To my lovely wife and parents
ACKNOWLEDGMENTS

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Power line communication systems (PLC) are becoming prominent in home and personal environments for local area networks and broadband power line internet access due to its attractive deployment features and high data rates. To mitigate the harsh condition of power line channel and effectively utilize the power line bandwidth, robust physical (PHY) and medium access control (MAC) protocols are required.

Home Plug is most commonly used technology for PLC, which defines its MAC based on CSMA/CA and random backoff algorithm. Similar to 802.11 DCF, the MAC efficiency of this protocol degrades when the network is congested with increasing number of stations.

A comprehensive study of IEEE 802.11 DCF based adaptive backoff mechanism and further investigate their efficiency to compare with the performance of Home Plug MAC has been made in this project. Furthermore, the optimum constant contention window (CW) for the Home Plug 1.0 MAC based on a discrete time homogeneous Markov Chain model was investigated and simulated.

Since the constant contention window based MAC protocol works with the knowledge of number of contending stations, an estimation mechanism was
implemented to achieve a high MAC efficiency. By using the deferral counter which is built in the current Home Plug MAC, an accurate tracking of number of users in the channel has been accomplished.
CHAPTER 1
OVERVIEW

Fast evolving bandwidth hungry multimedia applications and the emergence of end-user services like VoIP and HDTV has put growing need on data rates and reliability on service providers. To support this ever increasing demand for network connectivity, several home-networking technologies such as wired, wireless and no new wire networks have evolved to provide access to home environment [1]. As for wired network technology, Ethernet has been dominant to support distributed computing for its stability and robust security. Nevertheless, installation of new wires, high infrastructure cost and lack of mobility in Ethernet have triggered scopes for alternative networking technology. In recent years, wireless networks, such as 802.11x and Bluetooth, have led the way to meet the requirements of the prolific growth of portable devices and laptop computers. However, coexistence with ISM equipment and increasing herding in the 2.4/5 GHz band used by 802.11x are likely to degrade their performance. Retrofitting homes with new cables makes installation expensive and wireless resolutions do not necessarily provide reliable coverage to meet the demand of multimedia communication for the entire house. To that extent, the existing electrical wiring gives rise to a new affordable and ubiquitous LAN technology that provides hefty access points throughout the building. Nonetheless, there are obstacles in communication via hostile power line medium that must be dispatched to make power line communication (PLC) a feasible “no new wires” home networking solution. Home Plug is one of the most popular power line communication technologies, the latest version (v2.0) of which can support up to 1.5Gbps over power lines [2].
As power lines were initially designed to distribute electrical power in the frequency range of 50-60 Hz, using this channel for high-speed data communications poses some technical challenges. These include the electrical noise and random interference also experienced in PLC, due to connected electrical appliances constantly changing the voltage levels when switched on or off as well as unforeseen power surges introduced by external occurrences. Moreover, as a result of the variety of conductor types and cross sections in the PLC system, different impedance levels are introduced in the network causing multipath effect which leads to deep notches at certain frequencies [3]. In power line channels, the average attenuation for a particular band of frequencies can rise up to 80dB and it is not uncommon for this medium to exhibit a delay spread larger than 5 μs [2]. With the aid of meticulous research in the region of electromagnetic compliance, noise characterization and mitigation, channel modeling and measurement, Medium Access Control (MAC) and as well as field trials, the challenges of harsh channel condition and channel sharing in PLC systems have been effectively overcome.

As PLC systems relies on a common transmission medium, the network terminals must coordinate their transmission based on an efficient MAC protocol. Although the PLC system is basically a wired technology, Carrier Sense Multiple Access Collision Detection (CSMA/CD) does not perform well in this case as the hostile power line makes it difficult to detect collisions in the medium. Since power line channel has similar impairments as wireless medium, WLAN based Carrier Sense Multi Access with Collision Avoidance (CSMA/CA) is used in the MAC of Home Plug with the extension of random backoff algorithm of IEEE 802.11 DCF. Some well-known enhancements and
analytical performance evaluations have been carried out in [4-7]. Based on these studies, a thorough analysis for the Home Plug 1.0 MAC performance has been worked out by Jung et al. in [8]. The major drawback of existing Home Plug MAC, like the 802.11 DCF, is the unsatisfactory MAC efficiency under congested network. To compare the MAC performance of PLC systems of that with 802.11 based WLANS, in this thesis a detailed survey of the most recent works regarding MAC protocols for 802.11 DCF focused on the enhancement of adaptive backoff mechanism is presented. Also, the optimal constant contention window for Home Plug 1.0 and AV CSMA/CA MAC is presented.

**Medium Access Control Protocols**

The Medium Access Control (MAC) protocol, also known as Media Access Control, is developed to orchestrate the users which share a common medium because the information from a user is broadcast into the medium and all stations attached to the same medium listen to all the broadcasts. Therefore, collision between users is in the same medium is unavoidable. The task of MAC protocol is to coordinate the contending users to access the channel so that data can be transmitted from a source to destination in the same network.

The MAC layer is a sub-layer between Data Link Layer (DLC) and Physical Layer (PHY) and provides an interface between Logical Link Control (LLC) sub-layer and PHY.

Figure 1-1 shows generically the multiple access communication condition in which various stations share a transmission medium simultaneously. The transmission medium is broadcast in nature, and so all the other stations that are attached to the
medium can hear the transmission from any given station. When more than one station starts transmission simultaneously, their signal will collide and interfere with each other.

![Diagram of a shared medium](image)

**Figure 1-1.** Sharing a communication medium

In general, medium sharing schemes can be categorized into two broad classes. The first one is channelization schemes which involve a static and collision-free sharing of medium. According to this scheme, medium is divided into separate channels and these channels are dedicated to particular users. Although, channelization schemes are suitable when stations generate a steady stream of data that makes efficient use of dedicated channel. The another category is named dynamic medium sharing on a per packet basis that is more efficient scheme for a situation in which the user traffic is bursty. This category is also referred to as MAC schemes. The major role of medium access control is to minimize or remove the possibility of collision to achieve a reliable utilization of the medium.

Dynamic medium access control involves two basic approaches which are random access and scheduling. Figure 1-2 also shows the various medium access sharing schemes [9].
Medium sharing techniques

Scheduling

The scheduling method proposes a scheme such that stations access the transmission medium in an order. Basically, scheduling methods are categorized as reservation systems, polling systems as a special form of reservation system and token ring system.

![Scheduling Diagram]

Every node has its own minislot for reservation

Figure 1-3. Generic representation of scheduling

Figure 1-3 basically shows how reservation protocol works. According to this method, transmission starts with reserving the channel. Transmission from the stations are organized into cycles that can be variable in length. Each cycle begins with a
reservation interval and a reservation interval is divided into M mini slots. Each station uses their mini slots to indicate that they have a packet to transmit. Stations broadcast their reservation bit during the mini slot time to announce their intention for transmission and make reservation accordingly. By listening to the reservation interval, stations determine the order of frame transmission. The length of the cycle is up to the number of the reservation and variable length packets can be handled if the reservation message includes the frame length information.

In polling systems, a central coordinator operates the medium access sharing mechanism by sending a polling message to a particular node to ask whether there is any data to transmit. If the answer is yes, the station begins transmission in response to the poll. If the station responses with no, the central coordinator sends a polling message to the next station.

Figure 1-4. Polling System. A) Shared inbound and outbound link to the central coordinator B) Separate link to the central coordinator C) The system works without central coordinator.
When a station is done transmitting, there are different ways to pass the right to transmit to another station. Figure 1-4A shows an example of the situation in which N stations are linked to a central coordinator. This system has an outbound line where data is transmitted from the central coordinator to stations and an inbound line that has to be connected with N stations. The inbound line is shared so that a medium access control is required. Similarly, in Figure 1-4B, a central coordinator provides a medium access control mechanism. However, Figure 1-4C shows a system that has no central coordinator for medium access control. In this kind of system a polling order list is used to organize the reservation. Also, it is assumed that all stations can receive the transmission from all other stations. After a station completes transmission, it is responsible for sending a polling message to the next station in the polling list [9].

**Random Access**

**Aloha**

ALOHA, as the first random access scheme was first proposed in The University of Hawaii to establish a network between the campuses in different islands and the host computer on main campus. According to this protocol, each terminal sends their messages whenever they have something to transmit, thus the smallest delay time can be possible. The collision between packets will be possible since there is no coordination between stations but these can be treated as transmission errors and recovered by retransmitting the same data. When the traffic is very light, the collision probability is very small and retransmission is not frequent, thus delay will be minimum.

There is a huge difference between normal transmission error and those that are due to the frame collision. The normal transmission error is caused by noise effect and only affect a single station but errors due to the collision affects at least two stations and
so more than one retransmission is required. Also, if the stations use the same time out values for retransmission, then their future retransmissions will collide again. Therefore, the necessity of a random backoff mechanism which basically chooses a random number in a certain retransmission interval is proposed. Using a random backoff mechanism helps to reduce the retransmission error in the future.

The high probability of collision in ALOHA scheme reduces the maximum throughput of the ALOHA mechanism. The collision probability can be decreased by sensing the medium for the presence of a carrier signal from other stations and acting accordingly [9].

**CSMA**

Carrier sense with multiple access (CSMA) scheme differ according to the action of stations when they have a frame to transmit and the channel is busy. In 1-Persistent CSMA, stations first sense the channel. If the channel is busy, they keep sensing the channel continuously until the channel becomes idle. When a channel becomes idle, they begin transmission of their frames. Consequently, if there is more than one waiting station, collision will occur. In a sense, in 1-Persistent CSMA stations are attempting to access the channel as soon as possible leading to a relatively high collision rate.

In Non-Persistent CSMA, stations with a frame to transmit sense the channel. If the channel is busy, the station run the backoff algorithm and sense again after a random time. If the channel is idle, the stations transmit. Non-persistent CSMA mechanism attempts to decrease the collision rate but results in longer delays when compared to 1-Persistent CSMA.

The other CSMA mechanism is p-Persistent CSMA which combines above two schemes. According to the p-persistent CSMA, stations sense the medium, and if the
medium is busy, they continue to sense the medium until it becomes idle. If the channel is idle, with the probability of \( p \), a station transmits and with a probability \( 1-p \), the station waits an additional propagation delay time before sensing the channel again. With this method, it is intended that to spread out the transmission attempts by stations that have been waiting for a transmission to be completed and hence to increase the probability that a waiting station successfully seizes the medium [9].

Carrier sense multiple access with collision detection (CSMA/CD) is proposed to decrease the delay. According to this mechanism, if a station knows the collision happened, there is no need to wait to finish the transmission. When the collision is detected, the transmission is stopped. This improvement provides an efficient medium access control especially for long frame length. CSMA/CD is used in IEEE 802.x wired LANs effectively. This method cannot be used in wireless networks because detecting collision in wireless medium is not always possible. The PLC network environment is very similar to WLANs. Therefore, one of collision avoidance techniques is adapted to both WLANs and PLC networks. Carrier sense with multiple access with collision avoidance (CSMA/CA) is the MAC layer mechanism used in IEEE 802.11 WLANs and Home Plug 1.0 PLC networks.

**Conclusion**

As a result of intense researches in enhancing the performance of communication systems in terms of data transmission speed and minimizing data lost, a couple of communication protocols have been developed for wireless and power line communication networks such as IEEE 802.11 and Home Plug 1.0 respectively. Although, the proposed methods are able to meet the demands, fast evolving
multimedia applications and growing networks reveal needs for new high performance approaches.

To be able to provide better performance, many new algorithms, some of them presented in Chapter 2, have been proposed over standard IEEE 802.11 in wireless communications by changing the random backoff mechanism of multiple access control protocols. Not only in wireless environment but also in power line networks, as a result of growing networks new advancements have been done. One of them is Constant Contention based CSMA/CA mechanism.

In standard Home Plug 1.0 MAC protocols, the MAC efficiency drops drastically while number of active stations increases in networks, for instance from 80% to 30%. This result is not acceptable for high data rate required multimedia applications. Because of the fact that, our research in LIST has been focused on the previous multiple access methods and improve the efficiency for PLC and smart grids.

In Chapter 2, a survey in wireless and PLC environment in terms of MAC mechanism has been conducted and some of those mechanisms simulated to compare the performance. Chapter 3 presents a modified CSMA/CA protocols to enhance the MAC efficiency even in highly congested networks. Chapter 5 presents a dynamic tuning contention window size mechanism as a collaterally of Chapter 4.
CHAPTER 2
ANALYSIS OF CSMA/CA MAC LAYER PROTOCOLS FOR WIRELESS AND PLC ENVIRONMENT

To provide high throughput and fairness among active stations, a simplified and good MAC protocol for WLANs should provide an efficient mechanism to share the limited spectrum resources. An ideal MAC protocol would provide high throughput under high network traffic and low delay under low network load, however in reality it is very challenging to meet both the requirements. CSMA/CA, the most effective contention based wireless MAC protocol, has become the basis of 802.11x MAC. Nevertheless, the throughput performance of IEEE 802.11 MAC degrades significantly when the number of serving stations increase in the network, resulting in a higher collision probability. An efficient collision resolution algorithm is required to decrease the number of idle time slots or packet collisions. To that extent, many novel collision resolution algorithm and optimizations have been proposed and they can be classified in three categories: 1) changing the contention resolution algorithm; 2) adapting the protocol parameters to a rough estimation of network status (contending stations, network load, collision rate, etc.); and 3) accommodating the parameters of the protocol to an appropriate estimation of the network status. In the Chapter 2, the sharpest proposed mechanisms of the MAC layer protocol will be analyzed and explored the behavior of the protocol in highly congested network in wireless and power line communication environment respectively.

Wireless Environment

In wireless communication environment, almost all the MAC protocols have been developed on CSMA/CA backoff mechanism. Unlike the wired communication environment, collision detection mechanism does not work because of two main
reasons. The first reason is that, received signal power would be overwhelmed by transmitted power at the same station and so it is not possible to detect any collision. Also, hidden terminal problem in wireless environment which occurs when two different stations which are not within the coverage area of each other attempt to transmit to some station. This situation might cause a collision because detection may not be possible. Therefore, as a solution above problem, CSMA/CA protocol was developed. In this section, a brief explanation of modified MAC protocols and original IEEE 802.11 DCF will be analyzed.

**Standard IEEE 802.11 DCF MAC Protocol**

A CSMA/CA based MAC protocol with binary exponential backoff mechanism, named distributed coordination function (DCF), has been approved by IEEE. This medium access protocol can be summarized as follows. Figure 2-1 shows a generic working procedure of DCF algorithm.

According to this algorithm, a station keeps sensing the medium until an idle period equal to a distributed inter-frame space (DIFS) time is detected before sending a frame. After a DIFS period, the station initiates a random backoff counter which decrease by one slot time as long as the medium is sensed idle. If medium is sensed busy during backoff period, counter is paused until the station senses the medium idle again and resume decreasing after a DIFS time when medium is sensed idle. A station starts transmission when the backoff counter becomes zero. The backoff counter is chosen randomly between (0, CW-1) in every transmission attempt. The value CW is named as contention window. This value is initiated with an initial CW₀ and doubled in every unsuccessful transmission attempt, up to a predefined maximum contention window size and remains same until all transmission attempts end.
Upon receiving the frame successfully, the receiver sends an acknowledgement message (ACK) after a short inter-frame space (SIFS) time. If the station cannot get the ACK in predetermined time out duration, the transmitter retransmits the same frame by following the same backoff procedure [10].

An additional mechanism to solve the hidden terminal problem was defined optionally into this protocol which is known as RTS/CTS mechanism. RTS/CTS control is a handshake protocol can be optionally used for long length frames. According to this control mechanism, at the beginning of a transmission a short request-to-send (RTS) message sends to the other station and the receiver station sends a clear-to-send (CTS) message to the transmitter. If the transmitter gets this CTS, then begin usual backoff procedure. With this control mechanism, the system throughput is improved in case of collision due to the hidden terminal.

Simulation and Results

Based on the definition of IEEE 802.11 CSMA/CA MAC protocol, a simulation was implemented under the following assumption: the channel is saturated and under ideal conditions. Therefore, any loss of data frame sent by a node was not considered even control frame and hidden terminal problem. Also, each node has immediately data
packet available for transmission, after a successful transmission [10]. The simulation was run for different maximum contention window (CW) sizes.

The MAC efficiency can easily be calculated as follows:

\[
\text{Efficiency} = \frac{\text{Total # of Successful Transmission} \times T_{Frame}}{\text{Total # of Slots} \times T_{Slot}}
\]

Figure 2-2 shows the MAC efficiency of standard 802.11 for various maximum and minimum CW sizes with respect to the number of users in the network. As can be seen in Figure 2-2, the performance of this scheme is severely reducing while the number of the station is increasing.
**Power Line Communication Environment**

**Home Plug 1.0**

Home Plug 1.0 MAC protocol uses a carrier sense medium access with collision avoidance (CSMA/CA) and offer various improvements over IEEE 802.11 MAC protocol. Medium access techniques of Home Plug 1.0 compose of two components: Priority Resolution and Random Backoff.

![Diagram of Priority Resolution Slots in Home Plug 1.0](image)

**Figure 2-3. Priority resolution slots in Home Plug 1.0.**

**Priority resolution**

As a difference to IEEE 802.11, Home Plug 1.0 offers a priority resolution mechanism which addresses the quality-of-service (QoS) issue in communication networks. According to priority mechanism, user traffic is categorized based on their priority as CA0, CA1, CA2 and CA3 respectively. If the packet has higher priority, it has more chance to contend for the medium. Before a station contends for the channel, it sends a signal to the priority resolution slots PRS0 or PRS1 depending on priority of their data. Stations with CA3 data have the privilege to send signals to both PRS0 and PRS1 slots. Stations can send signals to PR0 with CA2 and to PRS1 with CA1 data, while station with CA0 data cannot send to any of these slots. Upon receiving the signal from contending stations, PRSs inform all the stations of their priority. If a station has low priority, it defers to others that have high priority. Once a station wins the priority, it starts its random backoff procedure as in Figure 2-3 [11].
Table 2-1. Priority function of BPC in terms of CW and DC.

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<th>Priorities Class CA1, CA0</th>
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<tr>
<td>BPC=0  DC=0  CW(W₀) =8</td>
<td>DC=0  CW(W₀) =8</td>
</tr>
<tr>
<td>BPC=1  DC=1  CW(W₁) =16</td>
<td>DC=1  CW(W₁) =16</td>
</tr>
<tr>
<td>BPC=2  DC=3  CW(W₂) =16</td>
<td>DC=3  CW(W₂) =32</td>
</tr>
<tr>
<td>BPC&gt;2  DC=15 CW(W₃) =32</td>
<td>DC=15 CW(W₃) =64</td>
</tr>
</tbody>
</table>

**Backoff mechanism**

The backoff mechanism of Home Plug introduces two more counters in addition to backoff counter (BC) that is introduced in IEEE 802.11 [2]. These are deferral counter (DC) and backoff procedure counter (BPC). DC and BPC enable the Home Plug to roughly estimate the number of contending station. After a station wins the channel, it first sets BPC to zero and chooses a BC value randomly between zero and CW where CW denotes initial contention window size. Then the value of DC is set to a value in Table 2-1 depending on BPC. If a station senses the channel idle, BC value decreases by one and once it reaches to zero, it starts the transmission while DC and BPC remains fixed. If the channel is sensed busy, DC and BC are decreased by 1. If DC goes to negative value before BC reaches to zero, BPC increments by 1 and reinitializes DC and BC according to Table 2-1. The same process is repeated when a collision occurs. DC is the new concept that has been introduced by Home Plug MAC and this mechanism apparently reduces the probability of collision by increasing the CW size even before a collision, so the collision probability is reduced by operating in higher contention window size. According to the Home Plug MAC, even if backoff procedure
restart after DC and BC reaches the maximum value, both DC and CW sizes remain
same until a successful transmission occurs [11].

Simulation and Results

According to random backoff algorithm of Home Plug 1.0 protocol, an
experimental performance analysis was conducted under following assumptions: there
are numbers of stations those are always contending the medium with a ready data
frame even after a successful transmission; all stations have data frames with the same
priority; channel has an ideal condition and collision can only be detected when at least
two or more station whose backoff counter reach to zero simultaneously and so they
send their packet. With these assumptions, the Home Plug 1.0 protocol was simulated
for a PLC network.

As can be seen from Figure 2-4, the MAC efficiency severely falls when number
of station rises since the collision probability increases. Also, Figure 2-5 shows a
comparative analysis between Home Plug 1.0 and IEEE 802.11 in terms of MAC
efficiency. As a consequence, Home Plug 1.0 gives better performance under same
conditions. However, for a constant number of stations, MAC efficiency of the low
priority class is better than that of the high priority class because the CW size of the low
priority class is larger than the other class of priority.
Figure 2-4. The MAC efficiency plot of Home Plug 1.0 protocol.

Figure 2-5. Performance comparison between original Home Plug 1.0 and IEEE 802.11 protocol.
CHAPTER 3
SURVEY ON CSMA/CA MAC PROTOCOLS FOR BACKOFF ALGORITHMS

Exponential Increase Exponential Decrease (EIED) and Linear Decrease (EILD) Backoff

Song et al. addressed the performance degradation of a heavily loaded network where the probability of collision is increased as after every successful transmission the backoff period is reduced aggressively [12]. To overcome this issue, Song et al. enhanced IEEE 802.11 DCF with Exponential Increase Exponential Decrease (EIED) and Linear Decrease (EILD) backoff algorithm. In EIED, whenever there is a collision, i.e. when the transmitter does not get any ACK back from the receiver, the contention window (CW) is increased exponentially by a backoff factor of $r_I$. After each successful transmission of a packet, the backoff counter decreases exponentially with a factor of $r_D$. EIED algorithm works as follows:

\[
\text{Successful Transmission} : CW = \frac{CW_{old}}{r_D} \\
\text{Failed Transmission} : CW = CW_{old} \times r_I
\]

where $(r_D, r_I > 1)$

In a transmission failure case, the EILD backoff procedure is identical to EIED. However, it linearly decreases the backoff counter by a factor of $r_D$ after successful transmission:

\[
\text{Successful Transmission} : CW = CW_{old} - r_D \\
\text{Failed Transmission} : CW = CW_{old} \times r_I
\]

The EIED and EILD set the value of CW based on their own observations without considering the overall scenario of the network. Although these algorithms result in a
good correlation between network load and transmissions, these methods are not sufficient for precision tuning of the backoff parameters.

**The Pause Count Backoff (PCB) Algorithm**

By monitoring the network traffic load, the PCB tunes a suitable CW to meet with the requirements of uninterrupted traffic flow in the network [13]. The PCB utilizes the notion of paused idle slots to estimate the number of wireless stations present in the network. In the IEEE 802.11 DCF, when a node is in backoff stage and senses the medium busy, it pauses the counter and waits until the channel is free. Each pause indicates that several nodes are using the wireless medium and observing these pauses can aid developing an overall sense of the network status. At first, the proposed PCB approach estimates the number of active competing terminals in the network based on the pause counts during the countdown procedure. In the second step, upon each successful transmission, CW is tuned to average pause count value multiplied with $\beta$ which is inversely proportional to the collision probability.

The PCB approach gives satisfactory throughput and fairness index, but its methodology does not extend in the highly congested case where the necessity of RTS/CTS is inevitable.

**Dynamic Tuning of IEEE 802.11 Protocol**

Cali *et al.* proposed a novel approach to modify the existing MAC protocol of Wi-Fi by deriving the average size of the contention window which aims at maximizing the throughput, thus establishing a theoretical throughput limit [14]. They also show that under congested network configuration the existing standard cannot achieve this theoretical throughput limit. To that extent, the authors propose a distributed algorithm that enables each station to tune its backoff algorithm at run time which can drive the
802.11 protocol close to theoretical capacity. In the standard protocol the tuning of the backoff window size is obtained at the cost of collisions. This means that in overload conditions a station tends to experience a large number of collisions before its window has a size which gives a low collision probability. This is the main reason why the capacity of the standard protocol is often far from the theoretical limit. In this paper, an analytical model named 'p-persistent IEEE 802.11' protocol has been developed which differs from the standard protocol in the selection of backoff interval. The p-persistent IEEE 802.11 is a memoryless backoff algorithm which samples the backoff interval from a geometric distribution with parameter p. Simulation results show that it is possible to tune, by observing the network status, the backoff window size at run time to obtain a capacity very close to the theoretical limit.

This distributed algorithm can be exploited in IEEE 802.11 networks for a particular congestion level to select the optimum size of the contention window without paying the collision cost. The authors propose the solution in two steps:

- **Step 1:** The standard IEEE 802.11 exponential backoff algorithm is employed to figure out the slot in which a given transmission would be triggered.

- **Step 2:** Immediately after first step, the proposed dynamic contention window size is applied to determine if it is appropriate to use the identified slot or is it better to discard the transmission.

In light and medium traffic conditions, the window size according to IEEE 802.11 guarantees lower congestion, in which case the standard backoff algorithm is adopted. However, when increasing number of stations contend for the channel, a contention window with optimal size is tuned (using the proposed algorithm) without paying any collision costs by deferring the transmissions. The results in the paper was obtained.
under the assumptions that the value of $M$ (Number of stations) is known a priori and there are no hidden terminals.

As a result, there are some negative consequences while applying the distributed algorithm. When there are hidden stations in the network the following events may take place: missed ACK, carrier sensing fault and undetected transmission. The occurrence of these events make this algorithm unreliable in presence of hidden stations.

**Adaptive Contention Window Backoff (ACWB) with Cross Layer Optimization**

A cross layer optimization based backoff algorithm for IEEE 802.11 DCF named ACWB (Adaptive Contention window backoff) is proposed by Wang and Yuan which dynamically tunes the contention windows size by estimating the number of active stations residing in the network [15]. In accordance with the information interaction between transport and MAC layer, ACWB improves the performance of MAC access on TCP congestion control and evades hidden terminal issues in WLAN. Unlike existing 802.11 BEB algorithm, this protocol initiates its mechanism with the calculation of contention window ($CW_{optimal}$) by estimating the active number of stations. A new term named Reserved Window ($RW$) is defined where $RW < CW_{optimal}$. The backoff procedure in ACWB works as follows:

$$\text{Backoff time} = \begin{cases} \text{Random}(RW, CW_{optimal}), & r_{time} \leq N \\ \text{Random}(0, RW), & r_{time} \leq N + 1.3 \end{cases}$$

Where $r_{time}$ is the number of times a frame has been retransmitted and $N$ is the minimum number of retransmission. When the network traffic is light, the reserved window is kept relatively small. However, the window size is increased when the network load is heavy so that the TCP ACK loss caused by hidden stations can be prevented:
Adaptive Reserved Window RW = \[
\begin{cases}
\left\lfloor \frac{CW_{\text{optimal}}}{2} \right\rfloor, \\
RW - 1, \\
\mu \times RW,
\end{cases}
\]

\text{Initial Tune after successful transmission}

\text{Initial Tune after failed transmission}

(\mu = \text{growth factor})

Although ACWB takes into consideration the effect of hidden terminals, it doesn’t specify how this protocol will accommodate with RTS/CTS mechanism. In addition, this paper doesn’t address the TCP congestion control for wireless networks which is a severe issue for throughput degradation.

**Adaptive Optimization based on Bayesian Estimation of Competing Terminals**

In [16], Toledo \textit{et al.} proposed a modified version of IEEE 802.11 DCF which utilizes the adaptive Bayesian estimator of the number of contending nodes developed by the authors of [17]. For filtering purpose in the non-Gaussian and non-linear system, an effective procedure named Sequential Monte Carlo (SMC) has been employed. In [17], several SMC-based adaptive estimators for the number of contending stations are developed which outperforms the well-known Extended Kalman Filter (EKF) based estimator. The authors proposed a modification of the IEEE 802.11 DCF by accommodating the contention window size according to the number of contenders present in the network. The authors examined the applicability of the algorithm in a distributed network by showing a sub game perfect Nash equivalent strategy which prevents the rogue contenders to take advantage from changing their parameters.

The accuracy of the Bayesian algorithm applied in the protocol is particularly beneficial when the competing nodes fluctuates heavily in small time scales, which makes this proposal attractive for optimization.
According to the simulation result, the SMC based estimation algorithm is accurate yet computationally simple, making it a good candidate for 802.11 network. However, this algorithm only works for the basic access mechanism, there is no mention how this estimation methodology will adopt in case of virtual carrier sensing (RTS/CTS).

**Fast Collision Resolution (FCR)**

In [18], Kwon *et al.* propose a novel contention based MAC protocol for WLAN named Fast Collision Resolution (FCR) algorithm. The key concept is to speed up the collision resolution by redistributing the backoff timers for all active stations. Furthermore, with successful packet transmission each station is assigned a smaller contention window to eradicate excessive number of idle time slots. When the stations detect consecutive numbers of idle time slots, the backoff timer is decreased exponentially fast to reduce unnecessary delay. The paper also introduces the idea of fairly scheduled FCR (FS-FCR) algorithm which ensures a high degree of fairness simultaneously achieving high throughput. The paper addresses issue of reducing the overheads (such as packet collisions and idle backoff slots) in each contention cycle to increase the throughput performance of a distributed contention-based MAC protocol. The major two factors affecting the throughput of standard IEEE 802.11 are transmission failures and the idle slots due to backoff at each contention period. Using the analytical throughput model of IEEE 802.11 and introducing the concept of absolute transmission probability, the authors summarize the operational characteristics of the proposed MAC protocol as following:

- Small random backoff timer for the station which has successfully transmitted a packet at current contention cycle.
- Large random backoff timer for stations that are deferring their packet transmissions at current contention period.

- Fast change of backoff timer for a station according to its current state: transmitting or deferring.

In short, FCR algorithm differs from the standard IEEE 802.11 MAC as follows:

1. Smaller initial (minimum) contention window size (minCW) than IEEE 802.11 MAC;
2. Larger Maximum contention window size (maxCW) than IEEE 802.11 MAC;
3. Increased contention window size while a station is in collision or deferring state;
4. Reduced overhead by exponentially decreasing the backoff counter when a prefixed number of idle slots are detected.

The authors address the issue of fairness in IEEE 802.11 MAC which inhibits unfair characteristics. FCR can degrade the fairness even more as it provides better opportunity for the successfully transmitting nodes by expanding the contention window of the deferring stations. To that extent, the authors merge the self-clocked fair queuing (SCFQ) algorithm with FCR to ensure fairness and name it fairly scheduled FCR (FS-FCR). The FS-FCR algorithm uses the same operations of the FCR algorithm, except that, if a station reaches its maximum successive transmission limit in its packet transmission period, the station will set its contention window size to the maximum value of maxCW. This will give other stations higher probabilities to transmit their packets at next contention period. Although FCR provides higher throughput and fairness among the serving stations, this introduces service tag at the queue of each station for each packet which adds computational complexity and additional overheads.
Traffic Adaptive Backoff (TAB) Protocol

In [19], Wang and Song proposed the Traffic Adaptive Backoff (TAB) protocol that improves the MAC efficiency of IEEE 802.11b DCF protocol. The legacy DCF protocol can detect the collision but it is not able to sense the severity. The TAB protocol examine the surrounding traffic load by using Network Allocate Vector Counter (NAVC) that is generated from NAV information of RTS, CTS packets in which required time duration and message length information for transmission are carried. NAVC is used to approximate the traffic density and set the max and min CW size as following:

\[
f(\text{NAVC}, \text{CW}) = \begin{cases} 
\text{CWmin} & \text{NAVC} \leq \text{NAVC}_{\text{min}} \\
\min\{\text{CWmax}, \max\{\text{CWmin}, 2\text{CW} \cdot \text{NAVC}\}\} & \text{otherwise}
\end{cases}
\]

If the traffic load is light, in the case of collision, CW size increases less than exponential increment. These protocol also provide fairness since the NAVC is updated according to the RTS packets. As a result, this protocol decrease packet drop rate and provides better latency performance with increasing traffic load.

Semi-Random Backoff (SRB)

In [20], Yong et al. proposed a new algorithm to increase the efficiency of IEEE 802.11 CSMA/CA MAC protocol by enabling slot reservation in contention based MAC protocols. Both of these reservation based and contention based mechanism are combined into Semi-Random Backoff (SRB) MAC protocol. In TDMA networks, a central coordinator assigns slots to the station by using a particular reservation frame. According to the reservation ALOHA (R-ALOHA), if a station uses a time slot successfully then the same time slot can be reserved automatically by the same station. To that extend, reservation based mechanism can be adopted into the IEEE 802.11 DCF mechanism with some modification. Basically, the operation in SRB protocol can
be illustrated by explaining a series of transmission cycle. In the first cycle, Station A and B contend to the medium by setting backoff counter randomly between [0, CWmin]. If any collision occurs, both station double their backoff counter and transmit again in the second cycle. These algorithm is same with legacy DCF thus far but after a successful transmission stations set their backoff values to a common deterministic value that is (CW_{min}+12) rather than a random value between [0, CWmin]. Afterwards, station A and B lock onto the slots in a manner like in reservation-ALOHA and the subsequent cycles follow the same process. In this algorithm there are two problems. First, protocol is not efficient under light traffic load since the reserved slots might be idle for the next cycle due to the failed slot reservation. Second problem is that performance gain can be drastically reduced if the contending number of stations exceed the fixed service ring.

**Delayed Contention (DC) DCF MAC**

Kuo and Lu proposed a new MAC protocol to address the unfairness issue on the IEEE 802.11 Binary Exponential Backoff (BEB) algorithm [21]. The reason for unfairness in BEB is because of doubling the contention window size in the backoff counter after every collision. A collision means collided packets need to wait a longer time which increases the average delay and quality of service. DC-DCF protocol works based on decreasing the number of contending station by suspending stations at their first attempt. If a station attempts to transmit a frame in first its first time, it is delayed for a backoff cycle so the previous collided frame will have a chance to transmit before the next frame. This algorithm not only provides fairness but also gives an opportunity to regulate the traffic because all the new stations were postponed initially. DC-DCF sets the backoff counter as follows:
\[
    \text{Backoff} = \begin{cases} 
    C + \text{random}(W), & \text{for first transmission attempt} \\
    \text{random}(W), & \text{for retransmission}
\end{cases}
\]

One advantage of DC-DCF protocol is its easy implementation on legacy DCF algorithm only by applying the new backoff modification above. \(C\) is a constant, it denotes how many new station attempts their first transmission and \(W\) is the contention window.

**Contention Window and Run Time Optimization for IEEE 802.11 DCF**

In [22] Deng et al. prove that the current collision avoidance mechanism in IEEE 802.11 is far from optimal, particularly when the number of users is high or in an error prone environment. The proposed algorithm allows a station to dynamically adjust its contention window size based on turn-around-time measurement of channel status. Distributed adaptive contention window scheme, which include run time estimation of channel status, estimating the number of active stations, optimizing the contention window, using a block code for error correction and priority Enforcement Mechanism is being proposed.

In [23], the authors proposed and evaluated a distributed mechanism, named Asymptotically Optimal Backoff (AOB), for improving the efficiency of the IEEE 802.11 standard protocol. The AOB mechanism dynamically adapts the contention window size to the current network contention level and guarantees that a network asymptotically achieves its optimal channel capacity. The algorithms proposed follows the same direction but in different approach as it is based on an estimation of number of active stations in the system and uses a very simple feedback signal. In addition to the theoretical analysis, the authors carried out comprehensive simulations implemented by network simulator (ns-2) to evaluate the performance of the proposed scheme. The
scheme proposed can easily be implemented in IEEE 802.11 networks with minor changes. The results showed that the proposed scheme works satisfactorily in most cases, offering a remarkable performance improvement in a noisy wireless environment but did not simulate the performance of the proposed algorithms in congested environment.

**Batch and Sequential Bayesian Estimator Approach**

In [24], Vercauteren *et al.* used Bayesian Signal Processing algorithms to improve the performance of 802.11 by estimating the number of competing terminals. The performance of the IEEE 802.11 protocol based on the distributed coordination function (DCF) has been shown to be dependent on the number of competing terminals and the backoff parameters. The estimation is based on the observed use of the channel and the number of competing terminals is modeled as a Markov chain with unknown transition matrix. The off-line estimator makes use of the Gibbs sampler whereas the first online estimator is based on the sequential Monte Carlo (SMC) technique. The unique advantage of the online estimators is that it can be applied to any hidden Markov chain with unknown transition probabilities and unknown distributions. Such characteristics makes it suitable for the 802.11 protocol. Simulation network simulator (ns-2) achieved better performance compared to other estimators for both artificial hidden Markov and real system based on 802.11 simulations.

Furthermore the approximate maximum a-posteriori (MAP algorithms) proposal offers a similar performance with considerably less computational requirement (lower power consumption), making it the preferred candidate for an actual implementation of the estimator on an IEEE 802.11 card. For the noisy realistic 802.11 data, the proposed Bayesian estimators offer superior performance but simulations should have also been
performed on the performance of the Bayesian estimators on a congested IEEE 802.11 environment.

**Fragmentation Mechanism**

In [25], Xi *et al.* examined the impact of channel errors and collisions on the performance of IEEE 802.11 fragmentation, and found that optimal fragment size depends on both channel condition and network size. The authors proposed an improved contention-free fragmentation burst (CFF) scheme, by which the source immediately retransmits the failed fragment without backoff procedure except for the first one. Finally, a channel adaptive fragmentation (ADF) scheme based on CFF was proposed to combat both channel errors and collisions. ADF can distinguish frame transmission failure caused by collision channel error in moderate noisy channel. The process of subdividing a MAC service data unit (MSDU) into smaller MAC level frames, MAC protocol data units (MPDUs), is called fragmentation. In IEEE 802.11 networks, an MSDU is normally fragmented into equal-sized MPDUs except for the last one before the transmission attempt. These MPDUs are put into the buffer at the transceiver. All the fragments are sent independently, each of which is separately acknowledged.

Based on CFF, the proposed channel adaptive fragmentation (ADF) scheme, which considers both channel error and collision, has the ability to adapt the fragment size to time-varying channel quickly. Moreover, ADF can distinguish frame failure caused by collision from that caused by channel error. ADF also acts as virtual RTS/CTS, therefore, it is effective under the situations where RTS/CTS is not suitable that is when high data rate is used. The proposals were simulated on GloMoSim simulator. The simulation results of legacy IEEE 802.11 fragmentation (LF) and non-
fragmentation transmission with different BER and number of sending nodes were also compared.

**QoS-enabled MAC Architecture for Prioritized Service**

The MAC modification in this IEEE 802.11 WLAN provides different delays and efficiencies dependent on the prioritization of a service [26]. Due to bandwidth limitation in the wireless environment, to achieve improved QoS, higher channel access priority is given to traffic more sensitive to delays. The DCF mode known for its efficient medium sharing capability and ease of implementation is modified to support the differentiated service while maintaining the backward compatibility. Collision is circumvented by choosing a backoff time (BT) from zero to a contention window size (CW) i.e. (0, CW) such that in case of collision, a new contention window size is selected based on the backoff increasing factor and a new backoff time is chosen. Hence, improved QoS may be achieved for higher priority traffic by allocating the right CWs, backoff increasing factor and frame length and also defining diverse inter frame space and backoff time distribution function with respect to traffic priority. Since different situations may arise based on the channel utilization, it was concluded that the best way to achieve QoS guarantees in the WLAN is by dynamically altering the adaptors setting. However, selecting the right parameters based on the channel characteristics or traffic priority is intricate.

**Opportunistic Multi-Radio MAC (OMMAC)**

To greatly improve the wireless network efficiency through increased usage of the spectrum, an opportunistic Multi-Radio MAC (OMMAC) which takes advantage of multi-radio diversity was introduced in [27]. Due to increased availability of multi-radio products with dynamic channel switching capabilities, the implementation of a higher
efficient and reliable wireless network intelligently utilizing the multiple channels and radios has become of great importance. The proposed OMMAC integrates medium access control, packet scheduling and rate adaptation to improve performance by utilizing the physical layer feedback from various sources. Optimum data rates may be achieved on different transmission links on the same channel as a result of disparate channel fading statistics, levels of interference and user geographic differences. OMMAC seeks to choose the best transmission pair for each channel instead of selecting the best transmission channel as employed in the per packet basis. To take advantage of the multi-radio diversity, this system applies multicast RTS, virtual multi-CTS and channel-based packet scheduling to gain knowledge of the channel condition over a number of candidate transmission links. This enables the measuring of various channels at the same time and reporting back on the gathered quality information at one time.

In comparison to other opportunistic transmission methods, OMMAC exploits multi-radio diversity to greatly improve the throughput as proven by NS2 simulations. A shortfall to this strategy is that, when a link is reported to be optimum for transmission, all transmitting nodes may attempt utilizing this link creating congestion and greatly reducing its optimality.

**Adaptive Backoff Scheme based on Binary Exponential Backoff Algorithm**

In [28] an adaptive minimum contention window binary exponential backoff algorithm (AWBEB) is introduced to enhance the performance of the IEEE 802.11 Distributed Coordination Function (DCF) scheme. To achieve this, a bi-dimensional discrete-time Markov Chain is modeled and a node’s transmission and stationary distribution probabilities are derived from the AWBEB algorithm. It is established that
the AWBEB algorithm quickly approaches the theoretical limit and throughputs of the system are higher than the DCF algorithm. In the IEEE 802.11 standard for wireless LANs, there are two main access schemes including the Distributed coordination function (DCF) for contention based, asynchronous, distributed accesses to a channel and Point Coordination Function (PCF) for centralized, contention free accesses. In the case of the DCF, binary exponential backoff algorithm is used in resolution of packet collisions on the medium by ensuring an idle medium before transmission is attempted. A backoff counter less than a chosen contention window is randomly selected based on uniform distribution and decreased by one for each time slot the medium is sensed to be free otherwise waits till the on-going transmission ends, only transmitting when the counter gets to zero. The contention window is doubled and the process restarted whenever there is a collision while transmitting with the station setting its contention window as minimum.

By increasing the contention window, the likelihood of two or more stations transmitting at the same time is reduced though more backoff overhead is introduced. It is observed that DCF becomes inefficient with increasing transmitting nodes. To help alleviate this situation, the AWBEB algorithm is proposed.

**Conditioned Enhanced Distributed Coordination Function (CEDCF)**

In [29], an Enhanced Distribution Coordination Function (EDCF) scheme is proposed for adjust the contention window (CW) size. In this case the CW is reset with an assumption that there is a drop in the contention level upon successful transmission which may result in new collisions and retransmissions as the contention level is likely to slowly alter. In the other scenario where the CW size is retained, high backoff values may be experienced leading to increased delays while the contention level may have
dropped. To achieve a trade-off, an intermediate CW decrease function is considered such that the channel state is monitored and the size of the CW is adjusted accordingly. This scheme is known as the Condition Enhanced Distribution Coordination Function (CEDCF). It is proven that the CEDCF scheme provides higher throughput in comparison to the EDCF and AEDCF algorithms. The standard provides a per-class adjustable CW based on the wireless network varying conditions by making comparisons of the collision rate to an optimized threshold hence allowing the station to take a decision on the rate of decrease. By this, end to end delay is decreased while a high level of channel utilization is maintained.

The CEDCF scheme is very effective in networks with changing traffic load in that, AEDCF is adapted when the network is overloaded and the CW is reset and EDCF used when the network restores to its normal state. Through this, during network congestion, CEDCF favors high priority flows and serves all traffic classes when the network restores to an uncongested state. This process is however complicated since determining the state of the medium for selection of which scheme to adapt is very difficult as the channel condition is unpredictable due to how randomized it is.

**Enhanced Collision Resolution for Distributed Coordination Function Protocol**

From the specified standard IEEE 802.11 DCF protocol, [30] introduces an enhanced collision resolution mechanism GDCF. A node begins transmitting when the medium is observed to be free for duration greater than the distributed inter frame space (DIFS). Should the medium be sensed to be busy, transmission is deferred until the detection of DIFS then a random backoff timer is generated before transmission. The backoff timer decreases when the channel is free (idle) and pauses otherwise. When the backoff timer reaches zero the node initiates transmission. Backoff of is
randomly uniformly selected from a contention window. With each failed transmission, the contention window is doubled. The GDCF scheme reduces the contention window size by half after each successful transmission as opposed to the standardized DCF which decreases the contention window to its initial value. The probability of collisions is significantly lowered with the gentle reduction of the contention window when there is a large number of competing nodes. It is also observed that GDCF aside drastically improving the MAC performance is also very flexible in supporting priority access. To achieve this, different values are chosen for different types of traffic. The problem with this method is that, when the contention for the medium reduces sharply, the contention window is found to remain large therefore the backoff timer is likely to be large and hence takes a longer time for the node to transmit though the medium may be free.
CHAPTER 4
CONSTANT CONTENTION WINDOW BASED CSMA/CA MAC PROTOCOL

Introduction

Although the standard Home Plug 1.0 MAC protocol is a sufficient medium access control technique for small networks, in networks with large number of nodes, the MAC efficiency is significantly reduced because of the collision overheads. To enhance the MAC efficiency even in large network, a new modification named Constant Contention Window based MAC has been proposed which finds the optimal contention window size based on the proceedings. As a difference from the standard Home Plug 1.0 protocol, the backoff procedure counter (BPC) value is kept constant for all situations. Therefore, instead of changing the CW value after every successful transmission, collision or DC value drops under zero, CW value is kept constant and the backoff counter is determined correspondingly. Also, the DC value, called as $\lambda$, is kept constant and reset to the same value after every successful or collision period [11].

System Model

A discrete time, homogenous, bi-dimensional Markov chain model in Figure 4-1, is used to model a single node in a network has n nodes. According to this model each state involves the current values of deferral counter (DC) and backoff counter (BC) for the actual nodes. Since the Markov Chain is described in the discrete time, the beginning of the each slots show the state of the system. Time which is spent during at the collision or successful transmission can be embedded into the time of Markov Chain since every collision and successful transmission attempt start at the beginning of a slot.
The probability that the node begin transmission is $p_0$, and relates to the probability that the backoff counter reaches to zero. Therefore, it can be defined sum of all states where backoff counter is zero.

$$p_0 = \sum_{i=0}^{\lambda} \Pi(i, 0)$$  \hspace{1cm} (4-1)

Similarly, the probability that the node sense the medium idle is $p_i$ and also serves as the probability of state transition between a node and the adjacent node which is one less in backoff counter value and same deferral counter value can be related with $p_0$ as follows:

$$p_i = (1 - p_0)^{i-1}$$  \hspace{1cm} (4-2)

The transition probability to a top row states is $1/W$ and this probability related to the random backoff timing. Also, for a nodes in which deferral counter is zero but backoff is nonzero, the transition probability to top row states is $(1-p)/W$. 
By solving Eq. 4-1 and Eq. 4-2, a relation between \( n \), \( W \) and \( \lambda \) can be established. Therefore, determining the value of \( p_0 \), will lead to find the optimal contention window size. For solving \( p_0 \), two different approach have been proposed.

First solution, in [11], defines the \( p_0 \) by using Markov chain model as an approximated solution. According to this definition, \( p_0 \) value is equal to the ratio of the states in which backoff counter is zero to the total number of states. However, the transmission probability \( p_0 \) was used as an approximation. On the contrary, the exactness of the Eq. 4-6 has been proved in this thesis as one of the contribution. Therefore, the same definition was used with the following analytical solution.

J. Lee et al. only provides an approximated solution for \( p_0 \). Unlike this approach, in this thesis we derived the exact solution by following definition of transmission probability. From the Markov chain model, the number of the states in which backoff counter has already reached zero is counted as \((\lambda+1)\). Also, the total number of the states can be calculated through the following arithmetic:

\[
Total \# \text{ of states} = w + (w - 1) + \cdots + (w - \lambda) = w(\lambda + 1) - \sum_{i=0}^{\lambda} \lambda i \quad (4-3)
\]

and the summation part of the Eq. 4-3 can be solved as:

\[
where \sum_{i=0}^{\lambda} \lambda i = \frac{\lambda(\lambda + 1)}{2} \quad (4-4)
\]

By substituting Eq. (4-3) into Eq. (4-4), Eq. 4-3 is simplified as below.

\[
Total \# \text{ of states} = W(\lambda + 1) - \frac{\lambda(\lambda + 1)}{2} = (2W - \lambda)(\lambda + 1)/2 \quad (4-5)
\]

As a consequence, by using Eq. 4-5 results in Eq. 4-6 and this proves the exactness of the Eq. 4-6.
\[
p_0 = \frac{\lambda + 1}{(2W - \lambda)(\lambda + 1)}
\]

(4-6)

\[
p_0 = \frac{2}{2W - \lambda}
\]

Furthermore, an analytical solution has been done to find the transmission probability for the given number of nodes in [32]. The analysis of exact solution is done by determining the state probability of every single states. Subsequently, by using the Eq. 4-1 that defines the sum of the states which were tracked during a successful transmission, the probability of transmission can be obtained. By tracking a calculation, the exact solution for defining \( p_0 \) can be concluded as in Eq. 4-7

\[
W - (1 - p)^{\lambda + 1} \sum_{i=0}^{\lambda - 1} (W - \lambda - i - 1) \binom{\lambda + 1}{i} p^i \\
= \sum_{i=0}^{\lambda} (1 - p)^{\lambda - i} \sum_{j=0}^{W - \lambda - 1 + i} (W - \lambda + i - j) \binom{\lambda - i + j}{i} p^j
\]

(4-7)

The Eq. 4-7 provides an analytical relationship between \( n, \lambda, W \) and \( p \), but Eq. 4-7 is dependent on number of user. The main contribution of this solution is to obtain the exact definition to solve \( p \) and using Eq. 4-2 to obtain \( p_0 \). This solution is dependent on \( n \), unlike the first solution. The difference between two solutions can be distinguished by comparing their \( p_0 \) output for a predetermined \( W \) and \( \lambda \) value and respect to the number of user. Figure 4-2 shows the variation of \( p_0 \) respect to increasing number of user for both solutions. Apparently, the approximation solution can approach to the exact solution solely for large \( n \). Notice that magnitude of error for small \( n \) is quite severe. However, the error between these two solution changes when \( W \) and \( \lambda \) changes as well.
Figure 4-2. Comparison for finding $p_o$ with different methods.

**Contention Window Optimization**

All parameters should be optimized to maximize the MAC efficiency, as was performed in [11]. MAC efficiency can be defined with these parameters. $P_s$ is the probability of successful transmission, $P_i$ is the probability of idle passage and $P_c$ is the collision probability. These three probabilities can be written in terms of $p_o$ as in Eq 4-8.

\[
P_s = np_o(1 - p_o)^{n-1}
\]
\[
P_i = (1 - p_o)^n
\]
\[
P_c = 1 - P_s - P_i
\]

(4-8)

The MAC efficiency can be defined as the ratio of a successful frame transmission time to the total time passed through a frame transmission.

\[
\eta = \frac{P_s T_{data}}{P_s T_s + P_i T_i + P_c T_c}
\]

(4-9)
where $T_I$ is time for idle passage, $T_S$ is time for a successful transmission and $T_C$ is time for collision. The MAC efficiency can be optimized in $p_o$ for predetermined $n$ as follows:

$$T_I \left( P_S \frac{dP_I}{dp_0} - P_I \frac{dP_S}{dp_0} \right) + T_C \left( P_S \frac{dP_C}{dp_0} - P_C \frac{dP_S}{dp_0} \right) = 0$$

$$1 - \frac{T_C}{T_I} = \frac{1 - n p_{o, opt}}{(1 - p_{o, opt})^{n-1}}$$

(4-10)

The corresponding value of $p_{o, opt}$ for given $n$ and the value of $W$ and $\lambda$ which best satisfy the Eq. 4-7 are the optimal parameters in the sense of MAC efficiency.

**Simulation and Results**

A discrete time simulation has been done to show the optimization and performance of the modified Home Plug CSMA/CA MAC protocol and compare with the standard protocol. First of all, $T_I$ and $T_C$ values in Eq. 4-10, set to 20 and 800 μs, respectively to find the optimal transmission probability $p_{o, opt}$, as in [11]. The optimal probability was found by substituting Eq. 4-5 into Eq. 4-7 and the optimal contention window size was determined as a function of $n$ when $\lambda$ value was fixed at 3 and 15. As a conclusion, an affine relation between $W$ and $n$ with a slope that is constant for all $\lambda$ and an intercept which varies with $\lambda$ was obtained.

As a conclusion of approximated solution and optimal transmission probability the optimal contention window size based on the number of user can be expressed as follows:

$$W \approx 5n + 10 \quad \text{for } \lambda = 3$$

$$W \approx 5n + 35 \quad \text{for } \lambda = 15$$

The analytical exact solution provide more accurate relationship. To obtain the optimal parameters, a search has been done through the reasonable values of $W$ and $\lambda$. 
For a given range value of $n$, a fixed value of $\lambda$ and $W$, Eq. 4-7 was solved to find the $p$ that is close to the optimal value of $p$.

First, for comparison with the approximated solution, the relationship between $n$ and $W$ was obtained as in Figure 4-3 and Figure 4-4. For sufficiently large $n$, this relation is affine as in previous solution but it is not linear for low $n$. The linearity is directly changed according to the $\lambda$ value. For comparison, the analytical relationship is expressed as follows:

$$W \approx 4.8n + 10.8 \quad \text{for } \lambda = 3$$

$$W \approx 4.8n + 41.5 \quad \text{for } \lambda = 15$$

Figure 4-3. Optimal contention window size for $\lambda=3$. 
In Figure 4-5, the MAC efficiency enhancement of adaptively tuning the optimal contention window size for a given $n$ was showed. For comparison, standard protocol was also simulated in parallel. The MAC efficiency was calculated by using Eq. 4-9 and by putting the reasonable value of $T_S=1100\mu s$ and $T_D=1000\mu s$ from [2] into Eq. 4-9.

**Conclusion**

The Markov chain model has a recursion free solution. Thus, avoiding from approximation might result in more accurate optimization. In [11], an approximation was used to find the optimal contention window size, which can approach the analytical solution for large $n$. The analytical solution provides that for a given $\lambda$, optimal contention window size is determined as a function of $n$. 

---

Figure 4-4. Optimal contention window size for $\lambda=15$. 
The MAC efficiency drop for large number of contending stations in Home Plug 1.0 standard protocol is avoided by estimating the number of contending stations and adopting the window size accordingly.

Figure 4-5. MAC efficiency of constant CW based MAC protocol
CHAPTER 5
ADAPTIVE TUNING OF OPTIMAL CONTENTION WINDOW SIZE

Introduction

In Chapter 4, an optimal constant contention window size based CSMA/CA MAC protocol has been presented. According to the simulation results the modified MAC protocol performs better in the sense of MAC efficiency even for large number of users. However, the success of the system depends on the assumption that the number of the actual nodes is known. Therefore, number of the actual nodes in the channel should be estimated accurately. In Chapter 5, estimation strategies will be discussed.

Estimating the actual nodes in the channel can be done by following two different ways:

1. Each node can estimate the number of contending station and transmit their acknowledgement.

2. Every single node estimates the number of contending station individually and independently.
Both of these approaches will be discussed and the result of the optimal contention window MAC protocol will be analyzed based on the estimated number of the nodes.

**Estimating Number of Contending Stations**

Since the success of the constant contention window based Home Plug MAC protocol depends on the accurate estimation of actual number of contending stations, the estimation schemes should perform as much as contention window optimization scheme. Aforementioned two strategies will be investigated in terms of feasibility in power line networks.

The first approach that each nodes estimates the number of users and transmit their acknowledgement can be applied into modified MAC protocol by adding acknowledgement bits at the end of a frame that is transmitted to other nodes. By doing that a node acknowledges the other node about the channel traffic. As soon as the node receives the acknowledgement, it adjusts its contention window size accordingly and makes a new estimation to send to the other nodes.

The second strategy is more reasonable one for power line networks because of the deferral counter as already implied in Home Plug. The deferral counter built into the Home Plug to make it more robust against the hostile power line channel. The deferral counter changes when a station sees an activity on the channel. When the predetermined defer counter value decrease under zero, it resets itself to a constant value and this repeat until the backoff counter become zero. The resetting period provides a knowledge about the traffic intensity in a network. To that extend, we have used the third strategy to track the number of stations in channel to apply into the modified Home Plug MAC protocol.
Mathematical Analysis

The estimation algorithm can be constructed by using the mathematical model which is derived from Markov chain model. Since the purpose of the mathematical analysis is establishing a relationship between channel condition and number of user, the Eq. 4-2 becomes the best candidate for initial point. In [11], The Eq. 4-2 was simplified by assuming $p_0$ is very small and using binomial expansion. The new simplified version becomes as in Eq. 5-1.

$$p_i \approx 1 - (n - 1)p_o$$

(5-1)

In this thesis, we have used the original and simplified version of Eq. 4-2 in order to prove the correctness of simplification. Therefore, we have generated two different definition for $n.$ Apart from this approach, $p_i$ can be estimated by observing number of idle slots within an observation window. The first step of this scheme is determining the observation window size that was chosen the sum of current CW size and remaining backoff timer. After that, the number of idle slots ($n_i$), successful slots ($n_s$) and collision slots ($n_c$) are counted. Finally, the ratio of idle slots and successful slots to the observation window size ($n_o$) give the probability that slot is idle as in Eq 5-2.

$$p_i = (n_o + n_s)/n_o$$

(5-2)

As a consequence, we found two different solutions for estimating number of user. By putting Eq. 5-2 and Eq. 4-6 into Eq. 5-1, an definition for estimation of $n$ is obtained as in Eq. 5-3.

$$n = \frac{2W - \lambda}{2} (1 - (n_o + n_s)/n_o) = 1$$

(5-3)
Beside this approximation, an exact analysis has been performed by using the Eq. 4-2 instead of simplified one as in Eq. 5-1. Using Eq. 4-2 with Eq. 5-2 and Eq. 5-3 results in Eq. 5-4.

\[
n = \frac{\ln\left(\frac{n_1 + n_2}{n_0}\right)}{\ln\left(1 - \frac{2}{2W - \lambda}\right)} + 1 \quad (5-4)
\]

The value for observation window size should be selected adequately to have an accurate observation. Therefore, in this scheme observation window size is chosen as sum of the current contention window size and residual of backoff counter value.

To avoid the estimation error since the result of above methods is based on some assumptions, a filter should be used to obtain more precise estimation. To that extend, a linear ARMA filter was used that can smooth the result.

\[
n_{t+1} = an_t + \frac{1 - a}{q} \sum_{i=0}^{q} n_{t-i} \quad (5-5)
\]

According to this filter, if a node estimated more than \( q \) times, \((q+1)\) th estimation is averaged with the previous \( q \) estimation. In the Eq. 5-4, \( q \) represents the number of averaging factor and \( a \) is smoothing factor which is selected as a result of experimental analysis. A value of 20 for \( q \) and 0.8 for \( a \) will be applied into the simulation [11].

**Simulation and Results**

To show the accuracy performance of estimation algorithm and designed filter, both estimation models were simulated. First an artificial channel that has changing number of users within a particular time range, was established. For this experiment, the channel was observed during 50x10^4 slot times and \( n \) values ranged 10 to 100 in
this channel. The simulation was run in order to show tracking ability of both mathematical models and results were shown in Figure 5-3 and Figure 5-4.

![Image of Figure 5-3](image.png)

**Figure 5-3.** Tracking number of nodes in a variable channel with approximation solution

The Figure 5-3 shows the estimation performance of approximation solution. Notice that there is a fluctuation for estimating actual number of nodes in the channel because of the assumptions that has been made in obtaining Eq. 5-1. Since a small changes in $p_o$ results in a large variance in $p_i$, estimating the exact number of user is getting difficult with the approximation solution. Unlike this solution, following an exact solution provides better estimation performance as can be seen in Figure 5-4. Notice that, fluctuation around the exact number of users is getting narrow. Thus, using exact solutions will be a better choice in terms of estimation accuracy. However, using the exact solution adds an undesired calculation complexity. It can be seen, by comparing both Eq. 5-3 and Eq. 5-4, that using an approximation decrease the complexity of calculation. Therefore, there is a trade of choosing estimation model.
Figure 5-4. Tracking number of nodes in a variable channel with exact solution.

Figure 5-5. MAC efficiency comparison for both estimation algorithm.

Judging both models just in terms of estimation accuracy is not reasonable since the main goal is maximizing the MAC efficiency and minimizing the system necessities.
Figure 5-5 shows the MAC efficiency of modified HomePlug with different estimation algorithm. Apparently, using exact solution enhanced the MAC efficiency slightly but the MAC efficiency of approximation solution is still around 80%. From this perspective, choosing exact solution at the expense of complexity is not reasonable but at least having the exact solution proves the correctness of approximation.

![Comparative MAC Efficiency of Adaptive Tuning Contention Window Size](image)

Figure 5-6. Comparison of MAC efficiency for estimation algorithm, for actual number of nodes and the standard HomePlug 1.0.

Moreover, Figure 5-6 shows the MAC efficiency comparison for estimating number of nodes, given number of nodes and the standard HomePlug 1.0 MAC protocol. Also, Figure 5-7 displays zoomed MAC efficiency plot for approximation solutions and exact solutions in terms of estimation and determining optimal window size. To have a better vision for this plot, a smoothed version of same graph was plotted in Figure 5-8.
Figure 5-7. Zoom view of MAC efficiency comparison for exact and approximation approaches.

Figure 5-8. MAC efficiency comparison with a smoothed plot.
Conclusion

In Chapter 5, adaptive tuning for optimal contention window size based on node estimation algorithm was analyzed as a supplement of the Chapter 4 in which the window size optimization was done. Since the success of the Constant Contention window based MAC is dependent on the knowledge of number of stations in the channel, estimation scheme should provide the most accurate result. Therefore, in Chapter 5 an individual node estimation scheme has been analyzed and simulated. The results show that even though, adaptive tuning of constant window size for Home Plug MAC shows a slight variance, it provides a sufficient performance even for large number of users in power line networks.
CHAPTER 6
CONCLUSION AND FUTURE WORK

In this thesis, a high performance MAC protocol for power line communication and smart grid was investigated. Not only the standard Home Plug 1.0 and IEEE 802.11 MAC protocols but also modified versions of these protocols in terms of MAC efficiency have been analyzed comparatively. Furthermore, a modification on constant contention window based MAC, by using exact analytical solution of transmission probability, has been done to remove the assumptions. Although, both analytical and approximated solution performs pretty much same and well, number of the station in the medium is a priori of the modified MAC protocol. To overcome this issue, an estimation scheme was implemented into constant contention window based MAC which can track the number of nodes in the channel continuously and successfully.

From the perspective of heterogeneous network comprised of both HomePlug devices which can support video distribution as well as large number of HomePlug Green PHY devices supporting smart grid applications, it will be highly desirable to maximize the MAC throughput. The current HomePlug GP MAC is using a simplified version of HP AV/P1901 with CSMA/CA and priority resolution. According to this HP GP protocol, HomePlug GP devices are restricted to a 10 Mbps peak PHY rate and 250 kbps MAC layer data rate is sufficient for the current GP devices. However, 10 Mbps rate is peak value and calculated without error detection, error correction coding. In real case, PHY rate decrease down to 1 Mbps that corresponds approximately 300kbps MAC rate. With a 80% MAC throughput, 240kbps MAC rate can continue to support HomePlug GP devices but decrease in MAC efficiency will be insufficient. This efficiency rate is not possible for large network with the current protocol since the MAC
efficiency degrades significantly when the number of user increase. For example, Figure 5.6 shows the degradation in Mac efficiency for a network. While the MAC efficiency is around 80% for small number of stations in network, it decreases to 10% for 100 stations. With 10% MAC efficiency, a network can provide 30kbps MAC rate that is inadequate. Thus, enhancement in MAC efficiency will be highly desirable.

In the light of all the fact mentioned above, adaptation and implementation of the adaptive tuning of constant CW MAC protocol for heterogeneous network will comprise our future research plan.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Muharrem Ayar received his Bachelor of Science degree in electrical and electronics engineering at Kirikkale University, Turkey in 2009 and his Master of Science degree in electrical and computer engineering at University of Florida in the fall of 2013. His research focused on wireless local area networks and communication protocols for PLC and smart grid. Specifically, he is working on performance enhancement of MAC protocol for power line and smart grid communication.