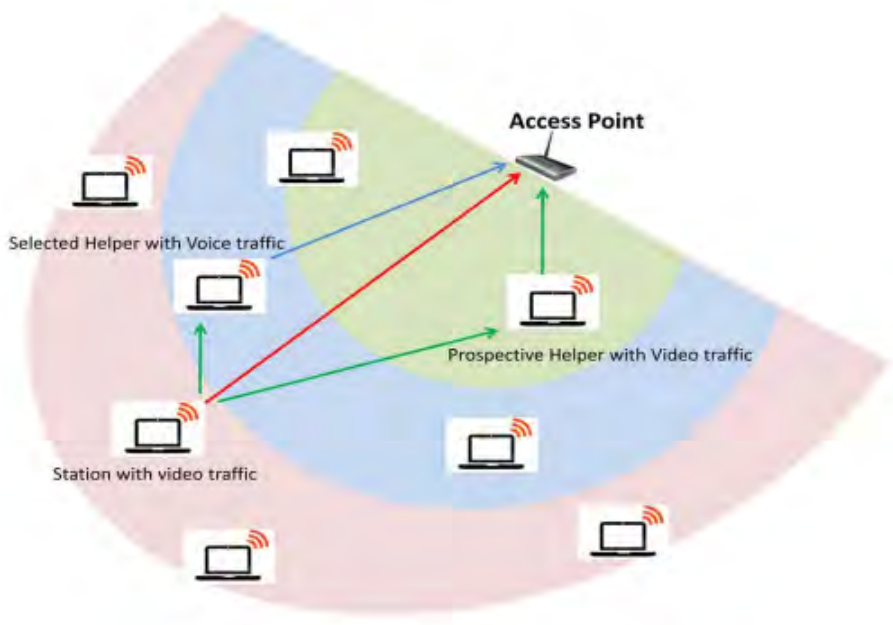


Figure 3.1: Proposed Cooperative MAC Protocol Showing Helper Selection Based on Traffic Priority

the amount of data that can be delivered during a given period of time. Multimedia applications are bandwidth-sensitive applications which require constant bandwidth and may seriously suffer because of variations in bandwidth [51]. The end-to-end delay is also a major concern for multimedia applications. Delay is the total time needed to deliver a packet that the sender generates to the time the application at the receiver receives it. Multimedia applications need tight delay characteristics to deliver the data packets in time and thus, to maintain QoS.

IEEE 802.11 standard is based on best-effort service model that means the standard serves all kind of applications in the same manner. This standard has no service differentiation for any kind of traffic; all the applications are served in the same way. But multimedia applications require high bandwidth, low delay and less loss-sensitive services to maintain QoS of the network. As a result, all types of data traffic suffer from same amount of delays, losses and variations in bandwidth as the network becomes congested. Thus, network performances degraded as they are not served properly.

Realizing the importance of QoS IEEE 802.11 Working Group has also been working on a new version of 802.11, called 802.11e, to introduce QoS support in 802.11 networks and recently the final version of the draft standard has been released [3]. The IEEE 802.11e standard introduces service differentiation for different type of traffic to support QoS of the network.

3.2 Proposed MAC Protocol

This research work is based on IEEE 802.11e and develops a MAC layer protocol to enhance the quality of service (QoS). The proposed protocol in this research work is based on the concept of cooperative communication to enhance the performance of the network. Most of the proposed cooperative MAC protocols for both IEEE 802.11 and IEEE 802.11e standard in different research works [9–11][13] searches an optimal helper to assist the sender in transmission according to higher data rate. The proposed MAC protocol also searches an optimal helper to increase the throughput and to reduce the delay. The main concentration of searching an optimal helper is not only the higher rate through the helper but also the priority of the helper class considered to enhance the QoS of the network. Below segments describe the

Bytes:	2	2	6	6	1	4
	Frame Control	Duration	Destination Address	Source Address	Source Node Traffic ID	FCS

(a) ERTS

Bytes:	2	2	6	1	4
	Frame Control	Duration	Destination Address	Source NodeTraffic ID	FCS

(b) ECTS

Figure 3.2: Frame Format of (a) Enhanced RTS (b) Enhanced CTS

whole procedure of the proposed protocol. Figure 3.1 shows the basic concept of the proposed protocol. In IEEE 802.11e standard, all contending stations can get a chance to access the channel to mitigate the channel fairness issue. But, when a station with low or moderate link rate between receiver and itself wins the channel contention, then it will degrade the network performance and affect the QoS of the network. The proposed protocol based on IEEE 802.11e EDCA and considers the above fairness issue to improve the network performance with the help of cooperative communication. Through cooperative communication, a helper that has its own traffic to send and can support at least two times better two hop link rate than direct link between sender and receiver is chosen. So, the proposed cooperative protocol for EDCA performs better than the legacy IEEE 802.11e. The below section explains the protocol details.

In IEEE 802.11e EDCA, traffic with different priorities is mapped into several Access Categories (ACs) at each station. For each AC, an enhanced variant of the DCF, called an enhanced distributed channel access function (EDCAF), contends for TXOPs using a set of EDCA parameters: the Arbitration Inter Frame Space (AIFS[AC]), minimum Contention Window size (CWmin[AC]), maximum Contention Window size (CWmax[AC]) [3]. Based on these parameters, each station contends to access the channel. The proposed protocol selects a helper to assist the sender with high priority traffic of its own and also has a high average rate to transfer data

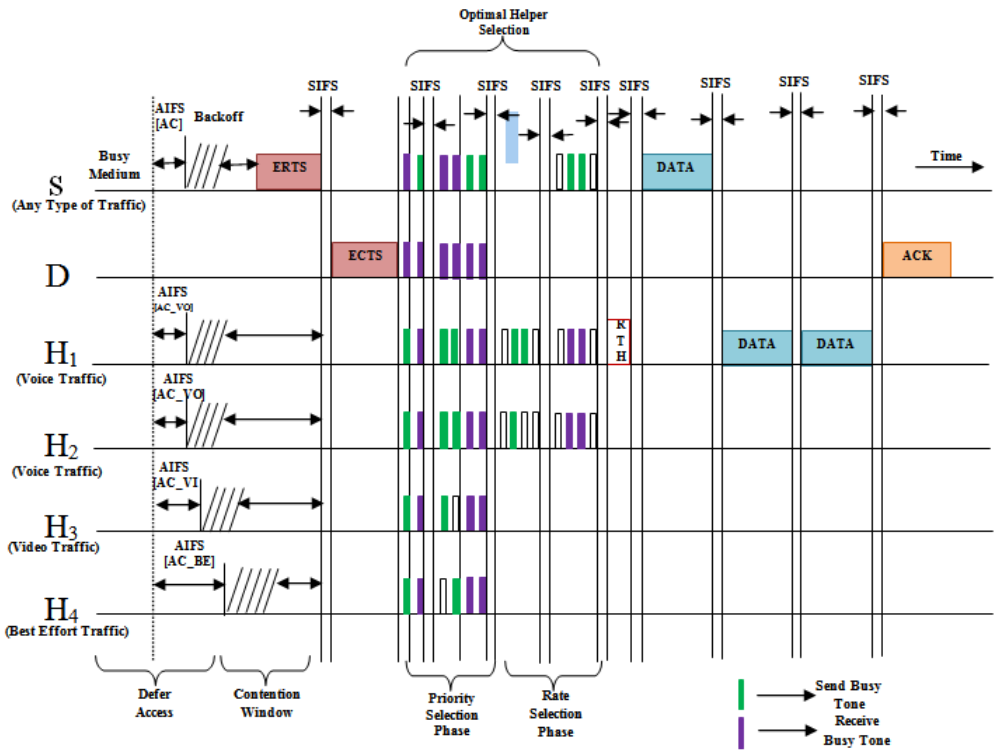


Figure 3.3: Cooperative MAC for EDCA (When no collision among RTH frame)

through itself. Figure 3.3 shows the proposed Cooperative MAC for EDCA (When no collision among RTH frame).

3.2.1 Basic Working Principle

1. When the source node has a packet to transmit to the destination, it senses the channel for idleness for the AIFS duration, AIFS is an arbitrary period of time which varies for different ACs. After waiting for AIFS interval, the source then backs off for a random duration according to the Contention Window (CW) selection. CW is also different for different ACs. Once the back off counter reaches zero, the source sends the ERTS packet at basic rate of the network (e.g., 1 Mbps for 802.11b and 6 Mbps for 802.11a and 802.11g) to the destination for channel reservation. ERTS is called Enhanced RTS with slightly modification of RTS by adding 1 byte extra field for sender traffic class ID. The source node should send ERTS to search for an helper node.

2. If the ERTS packet is correctly received and decoded at the destination node, it responds with an ECTS packet after waiting for SIFS duration. ECTS is

called Enhanced CTS which is also a modified version of CTS. An extra byte is appended to the CTS packet which contains the class ID. The frame formats for ERTS and ECTS are shown in Figure 3.2. ERTS and ECTS packets are sent to reserve the channel for transmission.

3. Each node that receives both ERTS and ECTS packets can act as a helper node. But, in this proposed protocol two criteria are considered for selecting an optimal helper - First, the node must have traffic equal or greater priority than sender node, and Second, the rate through helper is at least two times than the direct rate between sender and receiver. The helper nodes that fulfill those requirements can participate for the next helper contention process. The main objective of this research work is to find out an optimal helper which has higher priority data (AC) in its queue and as well as the data rate through the helper is at least two times better than the direct link rate.

4. The helper contention process (HCP) starts after SIFS time interval. The HCP starts by sending a busy tone to the source from all contending helper node. This busy tone is an indication to the source that at least one helper is present in the network. Otherwise, the sender assumes that no helper presence in the network that can fulfill the above mentioned criteria and it starts sending data through direct transmission. After receiving the busy tone from helper nodes, the sender also respond with a busy tone as permission for starting cooperation process. The HCP is divided into two parts one for priority selection and another for rate selection stage-

   - The objective of priority selection stage is to select higher priority helper for cooperation. The contending helper nodes send busy tones as like their access class (AC) ID. For example, a voice traffic class (AC_VO) has an ID 3, then it sends busy tone according to the binary representation of 3(11), for voice ID is 2 and it sends like (10), for best effort it sends 1(01). The sender then announces/repeats the busy tone of higher priority. After listening the announcement from sender all low priority nodes refrain from the contention. The remaining higher priority nodes contend for next rate selection phase.

- For higher rate helper selection, each high priority node first calculates the average rate for relaying and then, divides by the direct rate between sender and receiver. It finds that how many times the node is better than the direct link for relaying. All contending helper nodes send busy tones according to their link rate times. For example, if a node supports six times better than the direct link, then it sends busy tone like 0110 (binary representation of six). As a confirmation, the sender also announces/repeats the tone of the high rate supporting nodes. This announcement is necessary to avoid hidden node problem among helper nodes. The concept of rate selection process is briefly discussed in section 3.2.2.2.

In this research work, consecutive busy tones are used to select a higher priority and higher rate helper which increases the overhead of the network but narrow down the optimal helper selection and solves the hidden terminal problem in the network. Collision is a big issue in wireless network, but the busy tone process for helper selection reduces the collision rate and also improves the network performance.

5. After the above contention, winning helper node sends RTH frame to initiate the cooperation. If multiple helpers win the contention, then the RTH packets collide and after waiting SIFS+t_h time, the helper nodes become aware about the collision and resend the RTH packet again. After the collision, each node starts a backoff window to resend the RTH packet. The helper selection and contention resolution process are discussed in details in the below sections.

6. After successful reception of the RTH packet, the sender sends its data packets to the helper. The successful helper then relays this packets to the destination. If there are enough time remains in the TXOP the helper then piggybacks its own data packets to the receiver. The receiver on receiving all the data packets from helper then acknowledges the successful reception to both the helper and the sender.

7. In case that no relay feedback is received during the initial stage, then the source directly transmits data to the destination without any helper contention

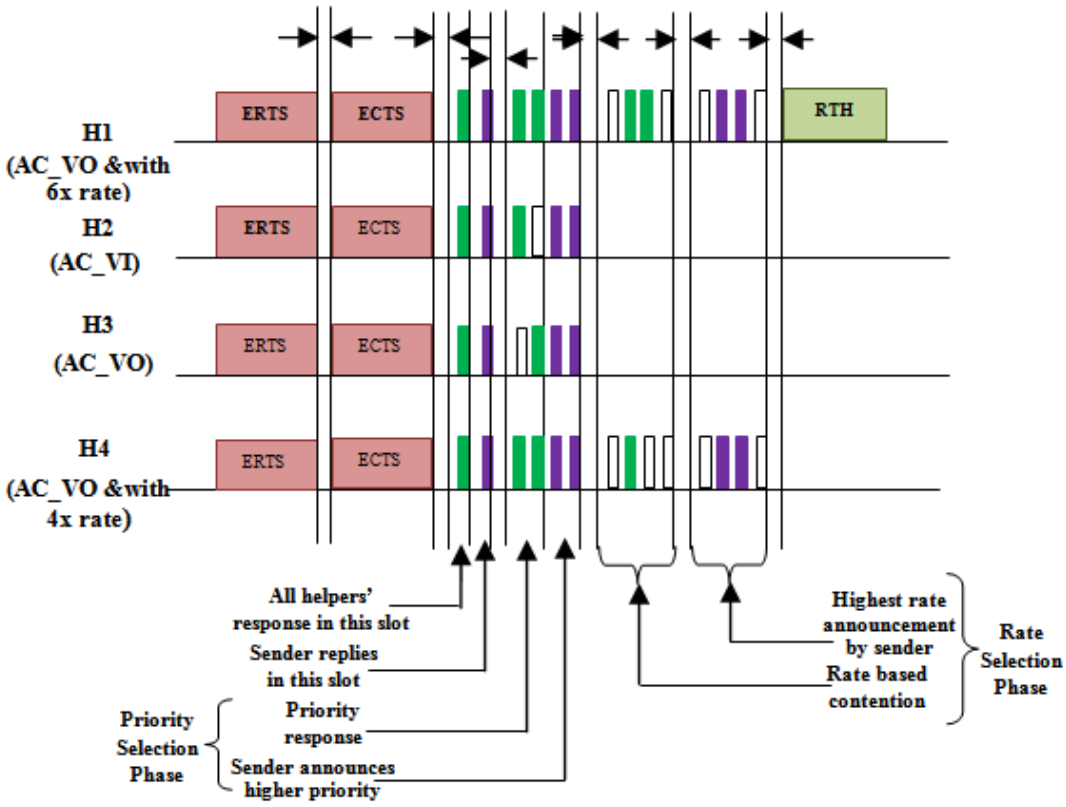


Figure 3.4: Helper Selection on the Basis of Traffic Class Priority and Link Rate

phase with direct rate between the sender and the receiver.

8. The frame formats of ERTS and ECTS packets are shown in Figure 3.2.

3.2.2 Helper Selection Process

Figure 3.4 schematically shows the operation of helper node selection process. After receiving the ERTS frame and the ECTS frame, each candidate helper node compares two basic parameters for contending the channel as a helper: (1) Own Traffic Class Priority: is the priority equal or higher than sender traffic?, and (2) The Two Hop Average Rate: is the average rate at least two or more times greater than the direct rate supported between sender and receiver?. The helper selection procedure includes two parts, i.e., Priority Selection Process (PSP) and Rate Selection Process (RSP) of the same priority helpers.

3.2.2.1 Priority Selection Process

All nodes that have equal or same priority traffic in its queue can contend in this phase. All neighbor nodes supporting the above mentioned parameters with equal or higher priority and two or more times two hop average rate first transmit a busy tone as a response of their existence. After listening the busy tone from the helpers, the sender become aware that at least one helper exists to help in the communication. The sender also responds with a busy tone as part of the permission to start the contention process. Now, for selecting higher priority helper all the nodes send busy tones according to their traffic priority class. As shown in Figure 3.4 helper H1 and H4 have voice traffic in their queue and the ID for AC_VO is 3. So, H1 and H4 send busy tone accordingly to the binary representation of the AC_VO ID 3 as 11 i.e. two consecutive tones received from those helpers. Helper H2 has video traffic in its queue and the ID for AC_VI is 2. That means H2 sends a busy tone in the first slot and senses the channel in the next slot (according to the binary representation of 2 is 10) if there are any higher priority helper exists. If it hears a tone in the next slot, then it immediately withdraw from the helper contention. Helper H3 first senses the channel for higher priority; if it hears no tone from the higher priority helper, then it sends a busy tone in the next slot. But, it is possible that there exist hidden nodes between helpers. To resolve the hidden helper node problem in our protocol, the sender announces /repeats the highest tone received from the helpers. So, those helpers that are unable to listen the higher priority helper tones from other helper's nodes now are aware that there exist higher priority helpers and then they withdraw their contention as a helper. Our proposed protocol eliminates the hidden helper node problems in the wireless environments. Higher priority nodes listen matching tones with their sending tones and they ensure that they win the PSP contention and go for the next rate selection phase. After this PSP contention, only same or higher priority traffic helper with different average rate nodes remain to contend for the next contention.

3.2.2.2 Rate Selection Process

The helpers with same traffic but different rate now contend here for selecting the highest supporting rate helper. Each candidate helper can calculate allowable

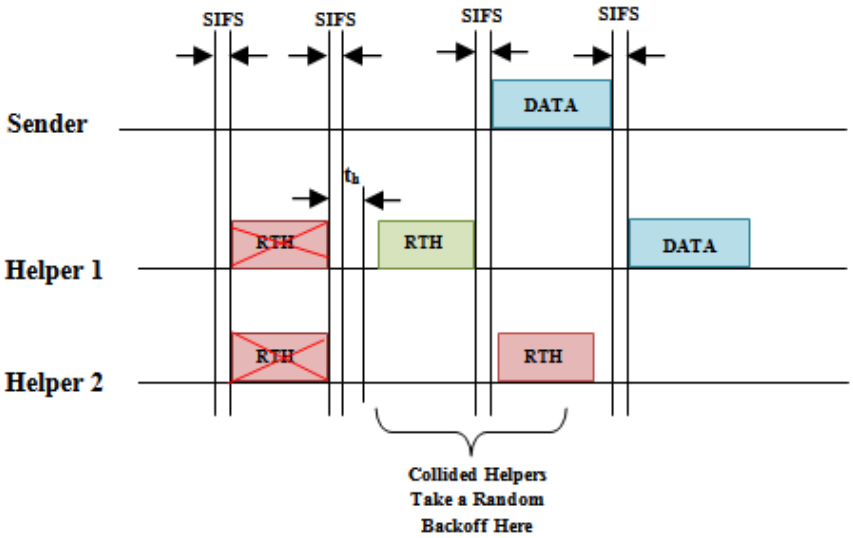


Figure 3.5: When the RTH Packets Collide and Randomly Choose a Backoff Window to Retransmit the RTH packet

maximum data rate between sender and helper (R_{SH}), maximum data rate between helper and receiver (R_{HR}) and its two-hop average rate by the received ERTS packet and ECTS packet. Both the sender and the candidate helpers can learn the maximum data rate between sender and receiver (R_{SD}). The two-hop average rate can be calculated by the formula:

$$\frac{1}{\left(\frac{1}{R_{SH}} + \frac{1}{R_{HR}}\right)} \tag{3.1}$$

After calculating the average rate R_{avg}, each node then divides the rate with the direct rate between sender and receiver to get how many times it is better than the direct link. Then each node contends according to the link rate times. Each node sends busy tone according to the binary representation of the link rate times. As shown in Figure 3.4 after priority contention node H1 and H4 win the contention and they enter for the rate selection phase. Helper H1 supports six times greater rate than the direct link and it sends busy tone according to the binary representation of six which is 0110 and helper H4 supports four times greater link rate than the direct rate and sends busy tone equal to 0100 (binary representation of four). For the hidden helper node problem, sender again announces/repeats the highest tone.

The node (here H1) listens the matching tone with its own and wins the optimal helper selection contention process. So, after priority and rate selection stage, there is possibly one optimal helper to cooperate with the sender for data transmission. The helper also has the chance to transmit its own traffic after helping the transmission of sender. The winning node then sends the Ready To Help (RTH) packet to the helper after waiting for SIFS time. After receiving the RTH packet, the sender knows which helper is selected from the contention process and sends the data packet to the intended helper node for cooperative data transmission.

3.2.3 Contention Resolution Process (CRP) in case of Multiple Helpers

Figure 3.5 illustrates the CRP. It is possible that there are multiple helpers with the same priority and same rate that simultaneously send their RTH packets to sender. As a result, RTH packets collide and after waiting SIFS+t_h time, the helper nodes become aware about the collision. In order to avoid the possible collisions caused by their concurrent cooperative packet transmissions and guarantee the application of successful data transmission, a simple strategy is employed that lets collided helper candidates re-contend once. Collided helper nodes again contend to send their RTH packet to the sender by randomly choosing a backoff slot with a small contention window and resend their RTH packet after waiting for the random time. If the RTH packet is successfully received by the sender, it starts to transmit its data packets after waiting SIFS time interval. When other contending helpers overhear the data packet from sender, then they all leave the contention. CRP process ensures that possibly least number of helpers win the helper selection process and probably one optimal helper send the RTH frame to the sender. The optimal helper then relays the data packet from source to the destination; if there is enough time remains in the TXOP then the helper also transmits its own data to the destination. The destination then acknowledges the correct reception of the data packets by sending ACK packets to both sender and helper node.

3.2.4 Data Packet Transmission Process

Based on the availability and performance of a selected helper, data transmission process is divided into three categories:

3.2.4.1 Data Transmission Without Helper

When there was no successive helper response after ERTS and ECTS frame exchange, the sender assumes that there was no helper present in the network to help in the data transmission. Then, the sender sends the data frame directly to the destination station with the basic data rate R_{SD} between the sender and the receiver. After receiving the data from the sender, the receiver acknowledges the sender about the successful reception of the data frame by sending an ACK frame to the sender.

3.2.4.2 Data Transmission with Helper and Piggybacks Helper Data

After sending ERTS frame and receiving an ECTS frame from receiver, the sender waits for some moments to listen the response from the receiver. When helper response from the helper end, the sender confirms about the existence of helper and sends a response to the network about the starting of a cooperative communication. If multiple helpers are present in the network, then according to the helper selection process, an optimal helper is selected during the process and this helper helps during the transmission process. The sender sends its data to the selected helper at the rate R_{SH} between the sender, and the helper and the helper then sends the data to the destination at the rate R_{HD} between the helper, and the receiver. After the helper selection process, the best helper with higher data rate compared to the direct link between the sender and the receiver has been selected to help in the data transmission. So, it may be possible that there are some time left after sending the sender data in the given TXOP. If there are enough time to transmit another packet (because the rate of cooperative communication is very fast than the direct transmission and the time after sender data transmission is finished in advance compared to the direct transmission), then the helper also transmits its own packet to the destination within the same TXOP. If the time is less than the time to transmit a data packet, then the data packet is fragmented into small packets and the fragmented packet is then transmitted within the remaining TXOP of the sender. Thus, it utilizes the network

bandwidth and reduces the delay that the helper needs to contend for channel access.

3.2.4.3 Only Transmits Source Data

When a comparatively medium rate helper wins the helper contention, then it may be possible that there was no such time for the helper to send its own data after assisting the sender. Then, the helper only transmits the sender data only and after finishing the TXOP the receiver sends an ACK frame to both the sender and helper as a notification of successful reception of the data frame.

3.3 Analytical Modeling of the Proposed MAC Protocol

In order to analyze the performance of the proposed protocol, a Markov model described in [20] is modified by varying different parameters of the proposed protocol. The main objective of the Markov chain model is to find out the normalized throughput of each AC for a saturated network. All of the mathematical equations required for the analysis are given below in the subsections.

3.3.1 Markov Chain Analysis

Let $b_i(t)$ represents the backoff counter values for a given node for the i-th AC, where t is given in slot times. And, let $s_i(t)$ is defined as the random process representing the backoff stage j. Then, having $b_i(t)$ and $s_i(t)$, a bi-directional process can be modeled with a discrete Markov chain. The notation $b_{i,j,k}$ assumes to represent the stages of the Markov chain. Where, i is just an index standing for the priority i class, j stands for the backoff stage and takes values (0,1,. . . . . ,m) and m is the maximum backoff stage, and k stands for the backoff delay and takes values (0,1,. . . . . , $W_{i,j}$), where $W_{i,j}$=2^j $W_{i,0}$and $W_{i,0}$=$CWmin[i]$ is the minimum contention window of the i th AC in time slots.

State $b_{i,sat,0}$ is the saturation state of the Markov model. This is included to the Markov chain in order to model network load condition. Under saturation, however, a node always has a frame to arrive to its transmission queue. A node does not remain in the $b_{i,j,k}$ state, but immediately chooses its backoff value. Let, $p_{i,c}$ denote the probability that the transmitted frame collides in the priority i class.

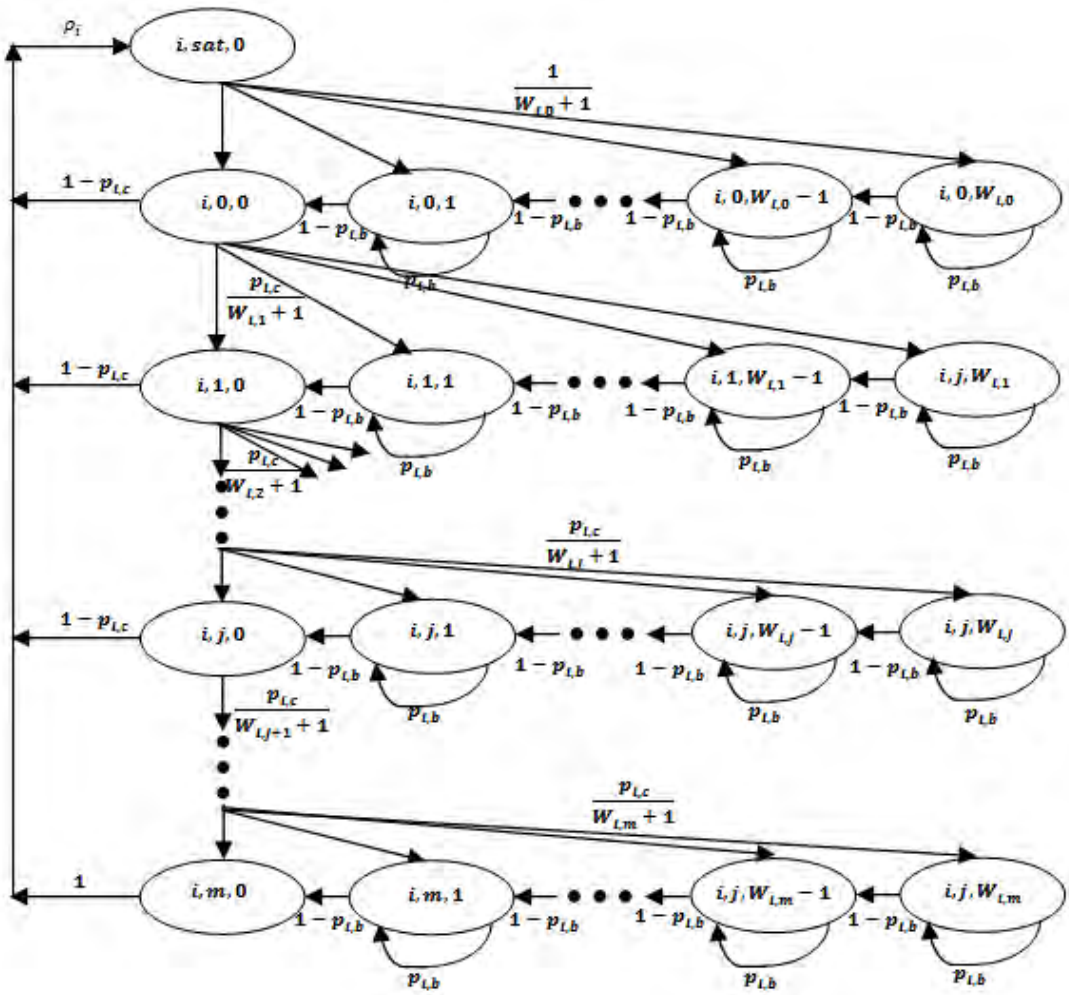


Figure 3.6: Markov Model [20] used for the analysis of the Proposed Protocol

The one step transmission probabilities for $0 < k < W_{i,j}$ is given by

$$
\begin{aligned}
P\{i,j,k \mid i,j,k+1\} &= 1 - p_{i,b} && 0 \le k \le W_{i,j} - 2,\ 0 \le j \le m \\
P\{i,j,k \mid i,j,k\} &= p_{i,b} && 0 \le k \le W_{i,j} \\
P\{i,j,k\} \mid \{i,j-1,0\} &= \frac{p_{i,c}}{W_{i,j}+1} && 0 \le k \le W_{i,j},\ 0 \le j \le m \\
P\{i,sat,0 \mid i,j,0\} &= 1 - p_{i,c} && 0 \le j \le m \qquad (3.2) \\
P\{i,sat,0 \mid i,m,0\} &= 1 && 1 \le j \le m,\ k = 0 \\
P\{i,0,k \mid i,sat,0\} &= \frac{1}{W_{i,0}+1} && 1 \le j \le m,\ 0 \le k \le W_{i,0}
\end{aligned}
$$

The first equation in (3.2) accounts for the fact that at the beginning of each slot time, the backoff time is decremented. The second equation states the backoff counter freezes when the STA senses that the channel is busy in the priority i class.

The third equation accounts for the fact that a new packet following a successful packet transmission starts with backoff stage 0 and thus, the backoff is initially uniformly chosen in the range $(0 < k < W_{i,j})$. The other cases model the system after an unsuccessful transmission. In particular, as considered in the fourth, if it has a successful transmission with the previous frame in the priority i class. In the fifth case, the STA enters the *i,sat,0* state after m times collision and the node then starts with a initial backoff value. Finally, the sixth equation of (3.2), when an unsuccessful transmission occurs at backoff stage, the backoff stage increases, and the new initial backoff value is uniformly chosen in the range.

It is easy to obtain a closed-form solution for this Markov chain. From the chain regularity, every transmitting state $b_{i,j,0}$ can be represented as the following function of $b_{i,0,0}$

$$b_{i,j,0} = p_{i,c}^{j}.b_{i,0,0} \tag{3.3}$$

$$b_{i,m,0} = \frac{p_{i,c}^{m}}{1 - p_{i,b}}.b_{i,0,0} \tag{3.4}$$

Owing to the chain regularities, for each $(0 \leq k \leq W_{i,j})$, the following equations can be obtained

$$b_{i,j,k} = \frac{W_{i,j} + k}{W_{i,j}}. \left\{ \begin{array}{ll} (1 - p_{i,c}) \sum_{j=0}^{m} b_{i,j,0} & j = 0 \\ p_{i,c} b_{i,j-1,0} & 0 < j < m \\ p,_{i,c} \left(b_{i,m-1,0} + b_{i,m,0}\right) & j = m \end{array} \right\} \tag{3.5}$$

Using the above equations, all stationary probabilities $b_{i,j,k}$ are expressed by $b_{i,0,0}$ and which is finally determined by imposing the normalization condition, as follows:

$$b_{i,\,sat,\,0} + \sum_{j=0}^{m} b_{i,j,0} + \sum_{j=0}^{m} \sum_{k=1}^{W_{i,j}} b_{i,j,k} = 1 \tag{3.6}$$

$$b_{i,0,0} = \frac{2\alpha}{2\rho_i \alpha + 2\left(1 - \rho_i\right)\alpha + 2\left(1 - p_{i,b}\right)\left(1 - 2p_{i,c}\right)\left(1 - p_{i,c}^{(m+1)}\right) + W_{i,0}\left(1 - p_{i,c}\right)\left(1 - 2p_{i,c}^{(m+1)}\right)} \tag{3.7}$$

where $\alpha = \left(1 - p_{i,c}\right)\left(1 - p_{i,b}\right)\left(1 - 2p_{i,c}\right)$

Now let express the probability that a station transmits in a randomly chosen slot time [25]. As any transmission occurs when the backoff time counter is equal to

zero, regardless of the backoff stage, it is

$$\tau_i = \sum_{j=0}^{m} b_{i,j,0}$$

$$\tau_i = \frac{1 - p_{i,c}^{m+1}}{1 - p_{i,c}} b_{i,0,0} \tag{3.8}$$

τ_i is a function of $b_{i,0,0}$ which relies on AC dependent probabilities: ρ_i, $p_{i,c}$, $p_{i,b}$. Probability ρ_i is a function of the overall service time for the *i-th* AC.

3.3.2 Throughput Analysis

Let $S_{th,i}$ be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. To compute $S_{th,i}$, let us analyze what can happen in a randomly chosen slot time. Therefore,

$$S_{th,i} = \frac{E\left[Payload\ Information\ Transmitted\ in\ a\ Slot\ Time\right]}{E\left[Length\ of\ a\ Slot\ Time\right]}$$

$$S_{th,i} = \frac{p_{i,s} T_{DATA}}{T_{CS}} \tag{3.9}$$

where $p_{i,s}$ is the probability of a successful transmission for the *i-th* AC and T_{DATA} is the expected time spent on transmitting a frame. In this thesis work, all frames are of the same length. Here we refer the reader to [20] for reference.

A transmission of data packets is successful if no other stations transmit to the channel at that time; that means only one node transmits its data at the given slot time. Let $p_{i,s}$ denote the probability that a successful transmission occurs in a time slot for the priority *i-th* AC. Then have $p_{i,s}$

$$p_{i,s} = n_i \tau_i (1 - \tau_i)^{n_i - 1} \prod_{j=0, j \neq i}^{N_c - 1} (1 - \tau_j)^{n_j} \tag{3.10}$$

where n_i is the number of nodes in the *i-th* AC and Nc is the number of ACs in that class.

Now, the overall probability of success for transmission for a given slot is defined as follows:

$$P_S = \sum_{i=0}^{N_c - 1} \mathrm{p_{i,s}} \tag{3.11}$$

Additionally, if T_e denotes to be the slot time, $T_{s,i}$ the duration of a successful transmission, $T_{c,i}$ the duration of a collision, p_B the probability of a busy medium, and $(1-p_B)$ the probability of a free channel, *length of a slot time* can be rewritten as $(1-p_B)\,T_e + \ P_S T_{s,i} + \ (p_B - P_S)\,T_{c,i}$. Therefore, from equation (3.12)

$$S_{th,i} = \frac{p_{i,s} T_{DATA}}{(1-p_B)\,T_e + \ P_S T_{s,i} + \ (p_B - P_S)\,T_{c,i}} \tag{3.12}$$

Time intervals $T_{s,i}$ and $T_{c,i}$ depend on the access method used. In the case of the basic access method, they are as follows [3].

$$T_{s,i} = T_{RTS} + T_{CTS} + \min\left[AIFS_i\right] \ + T_H + T_{DATA} + T_{SIFS} + T_{ACK} + 4\delta \tag{3.13}$$

$$T_{c,i} = T_{RTS} + \delta + \min\left[AIFS_i\right] \tag{3.14}$$

Where δ denotes the propagation delay and T_H is the time required to send the PHY and MAC header.

For the proposed EDCA MAC protocol the time fields with helper are slightly modified and they are given by as follows:

$$T^h_{s,i} = T_{ERTS} + T_{ECTS} + Busy\ Tone + T_{RTH} + \frac{L}{R_1} + \frac{L}{R_2} + 9T_{SIFS} + T_{ACK} + 6\delta + T_{AIFS[i]} \tag{3.15}$$

$$T^h_{c,i} = T_{ERTH} + \delta + T_{SIFS} \tag{3.16}$$

The probability that the channel is sensed busy for a given node of class i is determined by the given equation

$$p_B = 1 - \prod_{i=0}^{N_c-1} (1-\tau_i)^{n_i} \tag{3.17}$$

For a given node, the frame collision probability for the *i-th* AC $p_{i,c}$ in a slot time is equal to the probability that at least one other node transmits its data during the same slot time; therefore $p_{i,c}$ can be written as follows

$$p_{i,c} = 1 - (1-\tau_i)^{n_i - 1} \prod_{j=0, j\neq i}^{N_c-1} (1-\tau_j)^{n_j} \tag{3.18}$$

3.3.3 Delay Analysis

The average packet delay for a successful packet transmission is defined by the time duration from the time the packet is at the transmission queue ready to transmit the packet until an ACK frame for the transmitted packet is received. For delay analysis of a successful packet transmission, this research work uses the same approach according to [27]. The average packet $E[D_i]$ for any traffic class, provided that this packet is not discarded, is given by

$$E[D_i] = E[X_i] \ .E[slot] \tag{3.19}$$

Where, $E[X_i]$ is the average number of slot times needed to successfully transmit a packet and is given by:

$$E[X_i] = \sum_{i=0}^{m} \left[\frac{\left(p_{i,c}^{j} - p_{i,c}^{m+1}\right) \cdot \frac{W_{i,m}+1}{2}}{1 - p_{i,c}^{m+1}} \right] \tag{3.20}$$

where, $1 - p_{i,c}^{m+1}$ is the probability that the packet is not dropped and $\left(p_{i,c}^{j} - p_{i,c}^{m+1}\right)/1 - p_{i,c}^{m+1}$ is the probability that a packet that is not dropped reaches the j stage. Finally, the equation for $E[X_i]$ after applying some algebra can be written as:

$$E[X_i] = \frac{1}{b_{i,0,0}} - p_{i,c}^{m+1} \ .E[T_{drop}] \tag{3.21}$$

where, $E[T_{drop}]$ is the average time to drop a packet after experiences *m+1* times collision

$$E[T_{drop}] = \sum_{i=0}^{m} \frac{W_{i,m}+1}{2} = \frac{W_{i,0}.(2^{m+1}-1)+(m+1)}{2} \tag{3.22}$$

And $E[slot]$ is the average length of a slot is given by

$$E[slot] = (1-p_B)T_e + P_S T_{s,i} + (p_B - P_S)T_{c,i} \tag{3.23}$$

3.4 Summary

This chapter presents an efficient cooperative MAC protocol to enhance the QoS of IEEE 802.11e network. The proposed protocol introduces a novel scheme to search for an optimal and enhanced helper to assist the sender in transmission.

Also, a Markov Model is developed to mathematically analyze the proposed protocol for validation of the network performances in terms of throughput and delay of the network.

Chapter 4

Results and Performance Analysis

4.1 Introduction

In order to mathematically analysis the proposed model, MATLAB [52] simulation tool is used. The MATLAB tool is very popular and efficient to verify mathematical models. The proposed protocol is analyzed through a mathematical model and by using MATLAB, the developed equations are solved using this tool. All the equations from the Markov Model are used in the MATLAB editor and solved to plot different results for the proposed protocol.

4.2 Throughput Evaluation

The throughput from the analytical model analysis is compared with different protocols. The throughput is also analyzed with respect to frame size and data rates. The parameters used for analysis is shown in Table 4.1 and Table 4.2. Below sections described the throughput analysis performances.

Table 4.1: EDCA Parameters

Priority	**AIFSN**	CW_{min}	CW_{max}
Voice	2	7	15
Video	2	15	31
Best Effort	3	31	1023
Background	7	62	1023

Table 4.2: System Parameters for MAC and Physical Layer

Parameters	**Value**
Data Rate	IEEE802.11g
Basic Rate	1 Mbps
SIFS	10 μs
Busy Tone Time	5 μs
Slot Time (T_e)	20 μs
Propagation Delay (δ)	2 μs
MAC Header	224 bits
PHY Header	192 bits
ERTS Frame	168 bits
ECTS Frame	120 bits
RTH Frame	120 bits
ACK Frame	112 bits
Frame Size	1024 B

4.2.1 Comparison with Different Protocols

Figure 4.1 shows the normalized throughput of proposed protocol and EDCA in relation with number of nodes in the network. Figure 4.1 illustrates that y axis is normalized throughput and x axis is the increasing number of nodes. For this research work, there are equal numbers of nodes per class contending to access the channel is considered. Figure 4.1 shows that throughput decreases as the number of nodes increases as the Markov model is considered for saturated network for this research work and the proposed protocol outperforms the legacy EDCA protocol. AC0 (Voice) in proposed protocol performs better than EDCA AC0 class and figure 4.1 shows a 16% improvements in throughput is achieved by AC0 in the proposed protocol. AC1,

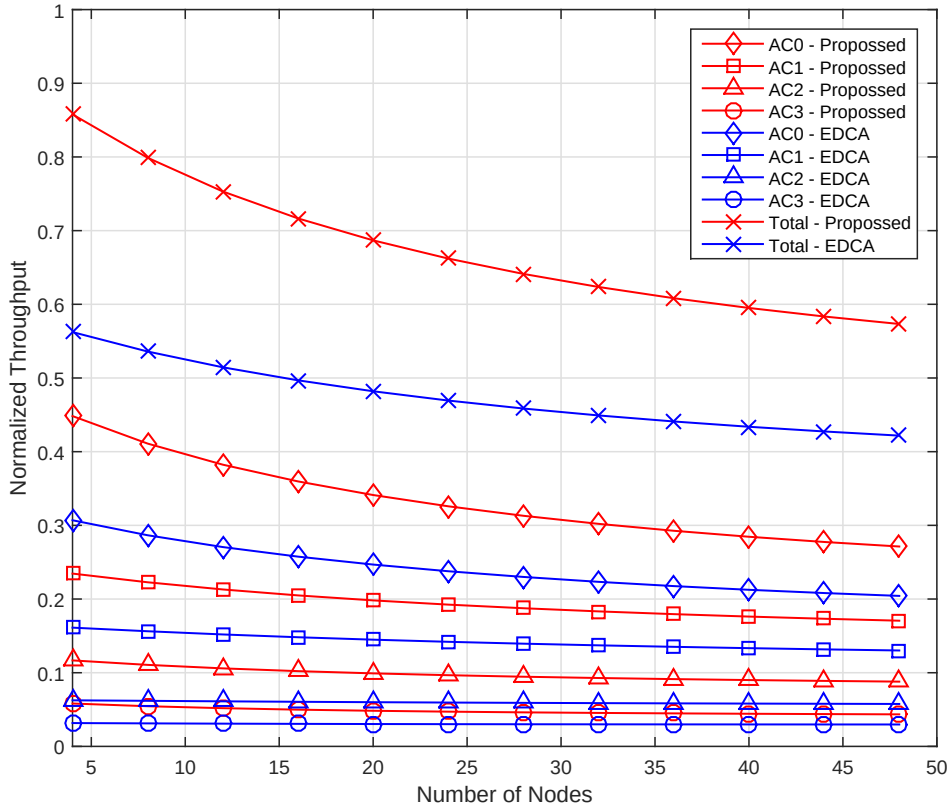


Figure 4.1: Normalized Throughput Vs Number of Nodes compared with Standard EDCA

which is Video class, also achieves a 7% improvement in throughput performance than EDCA AC1 class. AC2 and AC3, which are Best effort and Background traffics, also perform better than EDCA protocol. AC2 and AC3 classes have same performance as the CW for both classes and there is also a little improvement in throughput; more than 3% improvement achieved by proposed protocol compared with EDCA protocol performance.

The research work is compared with the CoopMAC [5] protocol which is a well known protocol for cooperative network as discussed earlier; the proposed protocol performs better in terms of class priority than CoopMAC as shown in Figure 4.2. But, when the overall throughput performance, is considered CoopMAC performs better because of the helper selection process of CoopMAC depends on higher rate of the optimal helper. The proposed protocol selects helper in terms of priority of the AC as a first choice and then, data rate is in second choice. But in CoopMAC

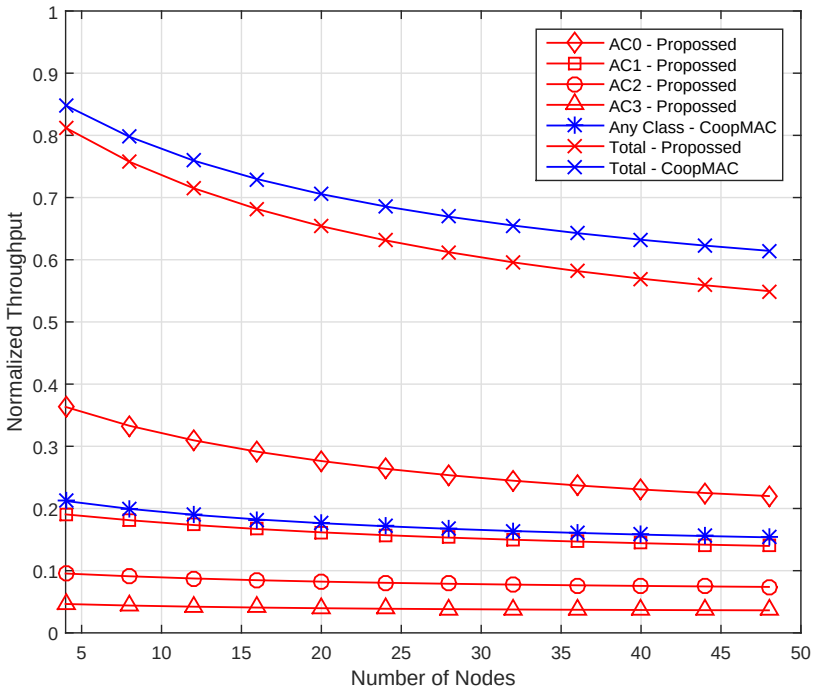


Figure 4.2: Normalized Throughput of the Proposed Protocol and CoopMAC

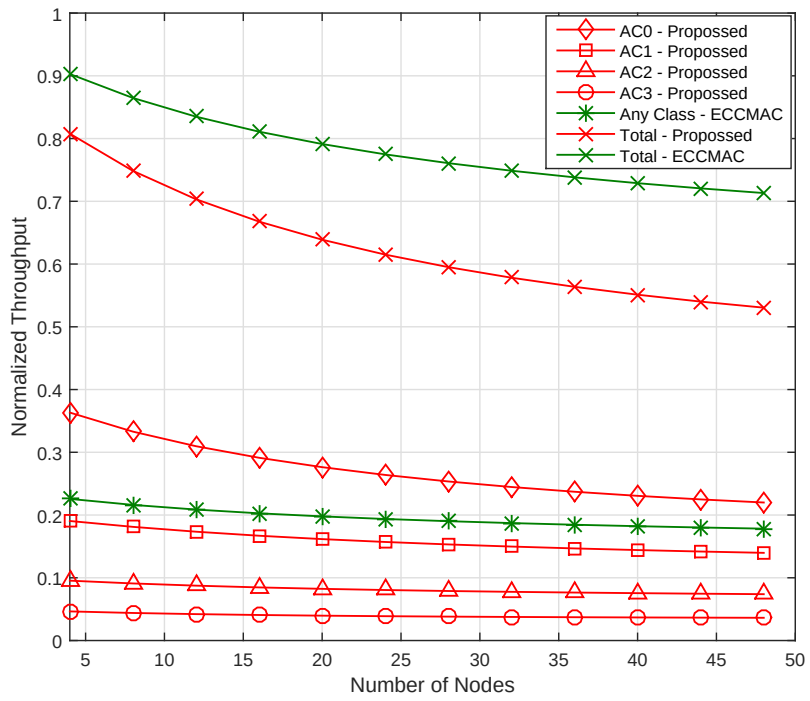


Figure 4.3: Normalized Throughput of the Proposed Protocol and ECCMAC

link rate is the main consideration to select an optimal helper for data transmission. For this reason, AC0 and AC1 whose are the higher priority traffics in the proposed protocol, performs better than any class of CoopMAC. In CoopMAC, all classes are treated as same manner; so, all the classes have the same throughput performance.

The proposed protocol is also compared with ECCMAC [9] which is a cooperative MAC protocol that considers some features of EDCA as discussed earlier. The ECCMAC selects helper in the same manner as CoopMAC does; for this reason, the higher rate helper performs better than AC1, AC2 and AC3 as shown in Figure 4.3. But, as same as CoopMAC here also the higher class AC0 performs better than any class for ECCMAC. The total throughput of ECCMAC is much better than proposed protocol because ECCMAC sends 3 packets at a time to reduce overhead. That's why, ECCMAC total performance is much better than proposed protocol.

Figure 4.4 shows the comparison among proposed, CoopMAC and ECCMAC in one graph. In figure 4.4 ECCMAC overall performance is better than CoopMAC and proposed protocol. As discussed earlier, ECCMAC reduces the overhead time by sending 3 packets at a time so the throughput for ECCMAC is much better

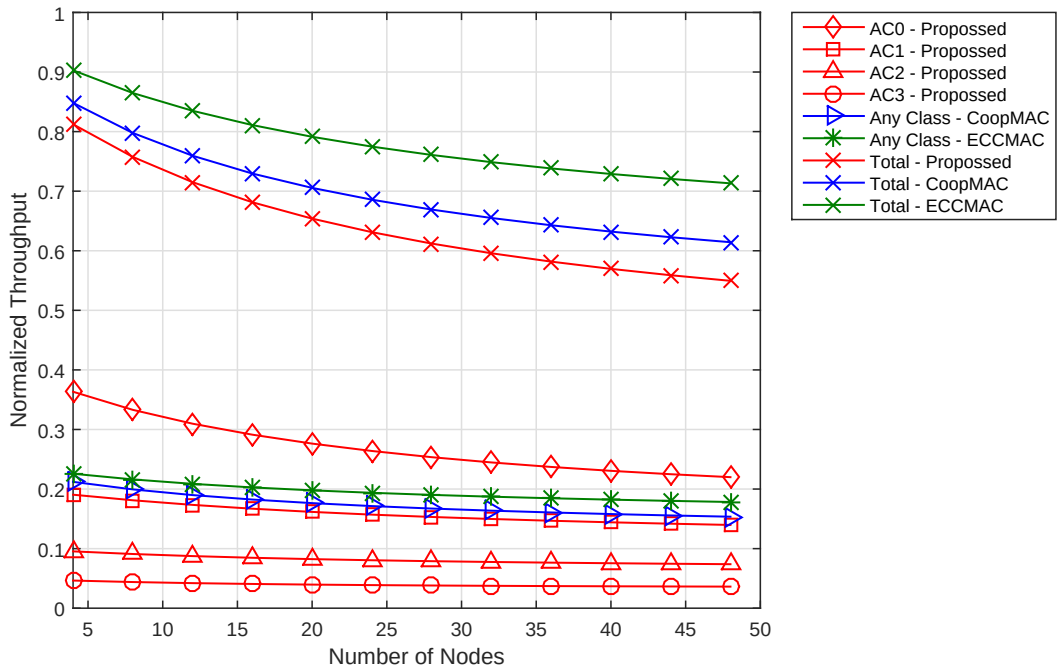


Figure 4.4: Normalized Throughput of the Proposed Protocol Compared with ECCMAC and CoopMAC

than other two protocols. But, the proposed protocol performs better than other two protocols if considering the per class performance. Figure 4.4 shows that AC0 class for proposed protocol performs much better than any class of CoopMAC and ECCMAC.

4.2.2 Effect of Frame Size on Throughput

Figure 4.5 shows that the throughput of each AC increases as the frame size increases for both the proposed and legacy EDCA protocol respectively when the network size is a set of 5 nodes per AC and data rate is set to six times faster than the direct rate between source and destination. But, the proposed protocol performs better than the legacy EDCA protocol for each AC as a function of frame size. When the data packets are small, throughput performance is less than for large data packets. Figure 4.5 shows that the normalized throughput increases as the packet size increases. This is simply because the larger packets lead to fewer transmissions per second; thus, the channel access overhead incurred per second decreases.

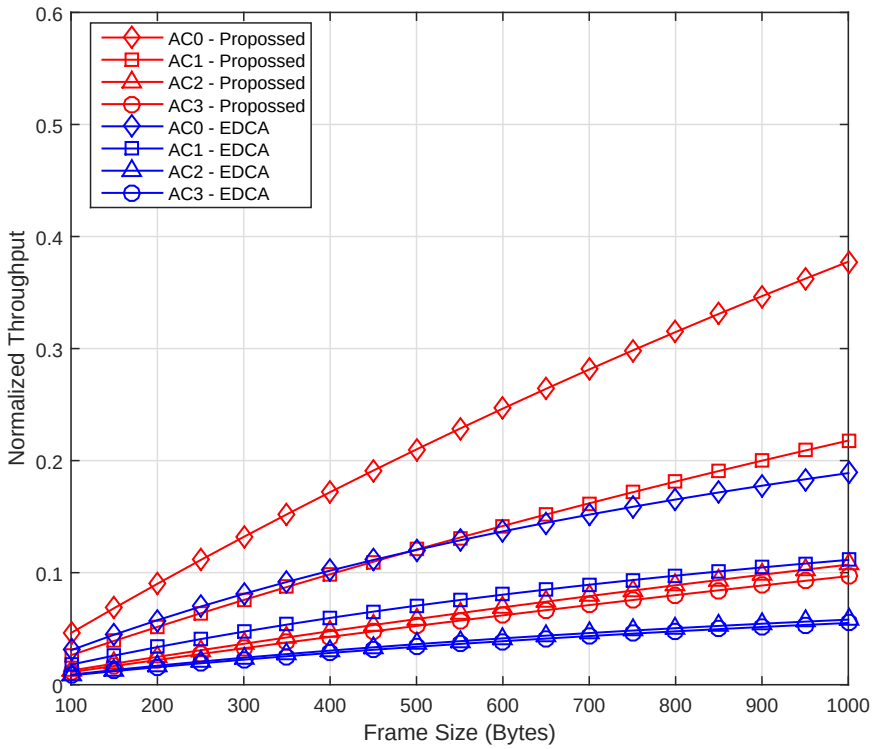


Figure 4.5: Throughput of the Proposed Protocol and EDCA when Frame size is variable

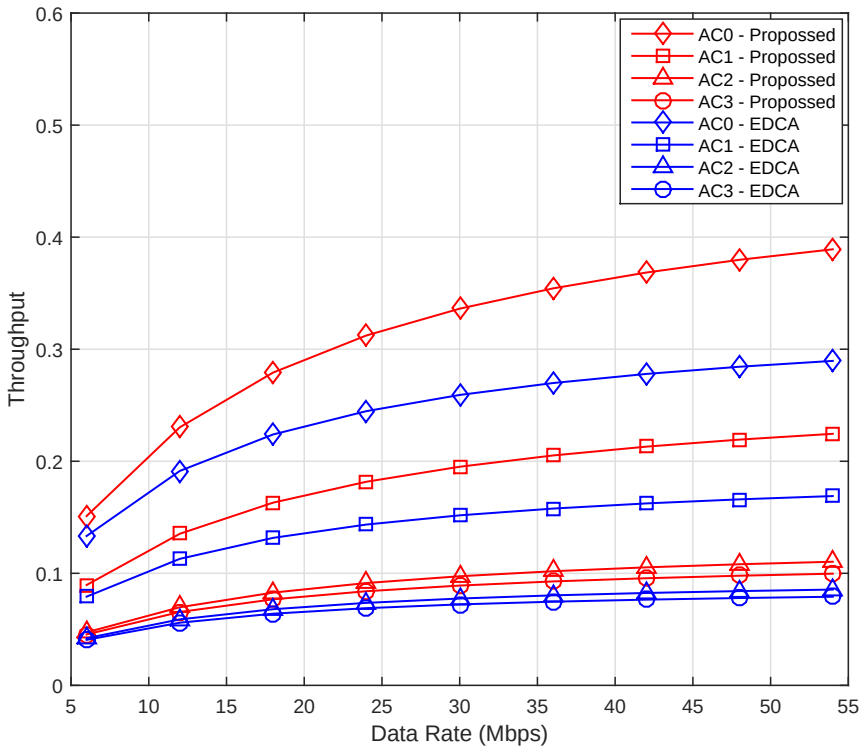


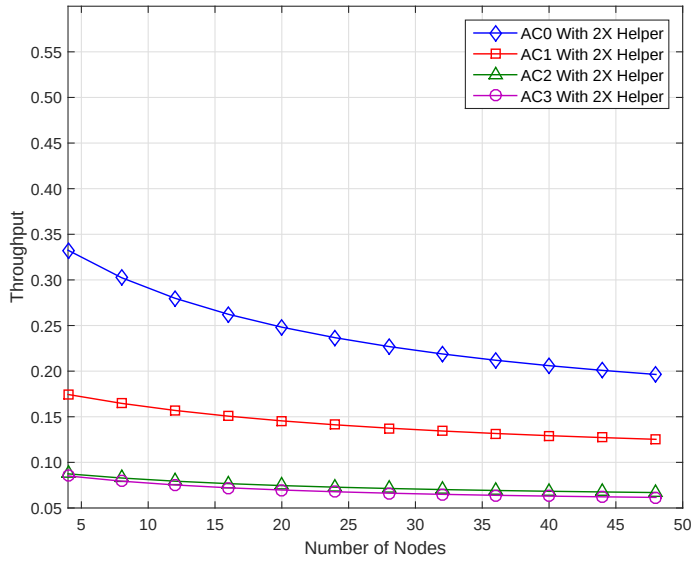
Figure 4.6: Normalized Throughput of the Proposed Protocol and EDCA according to Data Rate

4.2.3 Effect of Data Rate on Throughput

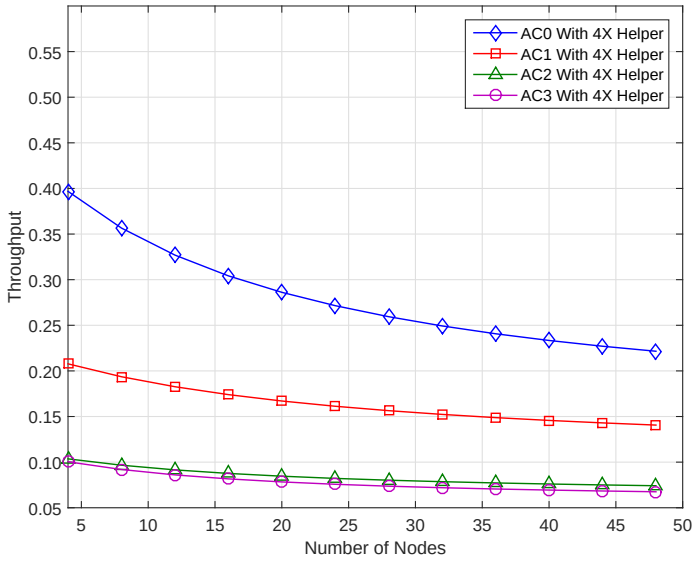
Figure 4.6 represents the throughput as a function of data rate. The frame size is fixed here as 1024 bytes and node number is fixed per AC. The behavior of proposed and standard EDCA is same for all class; the throughput is increased as the data rate is increased. But, there is a difference between the throughput of the proposed and EDCA protocol. AC0 class of our proposed protocol has at least 10% better performance than the legacy one and other class also performs better than the legacy one.

4.2.4 Effect of Helper Node's Data Rate

Figure 4.7 (a) & (b) and Figure 4.8 (a) & (b) shows the throughput for 2X, 4X, 8X and 16X rate helper performance as a function of number of nodes respectively. For the proposed protocol in this research work, we need at least two times faster helper to help in the transmission process and Figure 4.7 (a) & (b) confirms that overall



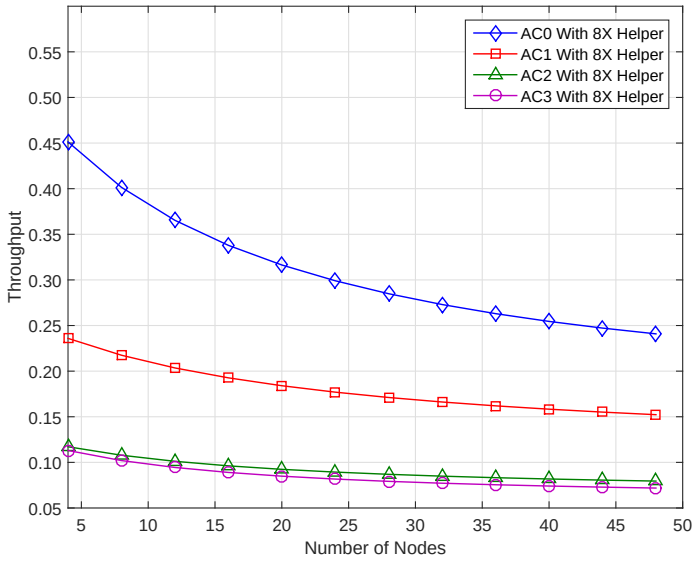
(a)



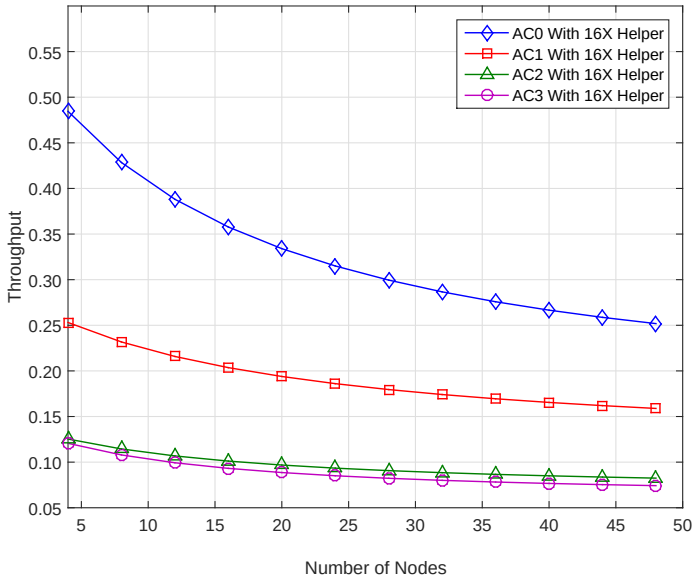
(b)

Figure 4.7: Normalized Throughput of the Proposed Protocol (a) in case of 2X times faster Helper Nodes (b) in case of 4X times faster Helper Nodes

66% throughput gain is achieved from the network. Figure 4.8 (a) & (b) shows that faster the helper the throughput performance is better. From the figures 4.7 (a) & (b) and 4.8 (a) & (b) the observation is that; there is a significance improvement from the faster helper choice. Those figures 4.7 and 4.8 ensure that a faster helper than the direct link, its obvious that the throughput performance is also better.



(a)



(b)

Figure 4.8: Normalized Throughput of the Proposed Protocol (a) in case of 8X times faster Helper Nodes (b) in case of 16X times faster Helper Nodes

4.3 Transmission Probability Comparison

Figure 4.9 shows transmission probability of different protocols. Transmission probability is the probability that a station transmits in a randomly chosen slot time. Proposed protocol is based on IEEE 802.11e EDCA standard and other protocols are based on IEEE 802.11 DCF standard. The transmission probability of a transmitting

station is a function of backoff process and AIFS (for EDCA) and DIFS (for DCF) parameters. The smaller the backoff window and IFS parameters, transmission probability is better. For EDCA, the above mentioned parameters are different for each type of contending class to set priority level and it is seen from the graph that transmission probability for EDCA and proposed protocol are different for different classes. And, obviously the transmission probability for higher classes (AC0 and AC1) than lower classes (AC2 and AC3) is much better for EDCA and proposed protocol. It is seen that the higher classes performs better because the backoff and AIFS parameter for them are chosen small to give the priority. For CoopMAC and ECCMAC, any types of data are treated as same manner as they work according to DCF standard. So, Figure 4.5 shows that for any type of class the transmission probability is same for the CoopMAC and ECCMAC. Also, the AC0 class for EDCA and proposed protocol always performs better in terms of transmission probability.

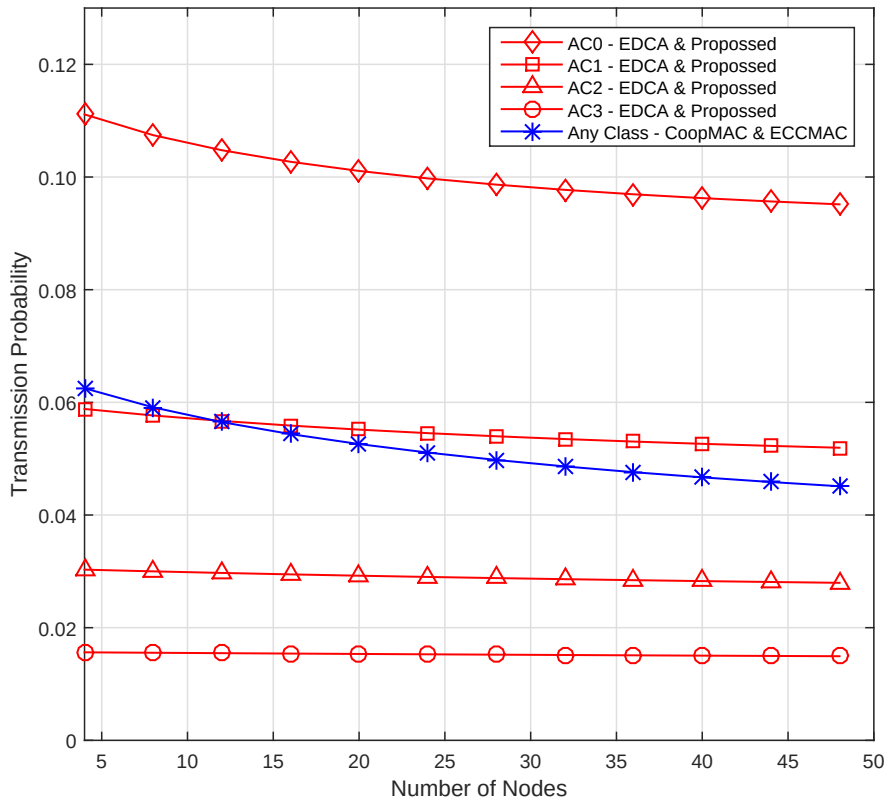


Figure 4.9: Transmission Probability of Different Protocols with Increasing Number of Nodes

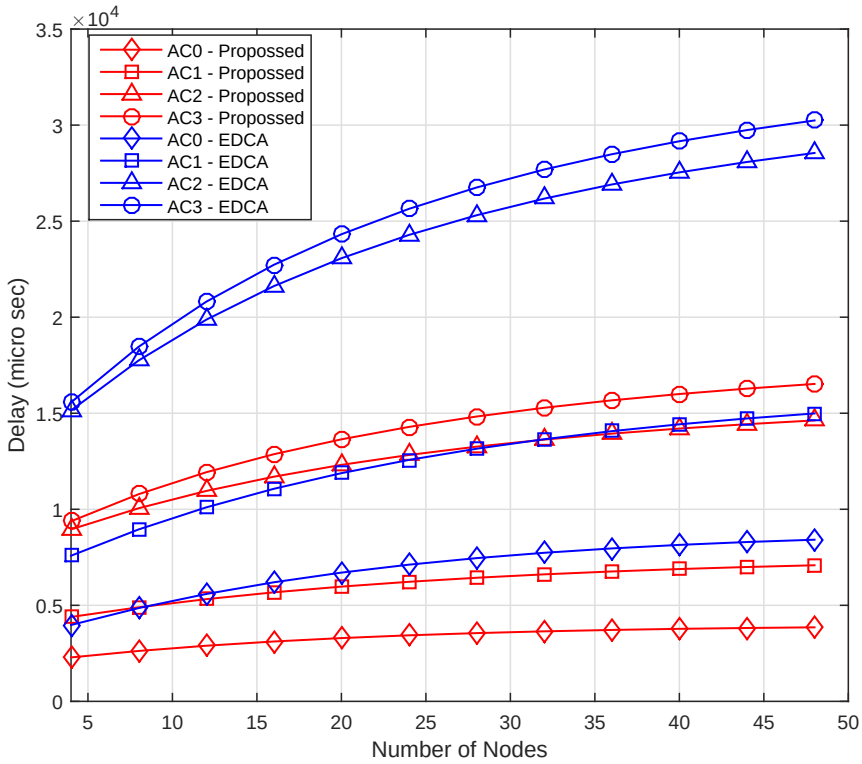


Figure 4.10: Delay of the Proposed Protocol and EDCA

This is because of all kinds of stations with any kind of data chooses the same backoff and DIFS parameters for contention. As a result, the collision between stations are high for those protocols.

4.4 Delay comparison

Figure 4.10 presents a comparison of the average delay between proposed protocol and standard EDCA when the network size varies from 4 to 48 nodes with same number of nodes per class and at the basic data rate of 6 Mbps and the helper link is four times faster than the direct link. The packet size is set to 1,024 bytes. The figure 4.10 shows the delay increasing as the number of contending nodes increases, as expected. This is because more contending nodes lead to less frequent transmissions from a node. It can be observed that the EDCA delay is larger than that of the proposed protocol for any access class AC0, AC1, AC3 and AC4. And, obviously the higher classes AC0 and AC1 transmit their data efficiently with less delay experience. Moreover, the disparity between EDCA and proposed cooperative EDCA increases

as the network grows. This is because (1) the average contention resolution period of the proposed protocol effectively chooses lower number of contending helpers that reduces collision contention than that of standard EDCA and (2) the high collision rate of EDCA leads to frequent retransmissions and thus, has much extra overhead. The low delay performance of higher classes in our proposed protocol is desirable for real time services.

4.5 Summary

This chapter presents the comparison of the proposed protocol with different protocols. Analytical results show the proposed protocol performs better than standard EDCA, CoopMAC and ECCMAC in throughput and transmission probability. The proposed protocol performs better than standard EDCA compared with different metrics, i.e., data rate, frame size and delay.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Due to the increasing demand for multimedia services that requires tight Qos provisioning, the IEEE 802.11e has been standardized. IEEE 802.11e EDCA is adapted to statistically prioritized channel access among wireless stations. A large amount of research work has been carried out to enhance the QoS support in IEEE 802.11 networks. IEEE released the final draft of the standard, called 802.11e, which is an extension to IEEE 802.11 to provide QoS support. IEEE 802.11e supports prioritized access mechanism which is called EDCA and parameterized access mechanism HCCA to support QoS. In this research work, EDCA is focused to enhance QoS of the network. EDCA supports QoS by traffic differentiation to prioritize the traffics.

Thus, EDCA partially satisfy the QoS requirements in practice. In this thesis work, the main contribution is to enhance the QoS requirements of IEEE 802.11e EDCA with cooperative communication. The proposed protocol searches a prospective helper node to assist the sender if the transmission rate between sender and receiver is very poor. The proposed protocol finds an optimal helper node on the basis of priority class and link rate to enhance the network performance.

An analytical model is developed to mathematically analyze the performance of the proposed protocol in terms of throughput and delay. The throughput is compared with different protocols in terms of increasing number of nodes. Performance results show the proposed protocol outperforms the legacy EDCA, and other protocols and enhances the QoS of the WLAN and as a result, increases throughput and reduces the delay performance.

5.2 Future Work

The proposed protocol performance is analyzed mathematically with a Markov Chain model considering a generalized network configuration that there present an equal number of contending nodes for each AC. In future, the above consideration will be extended to real time scenarios with varying number of nodes per AC.

In future, the research work will be simulated with an OMNET based simulation environment to validate with analytical results of the proposed protocol to increase the acceptance of the performances carried out in this research work.

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