Chapter 1

Introduction

1.1 Introduction

For the last few decades, wireless communication has become one of the fastest growing fields in the telecommunication and networking. Wireless networking is a rapidly emerging technology for connecting computers and establishing communication among wireless devices while moving from one location to another, and has become part and parcel of everyday life. The three most common types of wireless network topologies are Local Area Network (LAN), Metropolitan Area Network (MAN) and Wide Area Network (WAN). Distance is an important classification metric because different techniques are used at different scales. A local area network enables a group of computers in close proximity (e.g. building or a small campus) to communicate with each other and share resources like files, printers, etc. There has been a great increase in the usage of Wireless Local Area Networks (WLANs) to supplement traditional wired local area networks for the requirements of mobility, relocation, Ad hoc networking and coverage of remote areas that are difficult to connect by wires. A metropolitan area network is a large computer network that usually spans a city or a large campus and can be formed by connecting multiple LANs using high speed backbone technologies. Wide area network links millions of LANs that cover a wide geographic area such as a state, a country or may span even to inter-continental distances. The world’s most popular wide area network is the Internet. Wireless LANs are generally based on IEEE 802.11 standards which typically operate over the unlicensed spectrum reserved for industrial, scientific, medical (ISM) usage. Even though several standards have been proposed, the most extensively used WLAN technologies are those developed from the original IEEE 802.11 standard: 802.11b, 802.11a and 802.11g. These WLAN standards function only at the bottom two layers of the Open Systems Interconnection (OSI) reference model, namely, the Medium Access Control (MAC) layer and the Physical (PHY) layer. The MAC layer controls the access to shared wireless medium and the PHY layer provides transmission and reception of data frames over the wireless medium. In order to allow multiple users to access a common
channel, the IEEE 802.11 standard has defined two different access mechanisms: the basic access mechanism called the Distributed Coordination Function (DCF) and a centrally controlled access mechanism called the Point Coordination Function (PCF). Wireless local area networks are generally operated in infrastructure and Ad hoc modes.

In infrastructure topology, there is a fixed infrastructure that supports communication between mobile terminals and between mobile and fixed terminals, whereas an Ad hoc network is a wireless network in which the nodes form dynamic connections and allow the nodes to seamlessly communicate with other nodes within radio range, without any central control. So, Ad hoc wireless networks are the only means of communication in situations where the base stations for wired and mobile telephone systems fail due to natural calamities. Ad hoc networks can be set up easily to provide emergency communication in required areas, and even in remote locations such as deserts. Such characteristics make these networks well-suited for critical scenarios such as rescue operations during natural calamities and for military applications in battle fields. In emergency situations, information must be passed from one node to another with minimum number of collisions at the earliest possible time. But, the most common problem in congested wireless and Ad hoc networks is collision, which results in frequent retransmissions causing unpredictable delays and degradation of network throughput. Network performance degrades also due to propagation through erroneous channels. To overcome these problems, it is necessary to design an efficient MAC algorithm for IEEE 802.11 based wireless networks in real traffic scenarios under hostile channel conditions.

In the current DCF protocol, the node which transmits the packet more recently resets its contention window to minimum and may always get access to the channel, which is called channel capture effect. This results in burst data transmission from that particular node only and hence, there is a need to modify the original DCF protocol.

To reduce the number of collisions and to improve network performance, backoff algorithms are used in MAC protocol. The standard IEEE 802.11 MAC protocol uses Binary Exponential Backoff algorithm. Several backoff algorithms such as Exponential Increase Exponential Decrease (EIED), Double Increment Double Decrement (DIDD), Binary Negative Exponential Backoff (BNEB),
Hybrid backoff (HB), etc. have been proposed in the earlier literature to improve the system performance of IEEE 802.11 based networks. However, these algorithms, other than BEB algorithm, have not been designed for finite load and erroneous channel conditions. Also, using BEB algorithm, the delay performance of the network is poor. To alleviate the number of collisions and to improve Quality of Service (QoS) parameters such as throughput and End-to-End delay, the backoff procedure has to be modified.

In this thesis, modification of DCF protocol and development of new algorithm is done in two phases. The first phase involves the development of Collision Alleviating DCF (CAD) protocol. For this, a new Markov chain model is proposed for the DCF protocol to accurately predict the performance of the network under finite load and erroneous channel conditions. Parameters such as backoff freezing, packet collision errors and channel error conditions are taken into account while developing the Markov chain model. To reduce the number of collisions and to avoid channel capture effect, a post backoff stage is introduced in this model. This post backoff stage is used to provide inter packet backoff (IPB) delay between successive packet transmissions. Similar to the legacy DCF protocol, CAD protocol also uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme of BEB algorithm.

In the Second phase, a new Contention Window based Multiplicative Increase Decrease backoff (CWMIDB) algorithm is introduced for the proposed CAD protocol in which the size of the contention window will be selected based on the number of collisions. Since packet transmission procedures using backoff algorithm severely affect the performance of the MAC protocol, the backoff procedure for the existing backoff algorithms have been analyzed, which provides guidelines to develop a new algorithm. The CAD protocol and CWMIDB algorithm proposed in this thesis provide better throughput and End-to-End delay particularly, in critical situations such as rescue operations during natural calamities and military applications in battle fields.

1.2 Aim of the Thesis
The main aim of the thesis is to develop a new collision alleviating DCF protocol with CWMIDB algorithm for IEEE 802.11 based Wireless Networks operated in congested environments which can provide superior QoS parameters such as throughput and End-to-End delay. To achieve the aim of the thesis, the following tasks are carried out.

(i) A detailed study of various IEEE 802.11 standards and the protocol architectures have been carried out. Analysis of frame error probability using different modulation techniques over Rayleigh fading channel has been done to select a proper modulation technique and packet size in order to achieve better network performance.

(ii) A critical review of the existing backoff algorithms used in IEEE 802.11 based wireless networks and evaluation of their performance is done in order to form a basic understanding of the factors affecting the functionality of backoff algorithms.

(iii) A new Markov chain model has been proposed to accurately predict the performance of the network under non saturated traffic and erroneous channel conditions. To alleviate the number of collisions and avoid channel capture effect, a post backoff stage is introduced for DCF protocol and named, “Collision alleviating DCF (CAD) protocol”.

(iv) A new Contention Window based Multiplicative Increase Decrease Backoff (CWMIDB) algorithm is proposed to enhance QoS parameters such as throughput and End-to-End delay.

1.3 Applications of the Thesis

The proposed CAD protocol and the CWMIDB algorithm developed in this thesis for IEEE 802.11 based wireless networks are having the following applications:

(i) IEEE 802.11 based Ad hoc networks can be used in situations where it is impossible to set up an infrastructure for communication among the wireless devices such as in battlefields.
(ii) In situations of disaster like earthquakes, tsunamis, hurricanes, floods etc., which occur frequently these days, it is important to have an efficient emergency communication system for rescue operations and all nodes need to be able to obtain the channel for communication among the rescue team members. Using the proposed CAD protocol, channel capture effect can be avoided.

(iii) In densely populated areas such as airport lounges, where many people use their wireless devices, the number of collisions increases, and frequent retransmissions cause reduction in throughput. The procedure used for packet transmission using CWMIDB algorithm can reduce the number of collisions, thereby increasing network throughput while reducing the required delay.

(iv) Ad hoc networks are used in disaster situations when the centralized infrastructure fails. In these networks, since nodes have limited battery power, the reduction in packet collision is very important, else the nodes have to spend more energy for packet transmission. The CWMIDB algorithm developed in this thesis is very much helpful in such scenarios.

1.4 Literature survey

To provide the necessary information and to lay a solid foundation for the thesis, a critical review of the relevant literature is done. With regard to this, the features of various IEEE 802.11 standards, protocol architectures and various modulation techniques are studied. Wireless local area networks are generally based on IEEE 802.11 standard which usually operates in unlicensed frequency bands. The IEEE 802.11 technology is a good platform to implement single-hop Ad hoc networks because of its extreme simplicity (Anastasi G. et al., 2004). In this thesis, IEEE 802.11b protocol parameters are used to analyse the performance of various backoff algorithms. With slight modification, this can be expanded to IEEE 802.11a/g protocols.

In communication networks, several terminals share the same communication channel. This is based on the channel access scheme. The channel access method is based on a multiple access protocol and
a control mechanism known as Medium Access Control. In IEEE 802.11 WLANs, the fundamental access method of the IEEE 802.11 MAC is DCF, known as CSMA/CA (Part 11: Wireless LAN MAC and PHY specifications, 1999). DCF describes two techniques to support packet transmission: a two-way handshaking technique called basic access mechanism and an optional four-way handshaking technique, known as Request-To-Send/Clear-To-Send (RTS/CTS) mechanism. The standard IEEE 802.11 DCF protocol uses the Binary Exponential Backoff (BEB) mechanism for packet transmission and this algorithm was well explained by previous authors (Bianchi G., 1998).

Performance evaluation of a wireless network is an intricate problem due to interaction of a large number of wireless systems. In congested wireless networks, high collision rate and frequent retransmissions cause unpredictable delays which degrade network performance. Network performance degrades also due to propagation through erroneous channels. Hence, there is a need to enhance the performance of wireless networks for real traffic scenarios under hostile channel conditions. The modelling of IEEE 802.11 has attracted a number of studies. There has been extensive research on the performance of 802.11 DCF using CSMA/CA protocol. Several scientific publications have analysed the performance of IEEE 802.11 DCF by developing two-state Markov chain models. However, many of these models are based on simple assumptions and are therefore not suitable for real-time environments. Many researchers concentrated on performance evaluation of DCF by assuming ideal channel conditions (Bianchi G., 2000; Wu H. et al., 2002).

Bianchi was the first to derive a model that incorporates the exponential backoff process inherent to 802.11 as a two-dimensional Markov chain to analyze the saturated throughput of 802.11 and proved that the Markov analysis works well. The model developed by Bianchi has been the basis for further research going on for years. Here, it is assumed that collision probability is independent of the number of packets transmitted by each node, regardless of the number of retransmissions already suffered. To increase accuracy of results, busy medium conditions were taken into account (Ziouva E. et al., 2002). Some authors have addressed the finite load performance of IEEE 802.11 DCF with queuing models (Cantieni G.R. et al., Malone D. et al., 2005). Few authors added a new idle state to Bianchi’s model to represent the node with an empty queue (Liaw Y.S. et al., 2005). In Bianchi’s model, the node
remains in the $m^{th}$ backoff stage until the packet gets transmitted successfully; however, the packet is discarded after $m$ backoff stages in this model. The effects of non-ideal wireless channels were introduced in the model (Dong X.J. et al., 2005).

Authors have considered the impact of channel errors and incoming traffic loads on the performance of DCF (Zheng Y. et al., 2006). A post backoff stage was introduced and the equation for optimal constant window that maximizes network throughput in saturation conditions has been derived (Anouar H. et al., 2007). The wireless medium has been modelled as a two-state process with a probability of being busy, $p$ and a probability of being idle, $1-p$ (Ergen M. and Varaiya P., 2007).

Authors have developed a Markov model to analyze DCF throughput considering transmission errors and capture effect over Rayleigh fading channels (Daneshgaran F. et al., 2008). Their model exhibited much greater accuracy compared to previous research, for a network with high contention level. The effect of hidden nodes on the performance of DCF has been evaluated (Hung F.Y. et al., 2007; Yang J W. et al., 2009). Some recent papers have analyzed the performance of DCF in error-prone channel and in non-saturated conditions (Haitao Z. et al., 2011).

After studying several research publications, in this chapter, an exact Markov chain model is proposed to accurately predict the performance of IEEE 802.11 DCF protocol and to improve system throughput in the presence of transmission errors. The developed model is named as “CAD protocol”. Parameters such as backoff freezing, packet collision errors and channel error conditions have been taken into account for the proposed CAD protocol.

In highly congested environments and in emergency situations where many nodes are competing to access the channel at the same time, collisions occur, and this is a major problem in wireless networks and hence, backoff algorithms are used in MAC protocol to resolve collisions. In the existing BEB algorithm, when a frame is transmitted successfully, the Contention Window (CW) reduces to its minimum value, $CW_{min}$. Several backoff algorithms have been proposed for DCF protocol to reduce the number of collisions and improve system performance. Throughput can be enhanced by adjusting the DCF contention window (Wu H. et al., 2003). In this, the value of CW is kept unchanged when the retry counter reaches the maximum limit. The CW value is set to $max \left[ CW/2, CW_{min}+1 \right]$ i.e., the CW

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value is halved after a successful transmission and it is set to $\min [2 \times CW, CW_{\text{max}}+1]$ i.e., the $CW$ value is doubled whenever a transmission fails. As the value of $CW$ is kept unchanged when the retry counter reaches the limit, this will be used as initial $CW$ for the next data frame to be transmitted. This is the basic Exponential Increase Exponential Decrease (EIED) backoff algorithm. The basic EIED algorithm was modified and is called GDCF (gentle DCF) mechanism (Wang C. et al., 2004). Here, the size of the contention window is halved after consecutive successful transmissions which reduce the collision probability, particularly in networks with a large number of contending nodes. Similar to BEB algorithm, in GDCF, the size of $CW$ is doubled for each unsuccessful transmission. In DIDD (Double Increment Double Decrement) backoff mechanism, the contention window reduces to half after successful transmission of the data frame (Natkaniec M. et al., 2000). The major drawback of DIDD algorithm is in situations where the buffer of most of the stations is empty; in such cases, a lot of time will be wasted to get back this large $CW$ to 0 in order to transmit the packet. According to Natkaniec, DIDD increases the throughput by 9% and decreases the mean packet delay by 23% for 25 stations as compared to the original BEB algorithm. The results obtained by Natkaniec are based on simulation and do not derive any analytical model. A mathematical model was developed for DCF protocol using DIDD algorithm to analyze the performance of the network considering frame retry limits (Chatzimisios P. et al., 2005). A Hybrid backoff algorithm is proposed to improve saturation throughput and decrease the packet drop probability of wireless LANs (Xiangyu P. et al., 2007). Authors have proposed a new algorithm named Binary Negative Exponential Backoff (BNEB) algorithm (Choi B.G. et al., 2009). In BNEB algorithm, the size of contention window is initially set to $CW_{\text{max}}$ to reduce the probability that more than two stations select the same backoff counter value. The size of $CW$ reduces by half after successful transmission of a frame. According to the authors, if a collision occurs, the station using BNEB algorithm can effectively resolve collisions by using the maximum contention window size. As the size of the contention window becomes smaller at higher backoff stages, the throughput reduces drastically when using BNEB algorithm, as compared to other backoff algorithms.
Since communication through Ad hoc networks plays a major role in emergencies, it is very important to design an efficient backoff algorithm for wireless Ad hoc networks. An efficient backoff algorithm should maintain a fair usage of the network among transmitting nodes, enhance network throughput and reduce End-to-End delay. In order to satisfy these characteristics, the backoff procedure should be modified. Even though several backoff algorithms have been proposed for DCF protocol, these algorithms (except BEB algorithm) have not been designed for finite load conditions. In the existing BEB algorithm, for each unsuccessful packet transmission, the size of the contention window increases exponentially. This reduces the probability of successful transmission of exposed nodes. Also, a particular node which has transmitted a packet most recently may capture the channel and may transmit subsequent packets. This results in burst data transmission from that particular node only and the nodes that joined the network later may not get access to the channel. To overcome these problems, a new Contention Window based Multiplicative Increase Decrease Backoff (CWMIDB) algorithm for the CAD protocol is proposed in this thesis.

1.5 Technical Approach

Literature survey reveals that even though several backoff algorithms have been proposed for the IEEE 802.11 DCF protocol, they are not suitable for congested wireless and Ad hoc networks. In IEEE 802.11, the MAC and PHY layers are responsible for data transmission. When data is transmitted over a wireless medium, the frames may be corrupted due to channel noise and other impairments such as fading, multipath, shadowing, interference etc. The probability of frame error rate depends on the modulation technique used, packet size, channel noise, etc. As part of development of a new algorithm, the basic concepts related to IEEE 802.11 standard, which are essential for analysis of wireless networks, are reviewed. Also, the frame error probability for IEEE 802.11b protocol has been analyzed under Rayleigh fading environments to find a suitable modulation technique and packet size. It is observed that when a node transmits its frames at higher data rates, the frame error probability is more, but the delay to transmit the corresponding frame reduces. On the other hand, the transmission of the frames at lower data rates takes a long time to transmit the data,
but it is compensated by a lower frame error rate. It is also observed that frame error rate depends on packet size and increases with an increase in packet size. So, by selecting a proper modulation technique and packet size, one can achieve better network performance.

The backoff procedures and the performance analysis of the existing backoff algorithms have been carried out to form a basic understanding of the factors affecting the functionality of backoff algorithms and to develop a new backoff algorithm.

Although several Markov chain models for the IEEE 802.11 DCF protocol have been proposed in the literature, they cannot predict the performance of the network accurately. So, in this thesis, a new Markov model is developed for the DCF protocol to accurately predict, as well as to improve the network performance, and is named as CAD protocol. In real networks, traffic is mostly unsaturated, so this model is developed for real network operations. The channel errors and errors due to collisions are also considered in the development of the model. In the proposed Markovian state transition model, a post backoff stage is added which provides delay between successive packet transmissions to avoid channel capture. Hence, each packet must be transmitted only after the post-backoff interval in both saturated and non-saturated traffic conditions. Otherwise, the node which has transmitted the packet most recently and the new contending nodes only will gain access to the channel and other nodes may not get immediate access. This leads to more collisions and higher channel capture effect.

Similar to legacy DCF protocol, the CAD protocol also uses BEB algorithm for data transmission. Similar to Bianchi’s model, in the proposed CAD protocol, the node remains in the \( m \)th backoff stage until the packet gets transmitted successfully.

The following modifications are made to the original DCF:

(i) To reduce contention among nodes, after successful transmission of a packet at any backoff stage, a node waits for a random backoff interval to access the channel again. The advantage of this practice is that channel capture is avoided. Under saturated conditions, the node selects this interval between (0, \( W_0-1 \)) at post backoff stage, where \( W_0 \) is the initial contention window (\( CW \)) size.
In unsaturated conditions, where the packet arrival follows Poisson’s process, the node waits in idle (-1,0) state until the next packet arrives in its queue.

The packet can be transmitted at any backoff stage when its backoff counter is zero. When the packet arrives at node’s buffer and the channel is idle, it goes from state (-1,0) to state (0,0) and transmits the packet. When the channel is busy, it selects the CW between (0, W₀-1) at (0,0) state.

Similar to Bianchi’s model, the key approximation in the proposed model is that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability of $P_{\text{col}}$. Also, it is assumed that transmission errors due to the imperfect channel can occur with a probability of $P_e$ and the channel is busy with a probability of $P_b$. The collision and transmission error probabilities are assumed to be statistically independent (Daneshgaran F. et al., 2008). Here, the state of each node is described by \{i, k\}, where $i$ indicates the backoff stage (0,.....m) and $k$ indicates the backoff delay. The backoff delay takes the values (0,1,....$W_i$-1) where $W_i = 2^iC_{\text{Wmin}}$. $W$, $W_0$ and $C_{\text{Wmin}}$ are interchangeable. The contention window will be increased either due to packet collisions or transmission errors since a node cannot distinguish a packet collision from a transmission error. A packet is transmitted successfully when there is no collision (this condition has probability $1 - P_{\text{col}}$) and the packet encounters no channel errors during transmission (this condition has probability $1 - P_e$). The probability of successful transmission is therefore equal to $(1 - P_e)(1 - P_{\text{col}})$, from which the equivalent probability of failed transmission, $P_{eq}$ can be expressed as

$$P_{eq} = P_e + P_{col} - P_eP_{col}$$  \hspace{1cm} (1)

In the literature, many researchers have analysed the performance of the wireless networks under saturated traffic conditions ($q = 1$). But, the network does not perform best when saturated and extensive research has been undertaken to help prevent the network from saturation (Zhai H. et al., 2005). So, the effect of $q$ is considered in the model.

Let $r$ be the probability with which a node transmits a packet in a randomly chosen time slot. A node transmits the packet when the backoff counter reaches the value of zero. The expression for
transmission probability and delay has been derived under non saturated and erroneous channel conditions for the developed Markov model. In this thesis, the Eq. for τ is derived as

\[
\tau = \frac{2q(1 - P_b)(1 - 2P_{eq})}{2(1 - P_b)(1 - 2P_{eq})(1 - q)(1 - P_{eq}) + q(1 - 2P_{eq})[q(W - 1)(1 - P_{eq}) + (2^mW - 1)P_{eq}^m] + Wq[(1 - P_{eq})2P_{eq} - (2P_{eq})^m] - (1 - 2P_{eq}[P_{eq} - P_{eq}^m]) + qP_b(1 - q)(W - 1)(1 - P_{eq})(1 - 2P_{eq})}
\]

(2)

A successful transmission may occur at one of the several backoff stages. The average packet delay depends on the number of backoff slots \(E[X]\). The Eq. for \(E[X]\) for the proposed model is derived as

\[
E[X] = \frac{W_0 + 1}{2} + \frac{b_{0,0}}{6(1 - P_b)}\left[ P_b(1 - q)(W_0^2 - 1) + \frac{4P_eW_0^2(1 - P_{eq}) - P_{eq}(1 - 4P_{eq}) - 3P_{eq}^mW_0^2 W_0^2}{(1 - 4P_{eq})(1 - P_{eq})} \right]
\]

(3)

Throughput and End-to-End delay analysis for the proposed CAD protocol has been carried out under saturated/finite load conditions in ideal and Rayleigh fading channel conditions.

From the analysis of the existing backoff procedures, it is observed that after each unsuccessful packet transmission, the backoff period increases linearly or exponentially depending on the backoff algorithm, which increases the packet delay. On the other hand, when the backoff period decreases for each unsuccessful transmission such as in BNEB algorithm, throughput also decreases. So, a new CWMIDB algorithm is proposed in this thesis in which the backoff period is selected in such a way that it increases and decreases alternately for each unsuccessful packet transmission until the contention window reaches its maximum value, which provides better QoS parameters than the existing backoff algorithms. The backoff procedure using CWMIDB algorithm is given below.

**CWMIDB Algorithm**

Step 1: Initialize Contention window \(CW\) to its minimum value \(CW_{min}\) and the maximum value of \(CW\) to its maximum value \(CW_{max}\) according to the specifications of the IEEE 802.11 standard.

Step 2: Sense the channel for a period of DIFS. If the channel is idle, transmit the data frame and go to step 5. Otherwise go to step 3.

Step 3: Set the backoff counter (BOC) between 0 and \((CW_{min} - 1)\). Now the size of contention window is 32 slots.
Step 4: Decrement the BOC by 1 if the channel is idle. If BOC reaches zero, transmit the data frame.

Step 5: If acknowledgment received, go to step 1 to transmit the next data frame. Else go to

Step 6.

Step 6: If the acknowledgement is not received select the BOC between 0 and \((W_i - 1)\) if \(CW < CW_{max}\). Else \(CW = CW_{max}\). Here \(W_i = 2^{i/2}W\) for even values of \(i\) and \(W_i = 4X2^{(i-1)/2}W\) for odd values of \(i\) where \(i\) is the retransmission attempt and \(W = CW_{min}\). Go to Step 4.

The proposed CWMIDB algorithm is applied to CAD protocol and its performance is evaluated and compared with the performance of existing backoff algorithms.

1.6 Organization of the thesis

The thesis comprises of six chapters including the Introduction and the Conclusions. Chapter 2 provides the background information relevant to this thesis. An introduction to IEEE 802.11 standards, protocol architecture with an emphasis on bit error and frame error probabilities using various modulation techniques over Rayleigh fading channel is presented. Chapter 3 presents the packet transmission procedures using basic and RTS/CTS mechanisms. Chapter 3 also presents a critical review of various existing backoff algorithms. A new Markov chain model for the proposed CAD protocol is introduced in Chapter 4. A detailed review is carried out on existing Markov models and their performance is compared with the proposed one. Chapter 5 introduces a new algorithm, namely Contention Window based Multiplicative Increase Decrease Backoff (CWMIDB) algorithm. The Markov chain model developed in Chapter 4 is used as basis for this algorithm. Likewise, the dependency of the protocol performance on the number of nodes, packet size, packet arrival rate, data rate etc. is explored. Chapter 6 presents the overall conclusions of this thesis and also gives directions for future research.