

An Approach to Increase Channel Utilization in the IEEE 802.11 Networks by Improving
Fairness at the Medium Access Control Sub-Layer

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By

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Dedication

This thesis is dedicated to my parents and my sister.

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Abstract

AN APPROACH TO INCREASE CHANNEL UTILIZATION IN THE IEEE 802.11 NETWORKS BY IMPROVING FAIRNESS AT THE MEDIUM ACCESS CONTROL SUB-LAYER

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The IEEE 802.11 Standard, serves as an access mechanism for multiple stations to exchange data over the wireless medium. This standard made it possible to provide Internet-based services to untethered stations. With the undisputed success of IEEE 802.11 Standard over the contemporary short-range wireless networks, this technology is being quickly adopted by the cellphone manufacturers, for their hand-held devices. In future, this will mean, a large number of devices will be capable of transmitting over IEEE 802.11 protocol. This access method however, results in collisions when two or more stations try to transmit simultaneously. Furthermore, the probability of collision, increases with the number of stations sharing the medium. The Binary Exponential Back off (BEB) mechanism, in Carrier-Sense Multiple Access/Collision Avoidance (CSMA/CA), reduces this probability of collision to some extent. However, under saturation conditions, the behavior of BEB is somewhat unfair, which leads to degradation of average channel utilization. Also, this degradation increases linearly with the number of stations contending for the channel. A new scheme, Enhanced Binary Exponential Back off (EBEB) is proposed, which enhances the average channel utilization by improving degree of fairness for BEB at the Medium

Access Control sub-layer. EBEB scheme can blend with all flavors of the IEEE 802.11 Standard. Also, EBEB stations can coexist with the existing BEB stations. In this thesis, analytical and simulation models for both schemes are developed, followed by comparison of analytical and simulation results for both schemes.

Chapter 1: Introduction

The almost unanimous adoption of IEEE 802.11 standard demonstrates, its success compared to contemporary short-range wireless standards. IEEE 802.11 is simple yet elegant, and therefore has attracted a lot of attention recently, from the booming hand-held devices industry. With the ground set for Voice Over Internet Protocol (VOIP) and the availability of short-range high speed wireless networks (Wi-Fi), almost about everywhere, the concept of Voice Over Wi-Fi (VOWi-Fi) is catching pace. Leading hand-held manufacturers like Nokia, Motorola, Belkin, Philips, D-Link have already expressed interest in developing VoWi-Fi enabled phones, which will be coupled to a pioneer VOIP-based service, Skype. This trend indicates that a new gamut of devices will suddenly communicate using the IEEE 802.11 standard. With almost all devices getting ready to be capable of communicating over the IEEE 802.11 standard, the capabilities of this technology as we see it today, is bound to be limited, sooner or later.

The IEEE 802.11 technology serves as an access mechanism for multiple stations to exchange data over the wireless channel, in a distributed manner, which results in collisions when two or more stations try to transmit simultaneously. In the legacy IEEE 802.11, when a station is involved in a collision, it doubles its contention window (CW) by incrementing its collision count. On a successful transmission, CW snaps to its initial window size instantly, for this station. This indicates, under saturated conditions, the station under consideration has a higher probability of transmission, as it has to choose from a CW which is smaller than or equal to the one during its previous successful transmission.

If large number of stations, uniformly distributed across all levels of collision count, and most of them successfully transmitted in the previous chance, it is highly likely that

a comparable number of them, will collide during their next transmission. This happens because the CW for every station is small, and the number of stations are considerable, not allowing enough room for randomness to guarantee successful transmission. Fairness suggests that, in a cooperative environment, where all stations are equal, a station which has had a successful opportunity, should step down, so that other stations may get a chance. Random selection of waiting time however ensures some level of collision avoidance, but when there is less space for randomness, it is difficult to guarantee collision avoidance.

In this thesis an effort is made towards improving the overall channel utilization by reducing the number of collisions and hence the Probability of Collision (p) between the stations sharing wireless channel. A novel scheme, Enhanced Exponential Binary Backoff (EBEB) is introduced, which serves this purpose, by inherently introducing some level of fairness among the participating stations, at the Medium Access Control (MAC) sub-layer.

Due to the wide acceptance of the IEEE 802.11 technology, it is desired that, any new scheme should coexist with the IEEE 802.11 legacy. EBEB described here, blends with all flavors of the IEEE 802.11 technology and, is also capable of coexisting with other IEEE 802.11 siblings.

The IEEE 802.11 Standard describes Ready-To-Send/Clear-to-Send (RTS/CTS) mechanism in addition to CSMA/CA. RTS/CTS is employed to improve performance by reducing the collision duration, to solve the Hidden Terminal¹ problem to some extent and, thereby improve throughput performance. However, RTS/CTS is not a complete solution, and may decrease throughput further[1]. Also, a study described in [2] shows that the performance gain obtained from RTS/CTS is uncertain. In this thesis, the discussion has restricted to the Basic-Access Method (i.e. without RTS/CTS).

¹simply described as: Node A cannot see Node B and vice-versa but, wireless access point (AP) or the Hub can see both A and B

In Chapter 2, overview of IEEE 802.11 network family is briefed. Chapter 3 discusses the models used to describe the system and analysis for the same. In Chapter 4, software design and development for a custom simulator used, is explained. Chapter 5 compares simulation and analytical results followed by Conclusion in Chapter 6.

Chapter 2: The IEEE 802.11 Network Family

2.1 Introduction

The IEEE 802.11 has been a great success, chiefly due to the rapid evolution of existing IEEE 802.11 protocols and the ongoing enhancements, which have quickly adapted with the users' trend. Most of these enhancements, including the IEEE 802.11 a/b/g/e/n have already been launched, and are amongst the most popular choices over other short-range wireless counterparts like BlueTooth or InfraRed, for providing high-speed data transfers within a reasonably good range. Some enhancements to this standard are still being reviewed. In this Chapter, only the most popular standards will be reviewed in detail, and thereby, a background for this thesis work is put forth. Most of contents of this chapter, is adopted from IEEE Standards documents in [6] and [7].

2.2 The IEEE 802.11 and OSI model

The International Standards Organization (ISO) proposed the seven-layer Open Systems InterConnection (OSI) Model. This model is shown in Figure 2.1. The IEEE 802.11 fundamentally operates at Layer 2 (DataLink) and Layer 1 (Physical)¹, as shown in Figure. 2.2. A good reference to understand the OSI model is available at [3]. The IEEE 802.11 standard was approved in 1997, operating in 2.4GHz ISM band, which was capable of providing data rates of 1 - 2 Mbps. Thereafter, specific IEEE Task Groups have proposed enhancements to the existing standards. Since the main focus of this thesis is improving Channel Utilization, the discussion here will be restricted to the enhancements which are somehow concerned

¹With exceptions of 802.11 c/f which are enhancements for higher layers and beyond the scope of this thesis

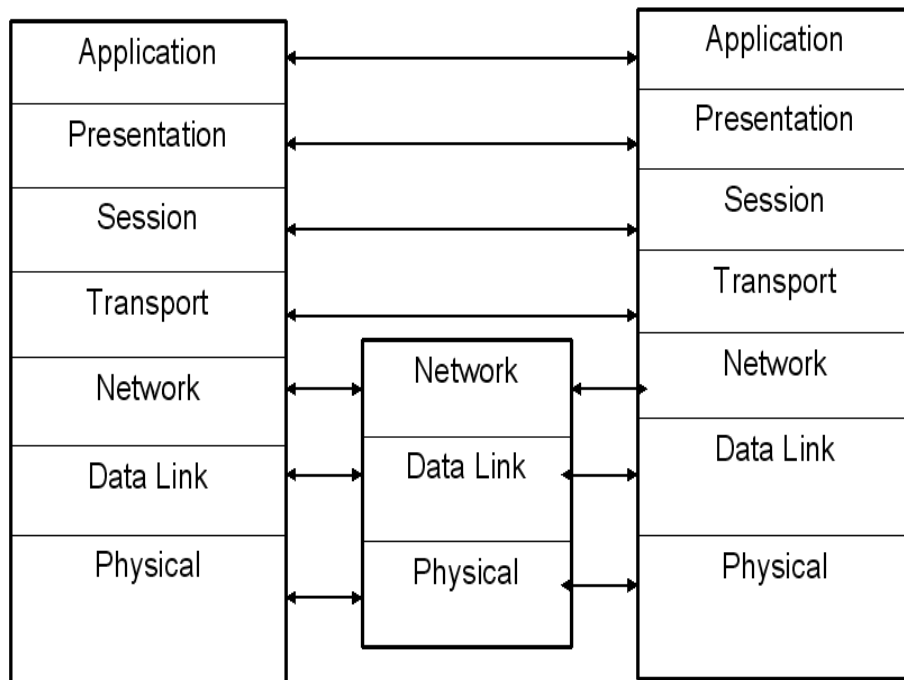


Figure 2.1: The OSI model proposed by ISO

with Channel Utilization. Each of these enhancements are discussed in the order of their release.

2.3 IEEE 802.11 Enhancements at a glance

2.3.1 The IEEE 802.11a

The IEEE 802.11a operates in 5GHz band and provides a maximum data rate of 54Mbps. The interference from other ISM-band appliances is minimum. The range is however limited, due to its inability to penetrate denser objects.

2.3.2 The IEEE 802.11b

The IEEE 802.11b was fairly popular, due to its good range capabilities and reasonably good data rate. Operates in 2.4GHz range and provides a data rate of 11Mbps. The interference from ISM-band appliances is visible.

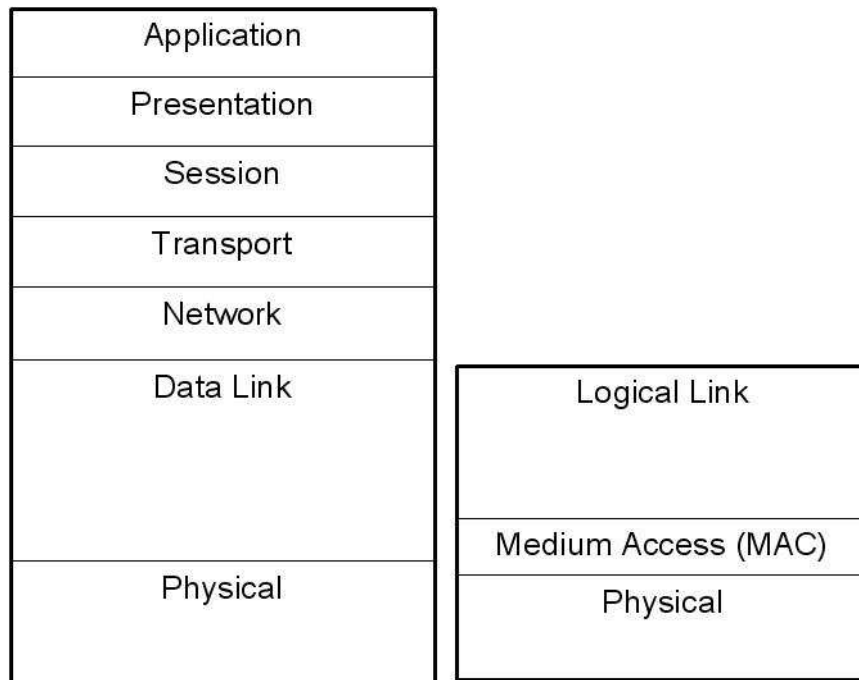


Figure 2.2: The IEEE 802.11 mapped to the OSI reference model

2.3.3 The IEEE 802.11g

The IEEE 802.11g enhancement of 802.11 technology was most embraced as it inherited the range from 802.11b and provided maximum data rate of 54Mbps as in 802.11a. Also, harmoniously coexists with 802.11b devices which were deployed earlier.

2.3.4 The IEEE 802.11e

The IEEE 802.11e is one of the most recently ratified enhancements. Its chief design goal is to improve Quality of Service(QOS) for delay-sensitive traffic like voice and video.

2.3.5 The IEEE 802.11n

IEEE 802.11n enhancement is still under review as of November 2008, and is expected to be ratified by the end of 2009. Although, the IEEE 802.11n compliant devices have started floating in the market. It is worth mentioning this standard here, as the main goal of this standard is, to push the maximum data rate barrier to 100Mbps as well increase the range.

With this prowess, it is likely to support delay-sensitive applications like Vo-WiFi for a large number of users gracefully. One of the marked improvements of this enhancement is, use of Multiple Input Multiple Output(MIMO) antennas, which improves the aggregate channel quality, by allowing coexistence of diverse sub-channels between a transmitter/receiver pair, that cancel out fading effects.

In the following part of this chapter a basic an overview of IEEE 802.11 Standards is described.

2.4 How the IEEE 802.11 Standard differs from Wired LAN?

As shown in the OSI model in Figure 2.2, IEEE 802.11 standard includes two layers: Physical Layer (PHY) and the Data Link Layer containing the MAC sub-layer.

2.4.1 Physical Layer

Fundamental differences prevail at the PHY:

- Wireless medium is less reliable than wired medium.
 - Impairments exist owing to multipath, scattering of signal due to interferers. Thus the channel is essentially time-varying with assymetric propogation properties [6].
 - Radio Frequency Interference exists in the ISM band, also used by common appliances in the vicinity (microwave etc.),capable of producing interference in IEEE 802.11 wireless channel.
- The topologies can change considerably as every wireless station is capable of roaming within the Basic Service Set (BSS), as well as across multiple BSSs, depending upon the mode of architecture supported. An extension to this argument is, every station may not be able to listen to every other station in the network, depending upon its

position in BSS. This is possible, as the range of every STA is limited by its transmitter power. This gives rise to “Hidden Terminal Problem” mentioned previously.

2.4.2 Medium Access Control Sub-Layer

The Medium Access Control (MAC) sub-layer aids multiple STAs to share the same wireless channel. The properties of PHY for IEEE 802.11 demand a difference at the Medium Access Control (MAC) sub-layer. One of the cardinal difference is the use of CSMA/CA instead of CSMA/CD. A wired LAN or Ethernet uses CSMA/CD to coordinate among distributed stations. If a collision occurs, all the stations can listen and can adapt their back off mechanism quickly. However, in a wireless medium, collision detection property is limited by the Hidden Terminal Problem. The MAC for IEEE 802.11 standard uses CA mechanism coupled to CSMA, which instead tries to prevent collision.

2.5 IEEE 802.11 Architecture

The flexible standard of IEEE 802.11 allows room for various modes of operation. A Basic Service Set (BSS) is referred to as a smallest and simplest unit of Wireless LAN. Any BSS requires at least two participating wireless stations to exist. A BSS also defines the joint coverage area of the participating stations such that, a new station entering this area is in a position to listen to other nodes. The modes of operation are discussed below:

- Independent Basic Service Set (IBSS)
- Distributed Systems and Access Points

2.5.1 Independent Basic Service Set

Figure 2.3 shows IBSS mode of operation. IBSS mode of operation can also be referred as ‘adhoc network’. BSS1 is one adhoc network with two STAs and BSS2 is another adhoc network with two STAs i.e. STA1 can listen to only STA2 and vice-versa, similarly, STA3 can listen to STA4 and vice-versa.

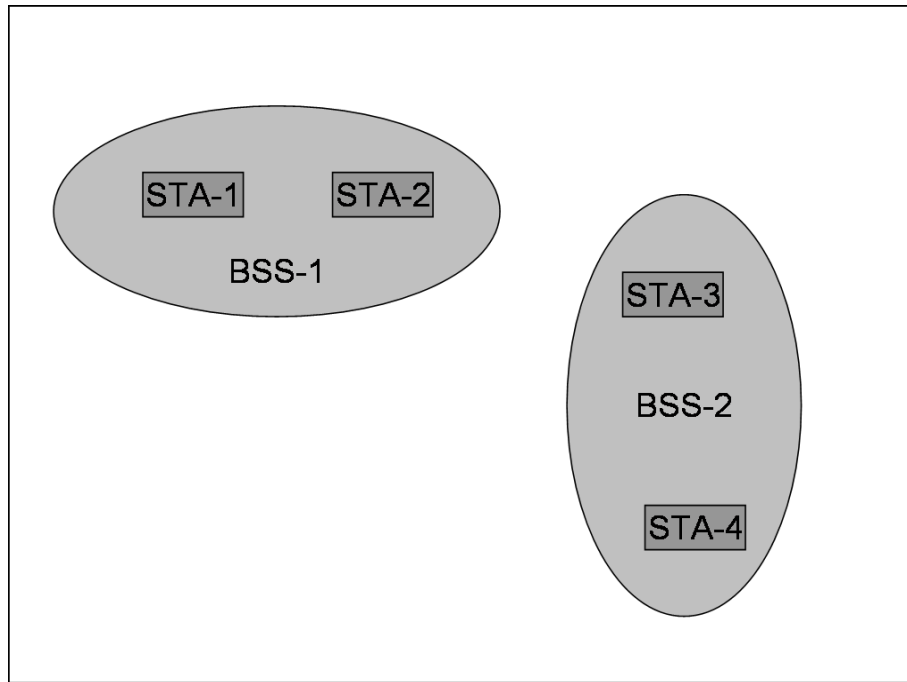


Figure 2.3: The IEEE 802.11 in IBSS mode

2.5.2 Distributed Systems and Access Points

Due to the limited range of a single BSS, attributed to the range of transmitter, it is not possible to provide coverage for a large area in IBSS mode. Hence, the IEEE 802.11 standard allows Distributed Systems and Access Points mode of operation. This mode is somehow similar to that of cellular network architecture. Every BSS contains a BSS controller, namely, AP, similar to BTS in cellular network. Every AP provides a wireless interface to other STAs, non Access Point Stations (non-APs). The non-APs use the AP as a relay or bridge between other non-AP STAs in a different BSS. The Distributed Systems (DS) connects all the APs together. Figure 2.4 illustrates the DS mode of operation.

Extended Service Set

The DS and BSS allow Extended Service Set (ESS). As the name suggests, the two distinct BSSs can be combined to form an ESS, such that they appear as a same IBSS to the LLC[6]. Stations may move between two BSSs, within a same ESS, and effectively be in the same

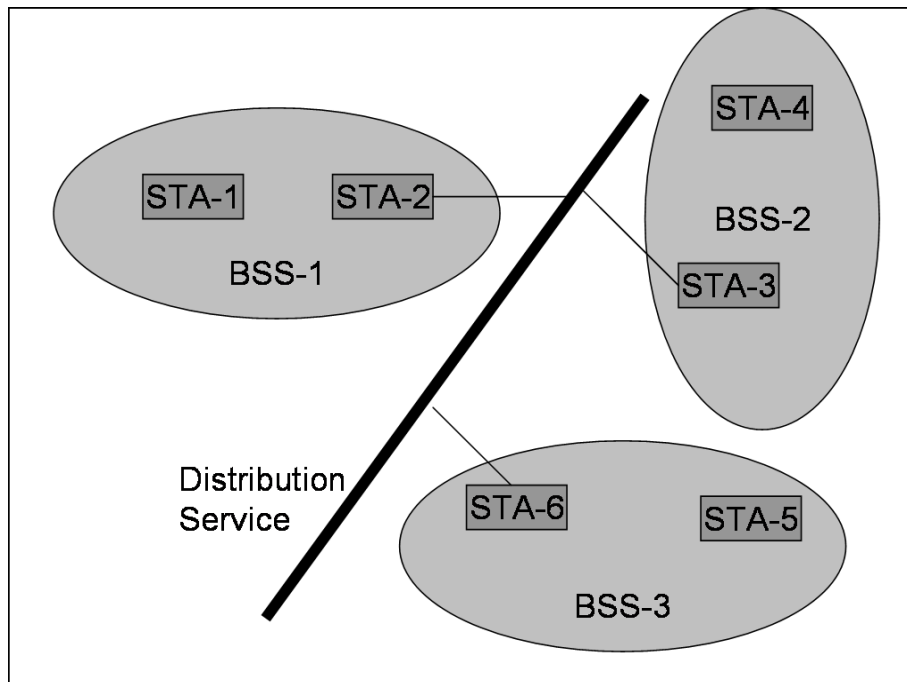


Figure 2.4: The IEEE 802.11 in Distributed Systems Mode

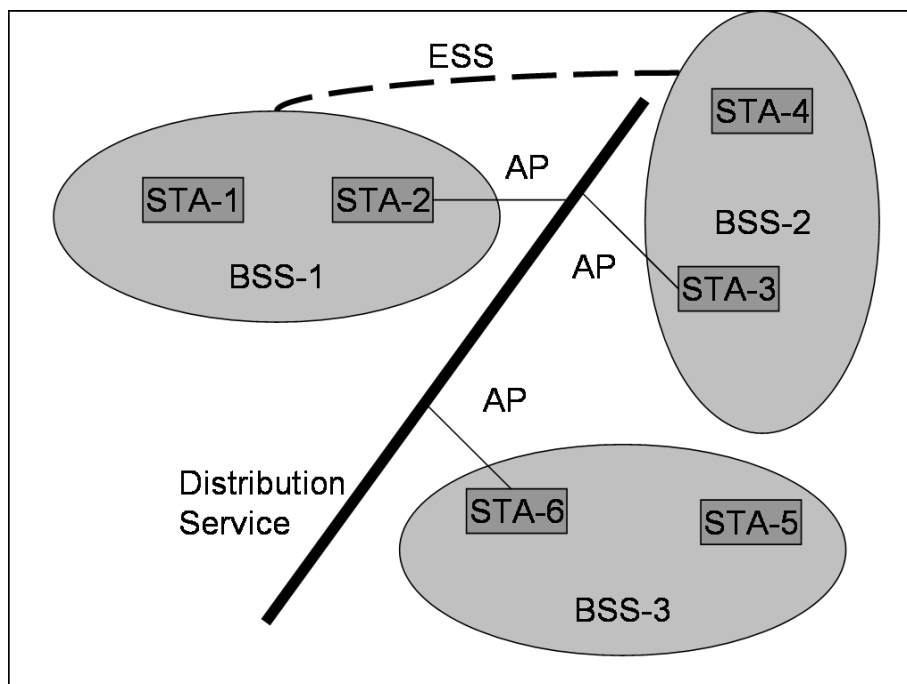


Figure 2.5: The IEEE 802.11 in ESS Mode

IBSS. In this case, the two distinct BSSs may partially overlap, be physically colocated to provide better coverage or even be physically non-colocated.

2.5.3 WLAN/LAN internetworking

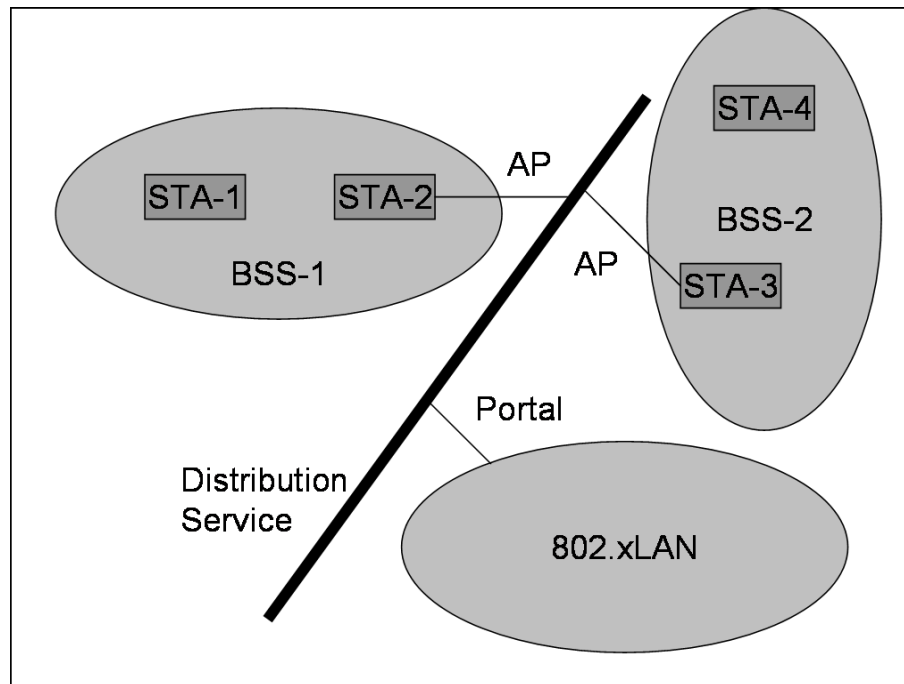


Figure 2.6: The IEEE 802.11 and LAN networking

It is worth mentioning the WLAN/LAN networking capability, as these scenarios are quite common where wired LANs have predominantly been in existence for quite some time. WLAN in these scenarios serve as means of extending the reach of LANs. Fig 2.6 depicts the logical connection between the two environments. All types of LAN network with the IEEE 802.11 Standard via the Portal as shown. IEEE 802.11 Standard does not constrain a DS to a particular technology, by explicitly not standardizing the details pertaining to DS implementations. However, this integration is taken care of via “services”. These services can be categorized as

- Station Services: Minimum set of services to be provided by all STAs, including APs, to be able to interface are:

- Authentication
 - Deauthentication
 - Privacy
 - MSDU delivery
- Distribution System Services: Minimum set of services a DS should provide to comply with interfacing requirements:
 - Association
 - Disassociation
 - Distribution
 - Integration
 - Reassociation

In this thesis, only the Distributed Systems and Access Points mode of operation has been discussed. This scenario is most commonly seen in enterprise environments where, many APs are deployed and the individual non-AP STAs connect to these APs.

2.6 The IEEE 802.11 Legacy

2.6.1 MAC Architecture

The function of Medium Access Control or MAC is very significant, as this layer is responsible for the behavior of STA accessing medium in a distributed environment. In this subsection, a brief outline of MAC architecture for IEEE 802.11 legacy is provided. Figure 2.7 depicts the MAC architecture. The details are available in the IEEE 802.11 Standards document at [6].

The MAC sub-layer

The IEEE 802.11 MAC describes two functions namely,

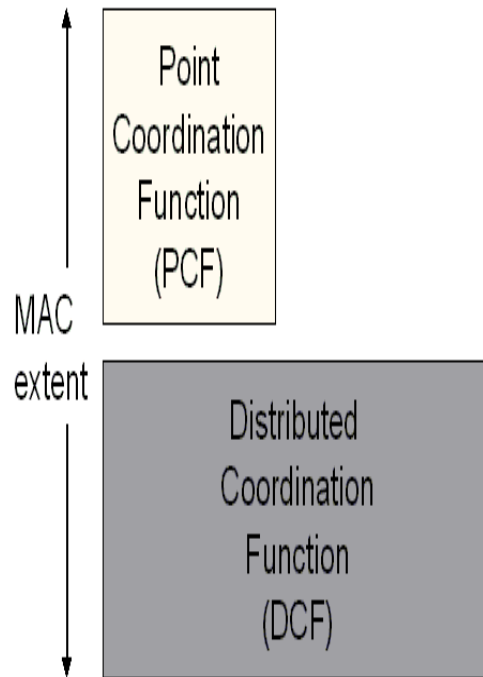


Figure 2.7: The IEEE 802.11 legacy MAC Architecture

- Distributed Coordination Function (DCF): The IEEE 802.11 legacy DCF is the key access method for IEEE 802.11 legacy standard. DCF is applicable for STAs operating in both IBSS and infrastructure-based environments. Additionally there are variants of this function:
 - Basic Access method, where the data packets contend directly for the wireless channel.
 - RTS/CTS method, where tiny control packets like RTS and CTS, are sent prior to actual communication of data. However, this mode of operation is optional.
- Point Coordination Function (PCF): This is an optional function, and is applicable only for the infrastructure based network configurations, due to its nature of synchronizing traffic from all STAs in a BSS/ESS.

Coexistence of DCF and PCF

The DCF and PCF can coexist under the same BSS/ESS and the two access methods alternate with the Contention Free Period (CFP) followed by the Contention Period (CP). During CFP, the PCF is in operation, whereas during the CP, the DCF is in operation.

2.6.2 The IEEE 802.11 operation

The channel is slotted in time. The IEEE 802.11 standard utilizes the Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) protocol in which, every station senses the channel and waits for a fixed amount of time, Distributed Inter Frame Space (DIFS), before transmitting. If the station finds channel busy, it waits for a random number of slots in addition to DIFS. The random number of slots in this case, are chosen from a maximum window size determined by the initial contention window size (CW_{min}), and the number of retransmission attempts (i) upto a maximum number of retransmissions, also known as Maximum Back Off (m). In other words, $CW = \max[CW_{min} - 1, 2^m CW_{min} - 1]$.

For every packet transmitted, the receiver acknowledges the transmitter after waiting for a Short Inter Frame Space (SIFS). If a packet is not acknowledged within a Retransmission time-out (RTO), the packet is assumed to have collided. Ethernet based stations have the ability to sense the medium as well as detect collision: Carrier Sense Multiple Access/Collision Detection (CSMA/CD) protocol. Collision Detection is possible in Ethernet-based networks, primarily because all the stations in Ethernet can listen to one another. This is not possible in IEEE 802.11 Networks, as a station can only listen to another station within its range: Hidden Node Problem.

On encountering a collision, the CW is doubled and the station waits a random number of slots within this CW for re-transmission. If acknowledgement was received, the station contracts its contention window to CW_{min} and the process continues. In this thesis, the scope of discussion is restricted to DCF only.

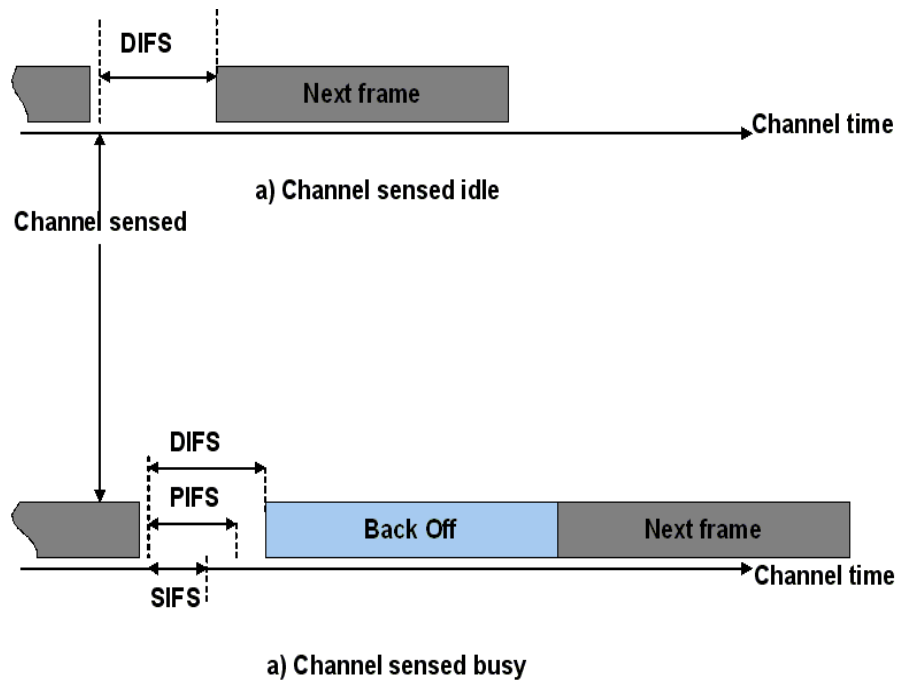


Figure 2.8: A comparison of IFS in the IEEE 802.11 legacy

2.7 IEEE 802.11 QOS support

DCF supports only best-effort traffic services[4]. Recently, the IEEE 802.11e Task Group proposed Enhanced DCF (EDCF), which was adopted as, Wireless Multimedia Enhancement, by the Wi-Fi Alliance, as a pre-standard implementation of 802.11e [5]. The IEEE 802.11e Standard does not make QOS guarantees for WLAN, however, it promises Prioritized and Parameterized QOS qualities [8]. In the coming subsections, the MAC architecture for QOS-based IEEE 802.11 networks is briefed and finally the architectural differences between the two standards is discussed.

2.7.1 The QOS-based IEEE 802.11 MAC Architecture

Figure 2.9 illustrates the MAC Architecture for QOS-based IEEE 802.11 networks. The basic difference between the legacy and QOS-based MAC architecture is clearly visible,

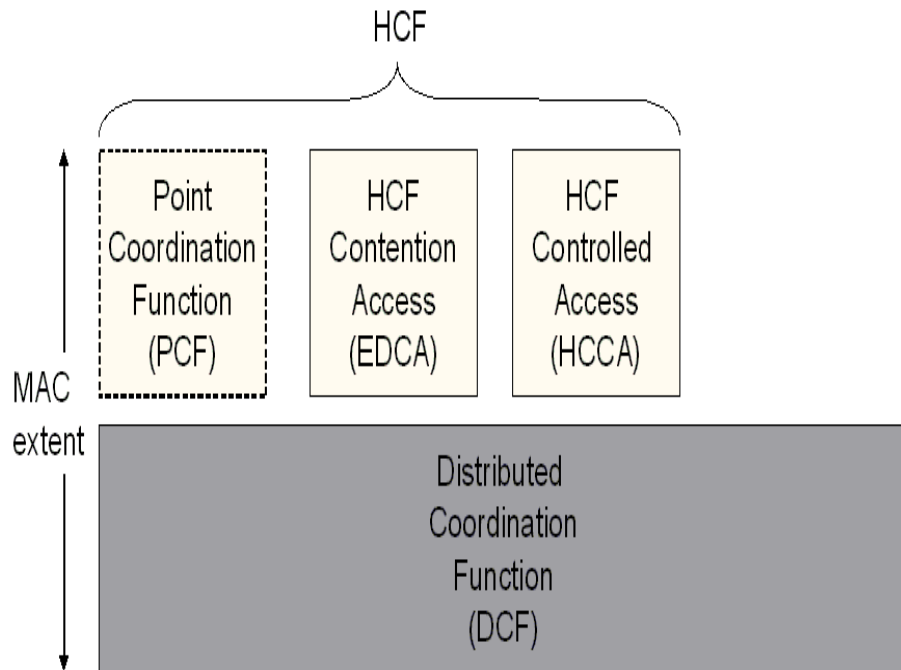


Figure 2.9: The QOS-based IEEE 802.11 MAC Architecture

the introduction of HCF, in form of Enhanced Distributed Contention Access (EDCA) and Hybrid Controlled Channel Access (HCCA). A note to be made here is that PCF is supported strictly for the purpose of backward compatibility. These blocks are described below:

- Distributed Coordination Function (DCF): The operation is described in the architecture specifications of legacy MAC
- Hybrid Coordination Function (HCF): The HCF is implemented in all STAs desiring to have QOS. HCF uses both contention based channel access method, EDCA or EDCA and a controlled channel access method HCCA for a contention free access.

EDCF

EDCF supports Prioritized QOS by using traffic differentiation. Traffic differentiation is provided by having separate queues for each type of traffic and a MAC-level Virtual Collision

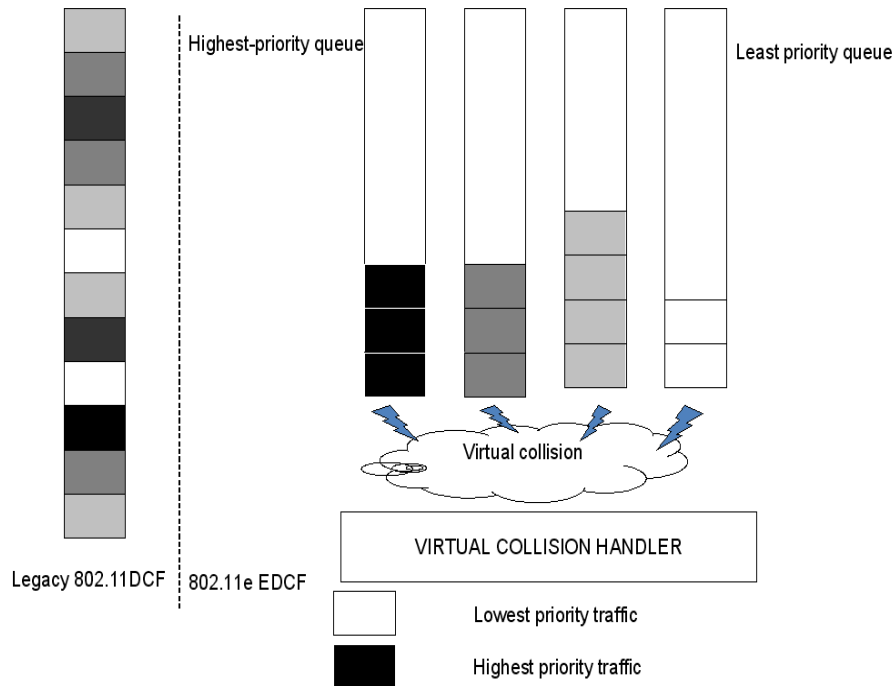


Figure 2.10: Illustration of EDCF compared to DCF

Handler to resolve conflicts between co-located² traffic streams (TS) [7]. Figure. 2.10 shows how EDCF differentiates traffic.

HCF

The Hybrid Controller in the HCF extends the PCF in the legacy IEEE 802.11 standard. HCF provides parameterized QOS, promising predefined delay limits for delay-sensitive traffic. HCF contains a mechanism, Hybrid Controller (HC), a ‘QOS-aware’ centralized controller, which polls stations during the contention free period. HC uses the highest priority Inter Frame Spacing (IFS) and hence, is able to gain access to the wireless medium quickly, if required. The IFS distinction is described in the next section. Polling a station is same as granting a non-AP STA an opportunity to transmit, also known as polled transmission opportunity (polled-TXOP).

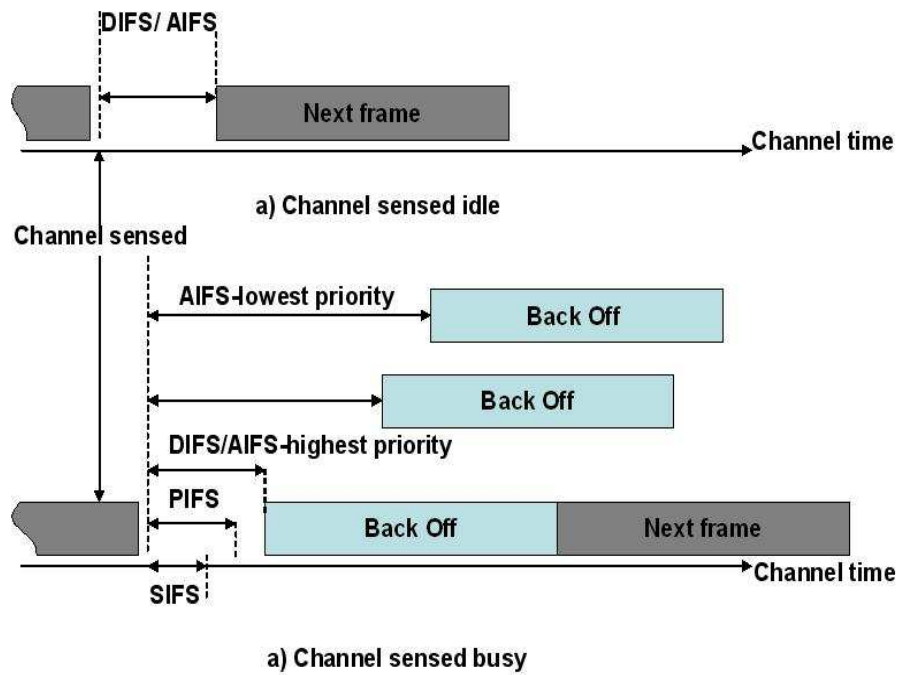


Figure 2.11: A comparison of IFS in the IEEE 802.11e

2.7.2 The IEEE 802.11e operation

Basically, each priority has a distinct IFS i.e. higher the priority smaller the IFS, which implies, a higher priority channel has a higher probability of gaining access to the channel (See Fig. 2.11 for details). Delay-sensitive traffic from voice and video applications, are classified as highest priority whereas, traffic from email-based applications, which are not so delay-sensitive, are referred to as lower priority traffic. Fig. 2.12 illustrates the IEEE 802.11e frame is divided into Contention Period (CP) and optional, Contention Free Period (CFP) [11]. During CP, stations contend for transmission opportunity (TXOP) whereas during the CFP, Access-Point (AP) polls the stations for backlogged queues. AP waits for the least IFS among these, to initiate CFP, if required. However, during CP, the non co-located TS have to still contend for wireless channel, as per EDCF rules. Details of IEEE 802.11e can be found in [5] and [7].

²co-located: located on a single wireless station; non co-located: located on distinct wireless stations

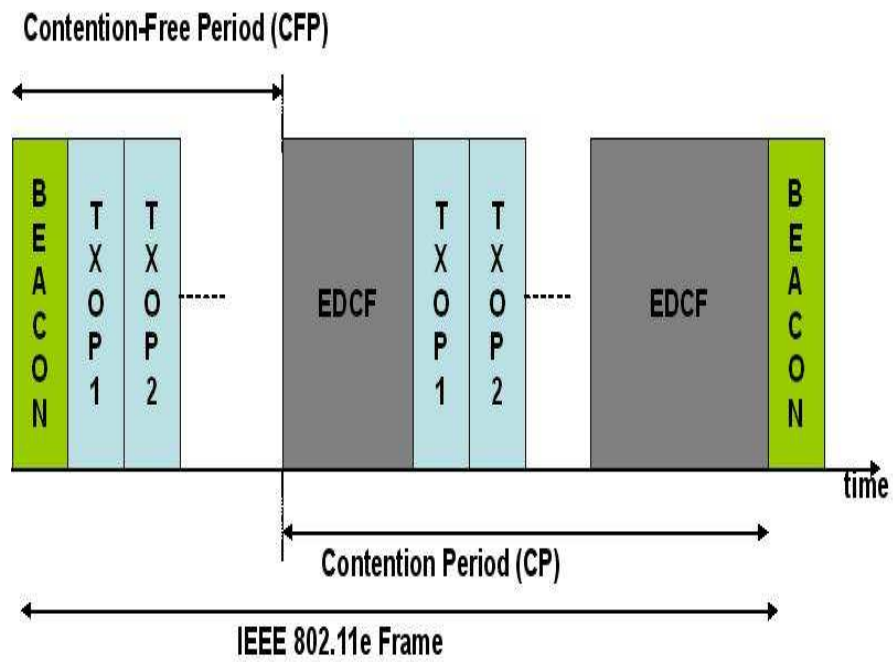


Figure 2.12: Contention Free Period (CFP) and Contention Period (CP) in the IEEE 802.11e Frame

2.8 Conclusion

In this Chapter, a general overview of the existing IEEE 802.11 standards were discussed followed by the legacy and QOS-based IEEE 802.11 protocols. In the following Chapter, an analytical model for existing Back Off scheme BEB is discussed followed by formulation of model for EBEB.

Chapter 3: The System Model

3.1 Introduction

In this Chapter, an analytical model for the Back Off mechanism is developed. This model is a Markov Chain state diagram representation, first proposed by author in [9] for the BEB scheme. This model was chosen, as it is simple and it models all the parameters of back off mechanism. The model assumes ideal channel conditions. All stations in this model have equal priority and every station is always in saturation condition, or every station always has a packet to transmit. In this thesis, this model has been extended to study the behavior of EBEB scheme and, to evaluate its performance relative to BEB scheme.

3.2 The Binary Exponential Back Off Model

The BEB model is illustrated in Figure 3.1. This model is a 2-dimensional Markov Chain state diagram where, the two dimensions are given by (i, j) such that,

- i : number of successive collisions, $i \in (0, m)$ and,
- j : contention window size, $j \in (0, CW_i - 1)$

Following equations can be obtained from the BEB Model shown in Figure 3.1

$$b_{i,0} = p^i b_{0,0} \tag{3.1}$$

$$pb_{m-1,0} = (1 - p)b_{m,0} \tag{3.2}$$

$$b_{i,k} = \left(\frac{CW_i - k}{CW_i} \right) b_{i,0} \tag{3.3}$$

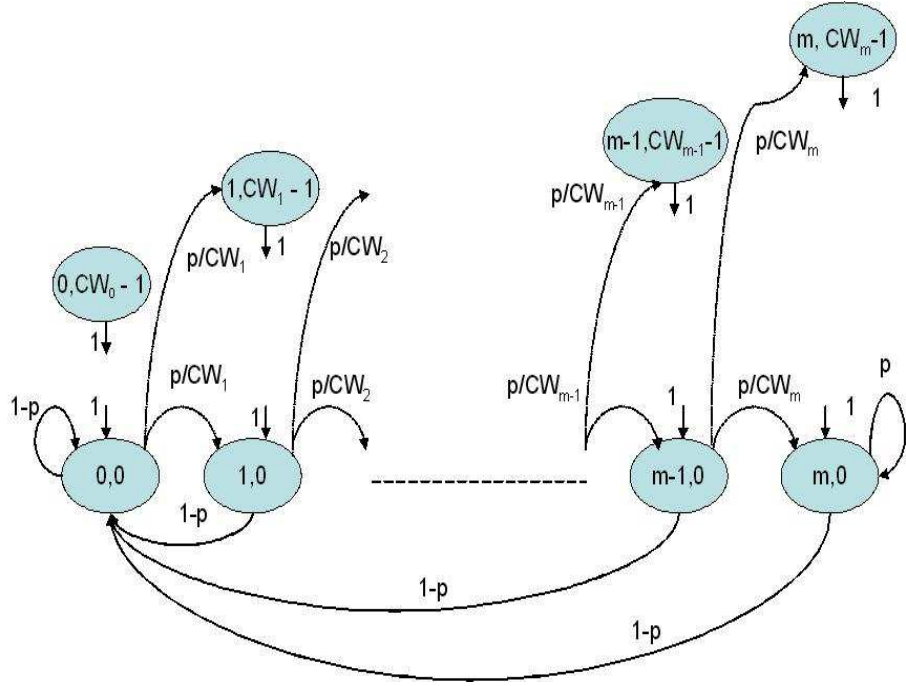


Figure 3.1: Markov Chain Model for BEB

$$\sum_{i=0}^m b_{i,0} = \frac{b_{0,0}}{(1-p)} \quad (3.4)$$

and finally, we have sum of all states equal to 1,

$$\sum_{i=0}^m \sum_{k=0}^{CW_i-1} b_{i,k} = 1 \quad (3.5)$$

Equation (3.5) can be further solved as follows:

$$\sum_{i=0}^m b_{i,0} \sum_{k=0}^{CW_i-1} \frac{CW_i - k}{CW_i} = 1 \quad (3.6)$$

$$\sum_{i=0}^m b_{i,0} \left(\frac{CW_i + 1}{2} \right) = 1 \quad (3.7)$$

Now, CW_i can be expanded as $CW_i = 2^i CW_{min}$. Let CW_{min} be denoted as ‘ W ’, henceforth, in the equations below. Substituting equations obtained from the state diagram earlier into (3.7) yields the following result:

$$\frac{b_{0,0}}{2} \left[W \left(\sum_{i=0}^{m-1} (2p)^i + \frac{(2p)^m}{(1-p)} \right) + \frac{1}{(1-p)} \right] = 1 \quad (3.8)$$

On solving further we achieve the value for $b_{0,0}$:

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \quad (3.9)$$

A station transmits only if it is in one of the $b_{i,0}$ states for all i . Now, the probability that a station transmits is equal to the probability of station being in one of $b_{i,0}$ states. Let ‘ τ ’ be this probability, and from this definition we have:

$$\tau = \sum_{i=0}^m b_{i,0} \quad (3.10)$$

Substituting (3.4) in (3.10) we get:

$$\tau = \frac{b_{0,0}}{(1-p)} = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \quad (3.11)$$

Equation (3.11) describes the relationship between ‘ p ’ and ‘ τ ’.

From the Probability definitions we have,

p = Probability that more than one stations transmit in a random timeslot

$$p = 1 - [\Pr(\text{no station transmits}) + \Pr(\text{only 1 station transmits})]$$

$$\Rightarrow p = 1 - [(1 - \tau)^n + \tau(1 - \tau)^{n-1}] \quad (3.12)$$

$$\Rightarrow p = 1 - (1 - \tau)^{n-1} \quad (3.13)$$

This can be re-written as:

$$\tau = 1 - (1 - p)^{\frac{1}{n-1}} \quad (3.14)$$

(3.11) and (3.14) are two non-linear equations in τ , p and n . These equations can be solved graphically or iteratively using MATLAB [16]. The graphical solution is illustrated in Figure 3.2 for $CW_{min} = 32, m = 3$ and $CW_{min} = 64, m = 5$.

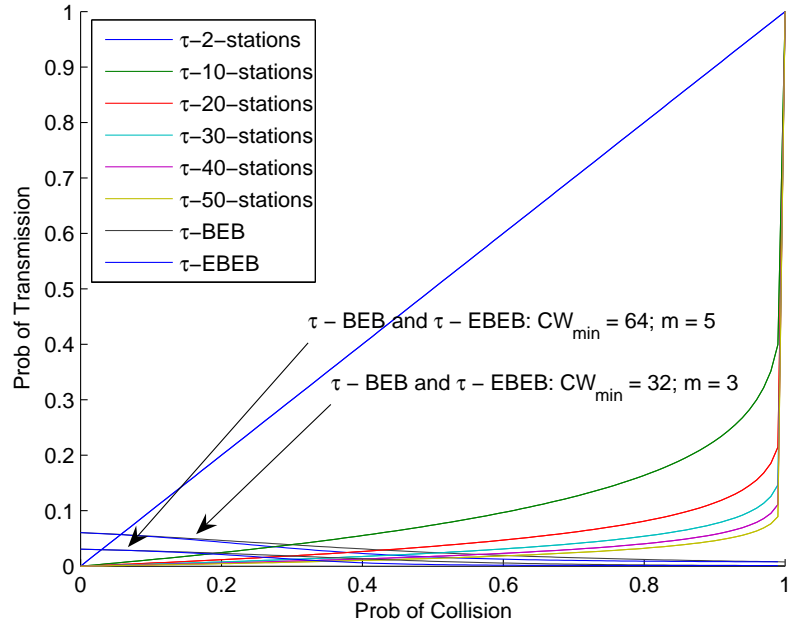


Figure 3.2: Graphical Solution of Non-Linear Equations

Channel Utilization

Channel Utilization is the fraction of average time spent over channel for a successful transmission to the total time taken. The model describes computation of average Channel Utilization (S) based on the values of τ and p determined in the previous sub-section . According to this model, S can be computed as follows:

$$S = \frac{P_{tr}P_sE(P)}{(1 - P_{tr})\sigma + P_{tr}P_sT_S + P_{tr}(1 - P_s)T_C} \quad (3.15)$$

Where,

$E[P]$ = mean payload size computed in units of time

P_{tr} = Probability of atleast one transmission in a given slot = $1 - (1 - \tau)^n$

$P_{tr}P_s$ = Probability of a successful transmission = $n\tau(1 - \tau)^{n-1}$

T_C = Avg length of time busy during collision = $E[P] + DIFS + \delta$

T_S = Avg length of time busy during transmission = $E[P] + SIFS + ACK + DIFS + 2\delta$

$E[P]$ = Expected Time taken to transmit Packet and Header over the Channel

δ = Propagation Delay

$SIFS$ = Short InterFrame Spacing

$DIFS$ = Distributed InterFrame Spacing

ACK = Time taken to transmit an ACK

The parameters discussed above are specified in [6] and [12]

Collision Probability

The two non-linear equations in τ and p can be solved iteratively. Equation (3.11) is an equation in τ and p , refers to BEB curve, which is independent of number of stations, n . Equation (3.14) is an equation in τ and p , that refers to the curve, which is a function of

n . From Figure 3.2, the intersection of two curves determined by (3.11) and (3.14) yields a point with (x, y) coordinates. The x -coordinate of this point of intersection is defined as the Collision Probability for BEB when the number of stations is equal to n .

3.3 The Enhanced Binary Exponential Back Off Model

In EBEB, on successful transmission, the station contracts its CW only to half of existing size, upto a minimum of CW_{min} , as opposed to CW_{min} each time, in BEB. This increases the likelihood of a station to wait for more slots, after a successful transmission. Hence, a successful station yields to other stations, so that they have a fair chance to transmit, introducing fairness. Also helps reduce the number of collisions, and eventually, increases the overall channel utilization and fairness.

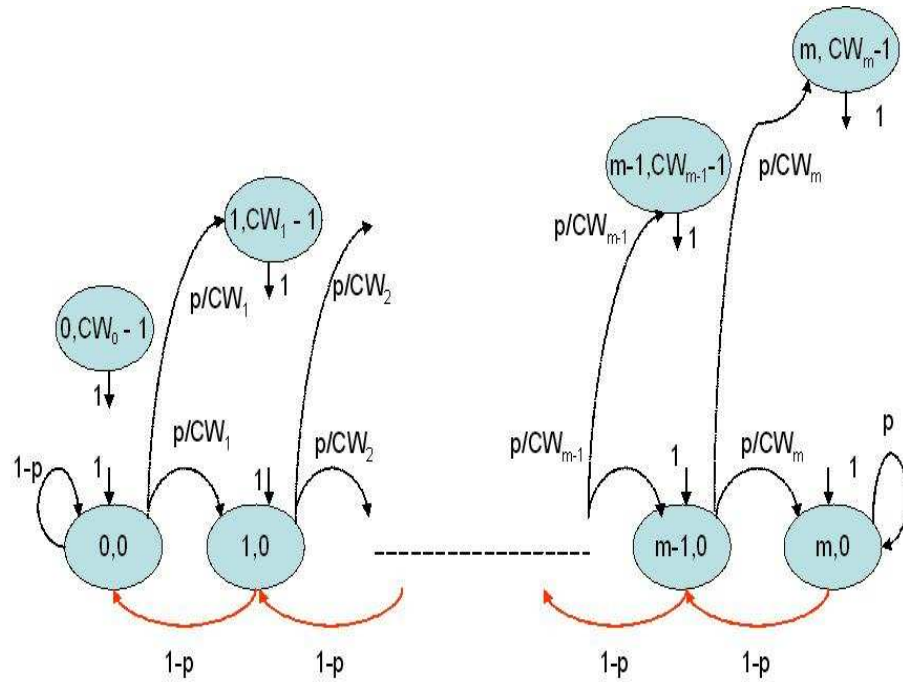


Figure 3.3: Markov Chain Model for EBEB

Fig. 3.3 shows the 2-dimensional Markov-Chain representation for EBEB scheme. Simplicity of this model can be observed from the fact, how easily the model can be adapted

for EBEB scheme. Following equations can be obtained from state diagram in Fig. 3.3:

$$\sum_{i=0}^m \sum_{j=0}^{CW_i-1} b_{i,j} = 1 \quad (3.16)$$

or the sum of all states is equal to 1.

$$b_{0,0}p = b_{1,0}(1-p) \quad (3.17)$$

$$b_{1,0} = b_{0,0}p + b_{2,0}(1-p) \quad (3.18)$$

$$\Rightarrow b_{0,0}p^2 = b_{2,0}(1-p)^2 \quad (3.19)$$

$$\Rightarrow b_{0,0}p^3 = b_{3,0}(1-p)^3 \quad (3.20)$$

This can be extended to:

$$b_{0,0}p^i = b_{i,0}(1-p)^i \quad (3.21)$$

$$\Rightarrow b_{i,0} = b_{0,0} \left(\frac{p}{1-p} \right)^i \quad (3.22)$$

$$\text{Let } \rho = \left(\frac{p}{1-p} \right),$$

$$\Rightarrow b_{i,0} = \rho^i b_{0,0} \quad (3.23)$$

We can further rewrite (3.16) using expansion shown in (3.6):

$$\sum_{i=0}^m b_{i,0} \left(\frac{CW_i + 1}{2} \right) = 1 \quad (3.24)$$

$$\sum_{i=0}^m b_{i,0} CW_i + \sum_{i=0}^m b_{i,0} = 2 \quad (3.25)$$

Now CW_i can be given as: $CW_i = 2^i CW_{min}$. Let CW_{min} be denoted by 'W' as before and

substituting (3.23) in previous equation, we get:

$$\Rightarrow b_{0,0} \left[W \sum_{i=0}^m (2\rho)^i + \sum_{i=0}^m (\rho)^i \right] = 2 \quad (3.26)$$

$$b_{0,0} \left[W \left(\frac{1 - (2\rho)^{m+1}}{1 - 2\rho} \right) + \left(\frac{1 - \rho^{m+1}}{1 - \rho} \right) \right] = 2 \quad (3.27)$$

$$b_{0,0} = \frac{2(1 - 2\rho)(1 - \rho)}{W(1 - \rho)(1 - (2\rho)^{m+1}) + (1 - 2\rho)(1 - \rho^{m+1})} \quad (3.28)$$

Let τ = Probability that station transmits in a random slot. Therefore, τ can be evaluated as before:

$$\tau = \sum_{i=0}^m b_{i,0} \quad (3.29)$$

$$\tau = b_{0,0} \left(\frac{1 - \rho^{m+1}}{1 - \rho} \right) \quad (3.30)$$

From equation (3.28) we get,

$$\tau = \frac{2(1 - 2\rho)(1 - \rho^{m+1})}{W(1 - \rho)(1 - (2\rho)^{m+1}) + (1 - 2\rho)(1 - \rho^{m+1})} \quad (3.31)$$

We have obtained a relation in τ and $f(\rho)$.

S can be computed for EBEB using the equation (3.15) and Collision Probability can be also be determined by iterative solution as described for BEB earlier. Figure 3.4 shows the difference in Markov Chain representations for both models. In the next section, the analytical results are illustrated and discussed .

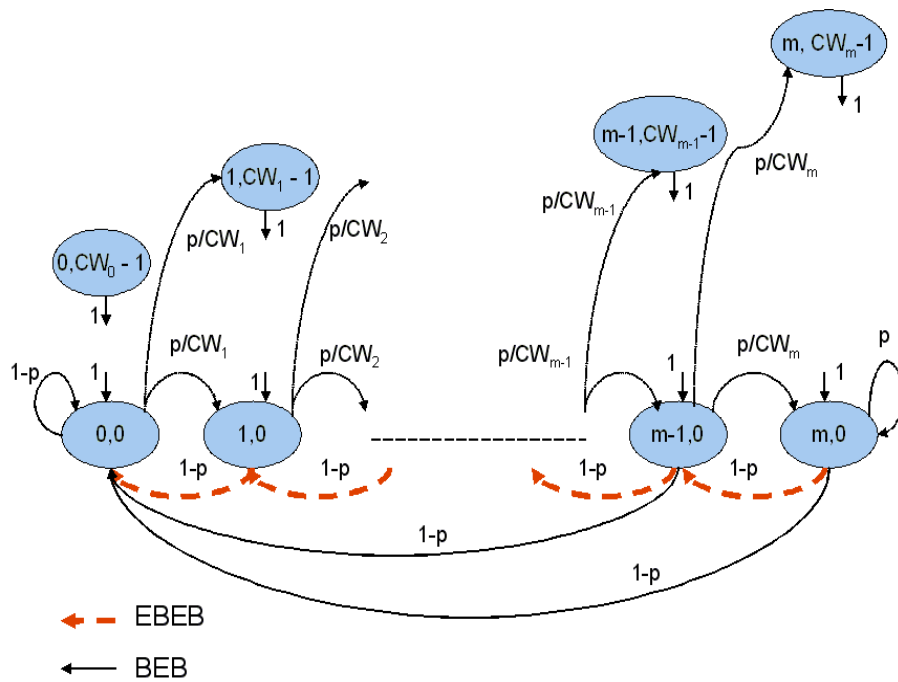


Figure 3.4: Comparison: Markov Chain representation for EBEB versus BEB

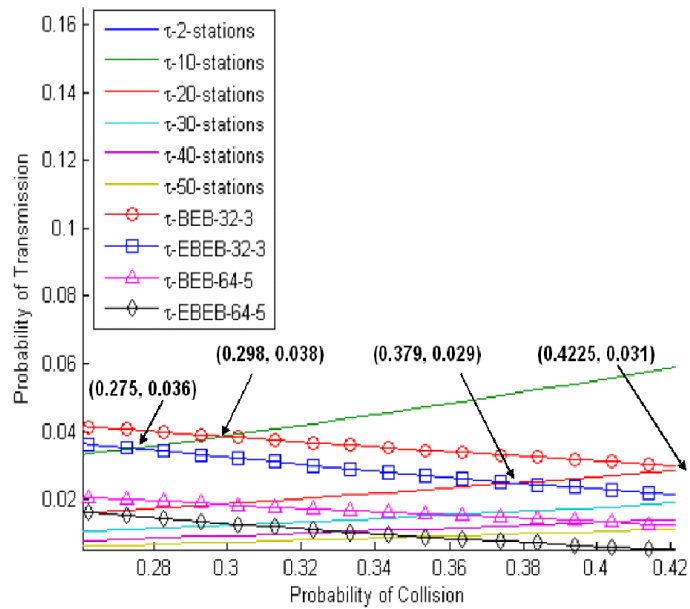


Figure 3.5: Comparison of solution to non-linear equations for BEB/EBEB - I

3.4 Comparison of Analytical Results

Figure 3.5 shows the intersection of curves obtained from non-linear equations (3.11) and (3.14) or (3.31) for BEB and EBEB, respectively, for cases: $CW_{min} = 32, m = 3$ and $CW_{min} = 64, m = 5$. We can make the following inferences from this figure:

- The EBEB curves allow a small reduction in probability of transmission for a relatively large improvement in probability of collision. This gain increases monotonically with the number of stations. This is valid of both cases, mentioned above.
- As CW_{min} and m increase, clearly, both probability of transmission and probability of collision decrease. This is illustrated in Figure 3.6.

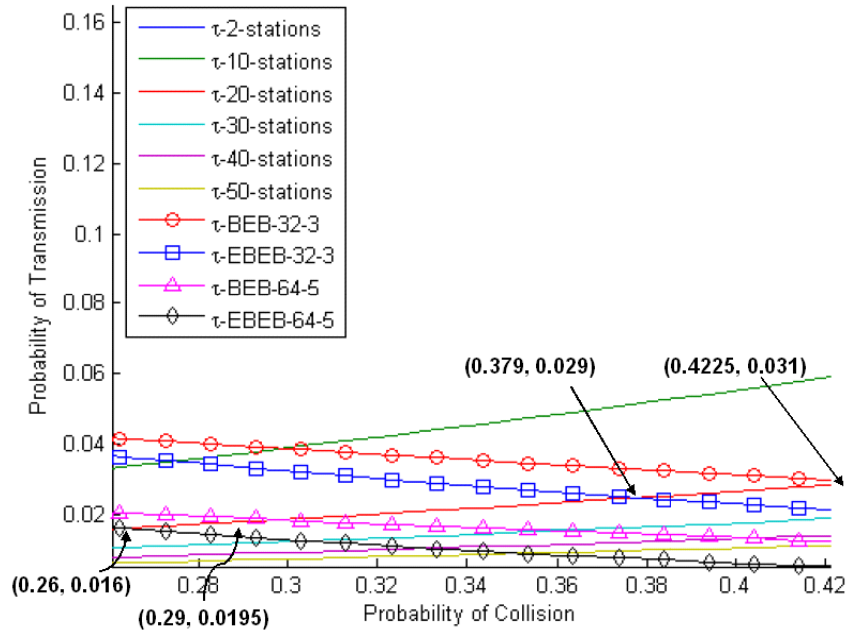


Figure 3.6: Comparison of solution to non-linear equations for BEB/EBEB - II

Smaller probability of transmission indicates higher delay due to waiting, whereas higher probability of collision indicates higher delay due to retransmissions.

Fig. 3.7 shows analytical comparison of EBEB and BEB schemes for Channel Utilization versus Number of Stations, where $CW_{min} = 32, m = 3$ and $CW_{min} = 64, m = 5$. It is clear from the analytical results that saturated Channel Utilization(S) for EBEB scheme is better than the existing scheme, BEB, for both cases specified above.

When number of stations are few, EBEB performance almost coincides with that of BEB. As the number of stations involved grow, evidently, EBEB performs better than BEB. This is true for all combinations of CW and m , as seen in the Fig. 3.7. Another important observation is, S increases with higher CW and m . This result is valid for both the schemes.

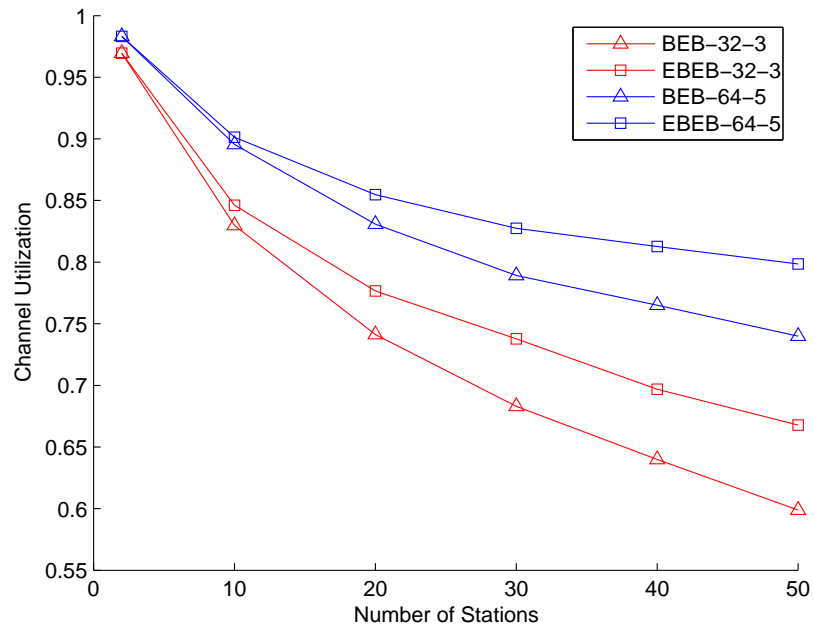


Figure 3.7: Comparison: EBEB vs BEB - Analytical Results for Channel Utilization

Fig. 3.8 shows Analytical comparison of EBEB and BEB schemes for Collision Probability versus Number of Stations, for cases: $CW \in (32, 64)$ and $m \in (3, 5)$. The Collision Probability increases as the number of stations increase. Again, the Collision Probability for EBEB is relatively less than BEB and is applicable for all CW and m as illustrated in

the figure. Increasing CW and m results in a smaller Collision Probability. Furthermore, these results are true for both schemes.

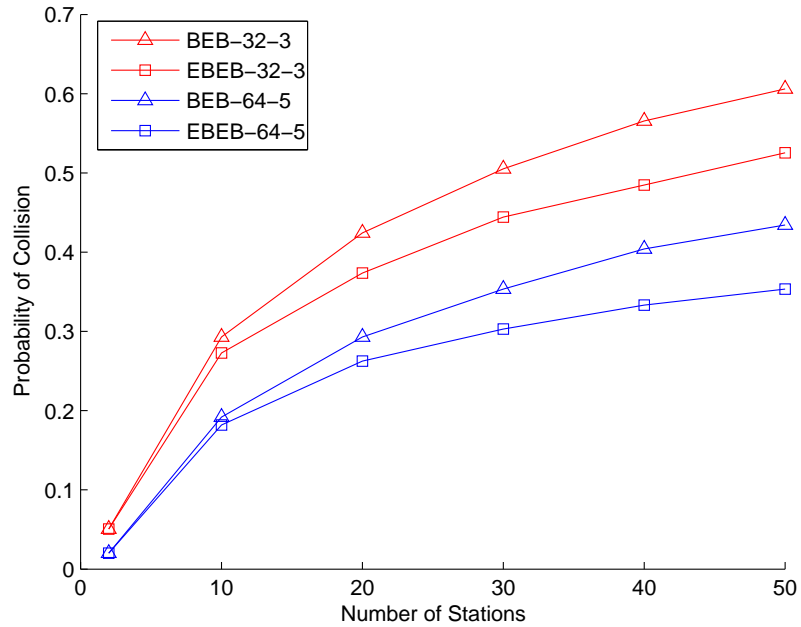


Figure 3.8: Comparison: EBEB vs BEB - Analytical Results for Probability of Collision

A closer look at Figures 3.7 and 3.8 reveals that, the results discussed previously in this section, complement each other. This is illustrated in Figure 3.9, plot of results obtained from analytical values Channel Utilization and Collision Probability. In other words, higher collision probability leads to smaller channel utilization and vice-versa. This is intuitive as, more collisions cause stations to wait longer, hence, the fraction of useful time spent reduces, relative to the total time spent. This reinforces our idea that EBEB has better overall performance compared to BEB, under saturation conditions.

3.5 Conclusion

In this Chapter, analytical performance of BEB and EBEB was evaluated. From the discussions above, it is clear that, the performance of EBEB is better than BEB irrespective

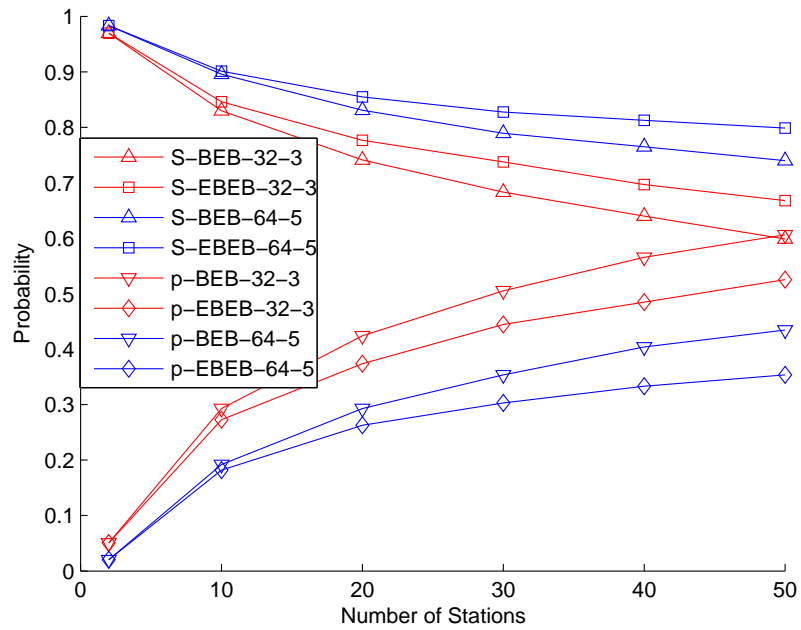


Figure 3.9: Channel Utilization and Collision Probability are complementary

of minimum CW and Maximum Back Off parameters. To substantiate the results from analytical model, a custom simulator for IEEE 802.11 environment is modeled. In the next Chapter, development of this simulator is described in detail.

Chapter 4: Modeling and Simulation of IEEE 802.11 Environment

4.1 Introduction

In this chapter, the software architecture of simulator is described. Simulator was developed, to evaluate the analytical results from the Model(s) described in the previous Chapter. Simulator is written in Java [15] and data analysis was done using MATLAB [16]. The simulator logs relevant data in text files, which are parsed by MATLAB scripts (m-files), to analyze and render results as illustrated here. Pseudocodes for both EBEB and BEB schemes are available in the Appendix Chapter.

4.2 Architecture

Figure 4.1 refers to the overall Simulator Architecture. The simulator can be divided into modules¹ and components². A Module is defined by a distinct Java Class, whereas a component, refers to a Java Inner-Class which runs as a separate Thread [17] with its own Thread Priority. Java Thread priorities are discussed in detail at [17].

4.2.1 Node

This is the simulator entry-point as well as the configuration interface. This Java class accepts parameters as arguments, validates these arguments and passes values to the simulation. The parameters that can be modified are:

- Number of Stations n

¹A Node, a Client, a Server is referred to as modules here.

²Sub-modules like Transmitter, Receiver are referred to as components here.

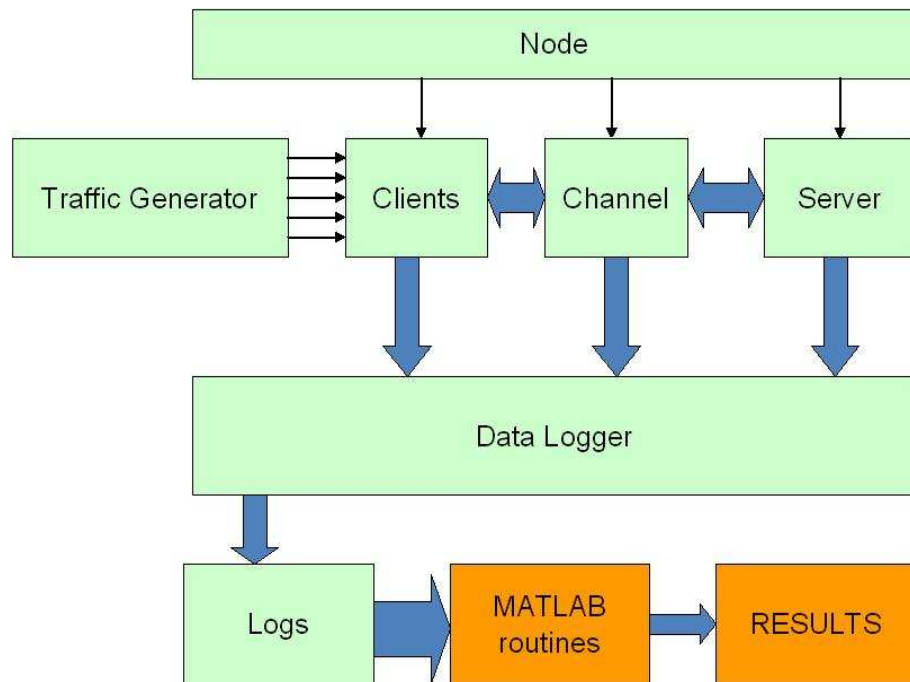


Figure 4.1: Simulator Architecture

- Messages per Station
- Minimum Contention Window CW_{min}
- Maximum Back Off m
- Retransmission Time Out
- Scheme to Simulate
 - Binary Exponential Back Off (BEB) OR
 - Enhanced Binary Exponential Back Off (EBEB)

4.2.2 DataLogger

DataLogger is an Application Programming Interface (API), which is used by other modules, to log data into text files . Each module owns a separate instance of DataLogger, specific to the log file they would be updating. All instances of DataLogger are synchronized.

Table 4.1: Priorities

Priorities	Modules
MAX(10)	Channel
9	Receiver components
7	Server Module
MIN(3)	Transmitter components

4.2.3 Non Access-Point

Each Client instance represents a 802.11 Non Access Point (non-AP) station. Each Client is basically a Java Class made up of several other components. The Priority of components/modules is tabulated in 4.1.

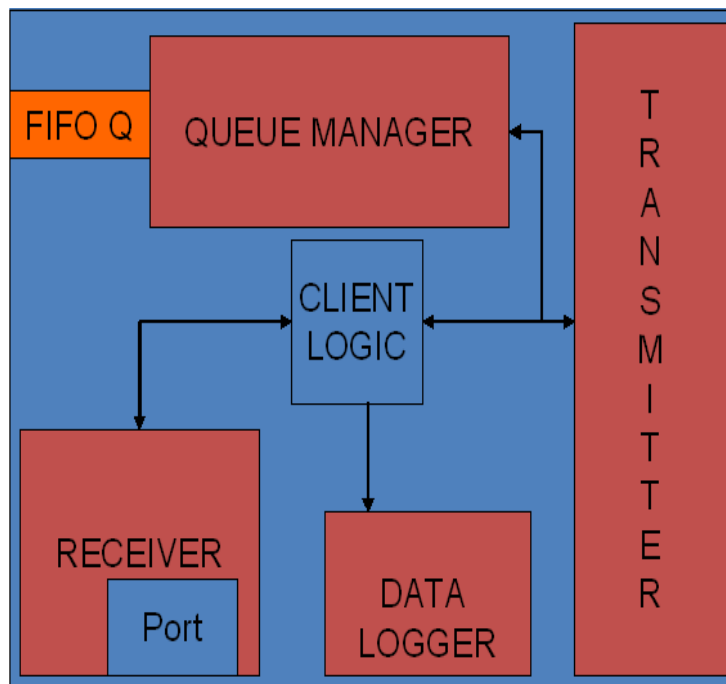


Figure 4.2: Non Access-Point STA Architecture

The Client has following components:

- Data Logger : This component interacts with the Data Logger module to enter data into log files. Logs events: message sent and ACK received into MessageLog file. Also, packet-dropped and packet-queued events are logged into AllClientQLog file.

- MessageLog : Message transmissions (including retransmissions) and ACK receptions are logged
- AllClientQLog : Contains log of the queue status of each client.
- Transmitter Module : Thread which transmits data on the channel if a message is available, in the transmit buffer. Transmitter has the lowest priority, as CSMA requires station to listen before transmit.
- Receiver Module : Keeps listening for ACK messages on a pre-assigned port, when the Client is not transmitting. Every Client is assigned an identity(ID) during the instantiation in Node Class. This ID is used to compute a unique Port³, over which the receiver Thread keeps listening. Care must be observed, to avoid overlapping of Ports with dedicated TCP/UDP ports. Information regarding well-known ports can be found at [14].
- Queue Manager : This module manages the FIFO Queue. Every new packet waiting to be transmitted is buffered. If the Client Queue is full, then the message is dropped.
- FIFO Queue : Contains messages. Each message is uniquely identified by the Station ID and a Message ID. Message ID is generated each time a new message is created to issue a unique identity to each message.
- Client Logic: This component is central logic which handles all components discussed above. The IEEE 802.11 protocol for non-AP station has been described here.

4.2.4 Access-Point

A Server instance represents an 802.11 Access Point(AP) station. There is only a single instance of Server Class. The Server instance is again, a Thread comprising the following components:

³A Port is an interface to connect another device to the machine containing this port.

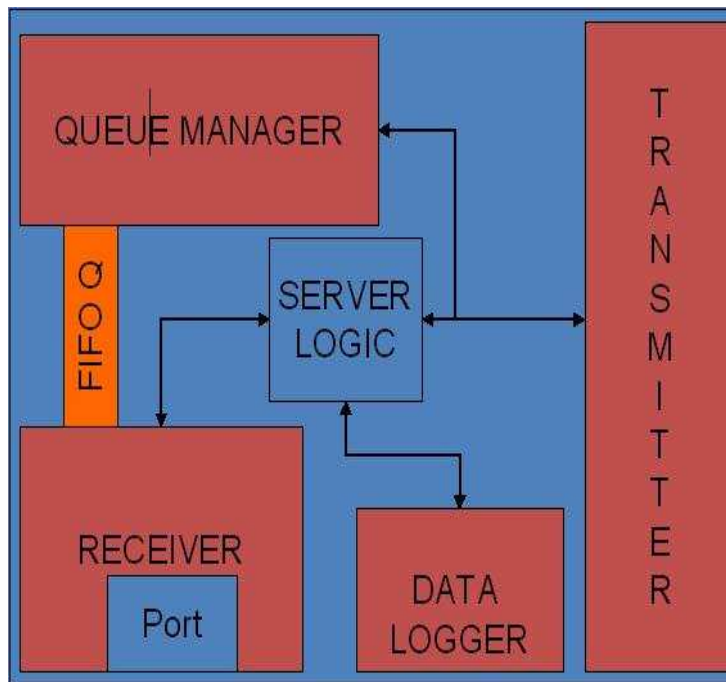


Figure 4.3: Access-Point STA Architecture

- Data Logger : This component interacts with the Data Logger module, to enter information related to message received events, into a log file, SMessageLog. Also, message-dropped and message-queued events are logged into SQLog file, via the Data Logger component.
 - SMessageLog : Contains Message reception log at the AP. Hence, information of only successful transmissions, from non-AP Stations, are logged here.
 - SQLog : Logs Queue status information updates for the AP. Every dropped message or buffered message event is log. Additionally, contains the number of messages in the queue at every such event.
- Transmitter : Thread which transmits ACK on the channel to respective clients if, an ACK for that station is pending. Transmitter has the lowest priority among other components in AP, but is higher than Transmitter component in non-AP, as there is only one AP for a large number of stations.

- Receiver : Keeps listening for successful messages from non-AP stations on a pre-assigned port, when AP not transmitting.
- Queue Manager : This module manages the FIFO⁴ Queue. Every new message arrived from the non-AP stations is buffered. If the Server Queue is full, then the message is dropped.
- FIFO Queue : Contains messages that can be uniquely identified by the Station ID and a Message ID, available in the Header.
- Server Logic: A component that synchronizes the components described above, based on the IEEE 802.11 protocol.

4.2.5 Channel

A Channel is a single instance, which represents the wireless channel. However, the channel defined here, is an ideal wireless channel as opposed to typical wireless channel. A typical wireless channel will have filtering losses due to shadowing, multi-path, scattering etc. The channel described here does not have any of this property, but only represents as a collision environment. This Channel models: If in a given time-slot more than one stations transmit, it results in collision, and no message is transmitted. Whereas, if only a single station transmits, the transmission is bound to be successful, since the channel is slotted, as described earlier. Also, the behavior of Channel can also be associated to a hub which relays messages from Clients to Server and ACKs from Server to Clients.

This Channel consists of following components:

- Data Logger : This component interacts with the Data Logger module to enter data into a log file, CollisionLog, containing information about collisions.

– CollisionLog: The statistics that can extracted from this log file are: total number

⁴FIFO refers to First In First Out

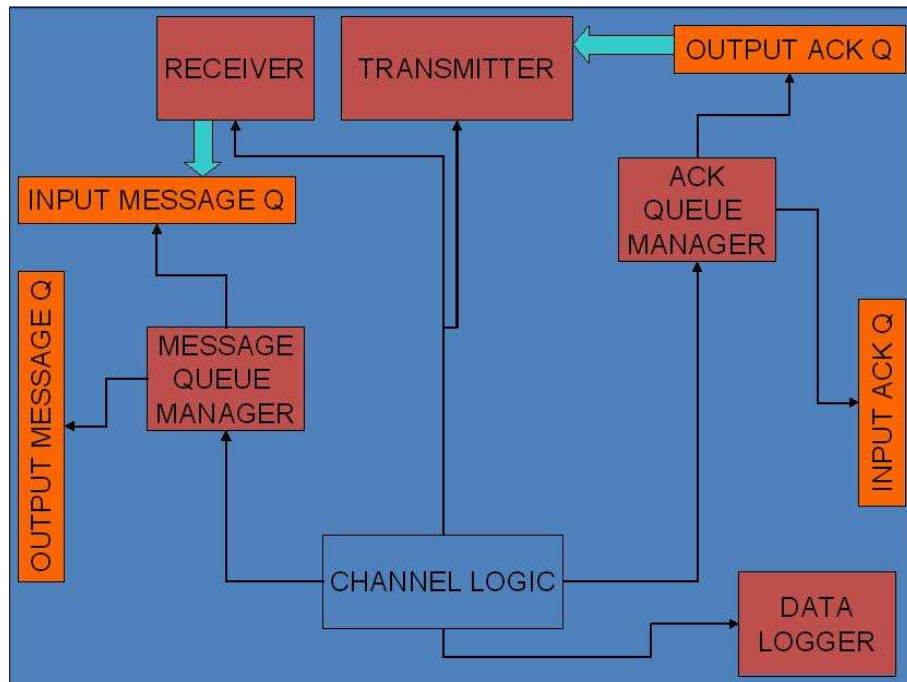


Figure 4.4: Channel Architecture

of collisions, number of stations involved per collision and time at which collision occurs.

- Receiver : Keeps listening for messages from non-AP stations and ACKs from Server, when not transmitting.
- Transmitter : Thread which transmits messages to the Server and ACKs to the Clients.
- Message Queue Manager : This component manages the FIFO Message Queue. Allows collection of messages from various Clients in a given slot and determines collision/no-collision based on the number of messages arrived in that slot. If collision occurs, it triggers a collision event, to be handled by Data Logger instance. If no collision, Transmitter component is allowed to handle transmission of message to the Server module.
- ACK Queue Manager : This component manages the ACK Queue. Based on the Header information in an ACK, the ACK Queue Manager identifies the transmitter

which is waiting for ACK and despatches the ACK appropriately.

- Message/ACK Queue :Contains messages, each of which, can be uniquely identified by the Station ID and a Message ID.
- Channel Logic: Synchronizes the operation of all components mentioned above.

4.2.6 Traffic Generator

This particular class was developed to provide distinct Packet Arrival Distributions, given the mean inter-arrival time. However, in this particular experiment, it is assumed that all the stations are operating in saturation mode, or there is always a packet to transmit at the non-AP station. Hence, no specific distribution is used. On the contrary, Queue Managers prefill Client buffers with messages, so as to emulate saturation mode.

4.3 Conclusion

Referring to the context of this thesis, the simulator renders following useful statistics with respect to the number of stations involved:

- average channel utilization
- average number of collisions and,
- average number of stations involved per collision

In the next Chapter, a comparison of simulation results against analytical results is shown.

Chapter 5: Performance Evaluation

5.1 Introduction

Simulator Architecture and design were described in the previous Chapter. In this Chapter, simulation results for Channel Utilization (S) and Collision Probability (p) are compared, with the analytical results obtained from the Models for BEB and EBEB, in Chapter 3. Plots from simulation results bolster the analytical results obtained in Chapter 3.

5.2 Simulation Results versus Analytical Results

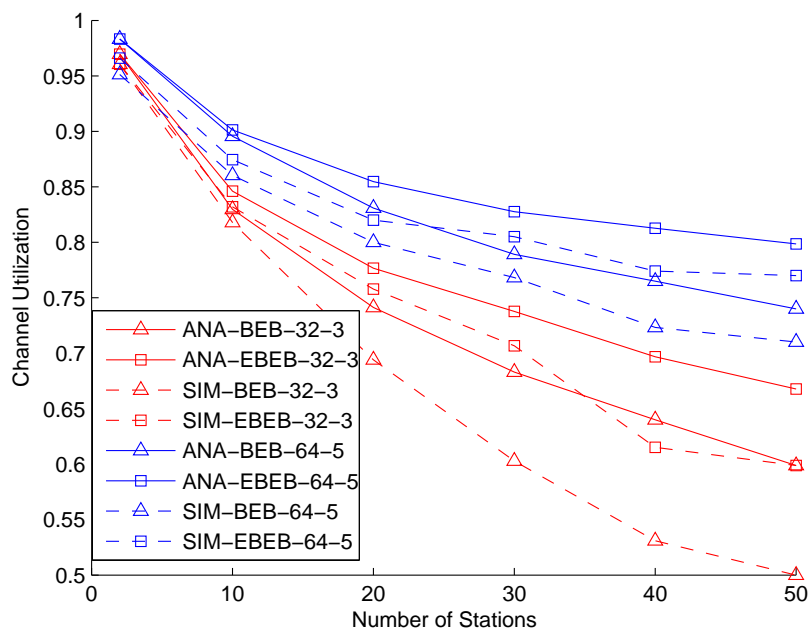


Figure 5.1: Channel Utilization (S): Analytical and Simulated Results EBEB vs BEB

Table 5.1 describes the parameters used in simulation. The simulation inputs have been referred from [12]. Readings shown here have been averaged over multiple trials. A distinct

Table 5.1: Simulation Input Parameters

Parameters	Value
DIFS	50 μ sec
SIFS	10 μ sec
σ	20 μ sec
Data + PHY header + MAC header	1024 bytes
ACK	14 bytes

Table 5.2: Performance Gain in Channel Utilization for EBEB over BEB

For Number of Stations	For $CW_{min} = 32, m = 3$	For $CW_{min} = 64, m = 5$
2	0	0
10	1.97%	0.647%
20	4.76%	2.87%
30	8%	4.86%
40	8.89%	6.23%
50	11.52%	7.91 %

seed was used each time, for each distinct Thread in a trial. Each simulation trial was run for a reasonable amount of time, required to reach the steady state. It has been ensured that, the gain due to decrease in Collision Probability for EBEB, has not come at the cost of increased delay, as our Channel Utilization measure is a function of average time required to transmit given number of messages.

Fig. 5.2 shows probability of collision, a function of average number of collisions and number of stations involved per collision, increases with the number of stations. As observed in analytical results, EBEB has relatively less number of collisions compared to BEB and hence less collision probability. Table 5.2 shows, relative performance improvement of EBEB over BEB, under saturation conditions and as the number of stations increase.

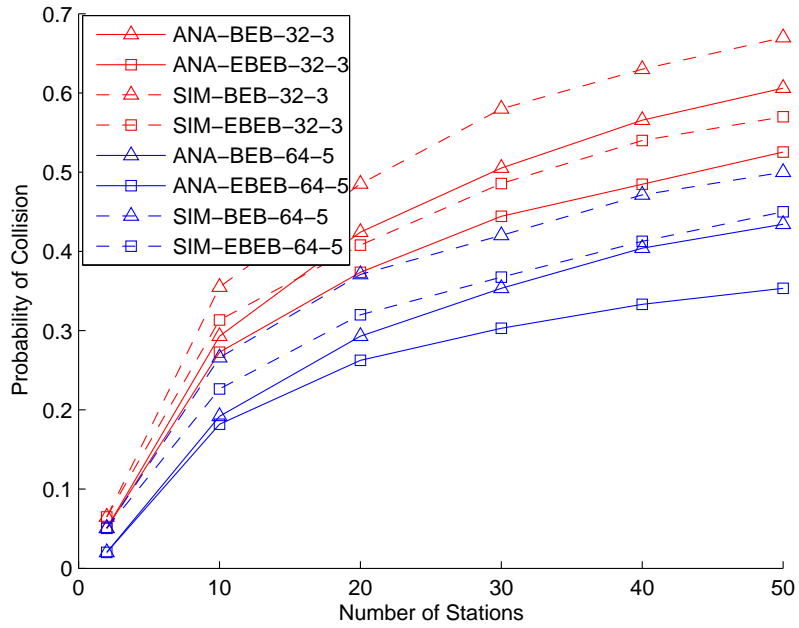


Figure 5.2: Collision Probability (p): Analytical and Simulated Results EBEB vs BEB

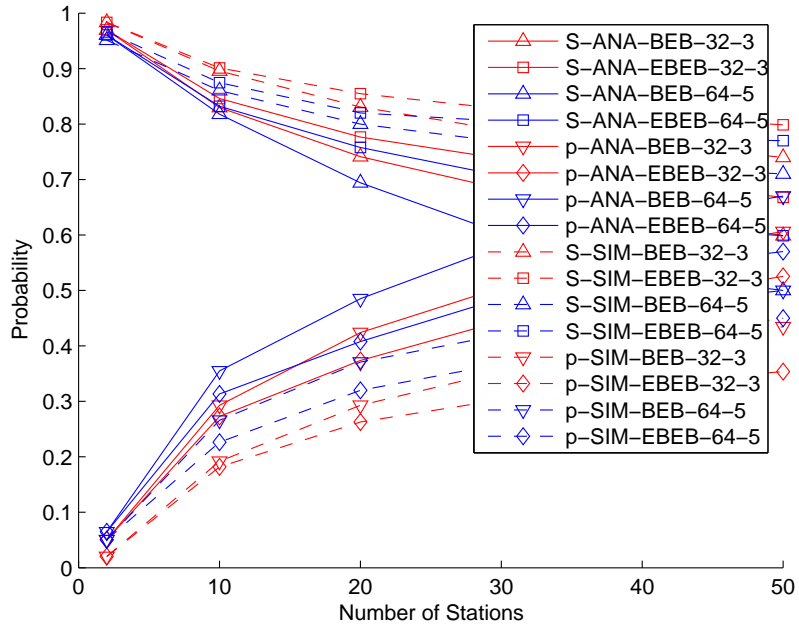


Figure 5.3: Channel Utilization (S) and Collision Probability (p) are complementary: Analytical and Simulated Results

5.3 Conclusion

In Figures 5.1 and 5.2 the Simulation Results are plotted along with the Analytical Results. The average error or deviation between the analytical and simulation results for Channel Utilization is about 5%. The Simulation Results also describe the same trend as in the Analytical Results: The Collision Probabilities and the Channel Utilization for both analytical and simulation results complement each other. Refer to Figure 5.3 for details.

Chapter 6: Conclusion and Further Work

6.1 Conclusion

From the discussions in Chapters 3 and 5, it was demonstrated that, the overall performance of EBEB is better as compared to BEB, under saturation conditions, independent of the initial contention window size and maximum backoff permitted. For $CW_{min} = 32; m = 3$, the maximum performance improvement was observed at $n = 50$, and was roughly equal 12%, whereas for $CW_{min} = 64; m = 5$, the maximum performance improvement was observed, again at $n = 50$, and was roughly equal to 8% (See Figure. 6.1).

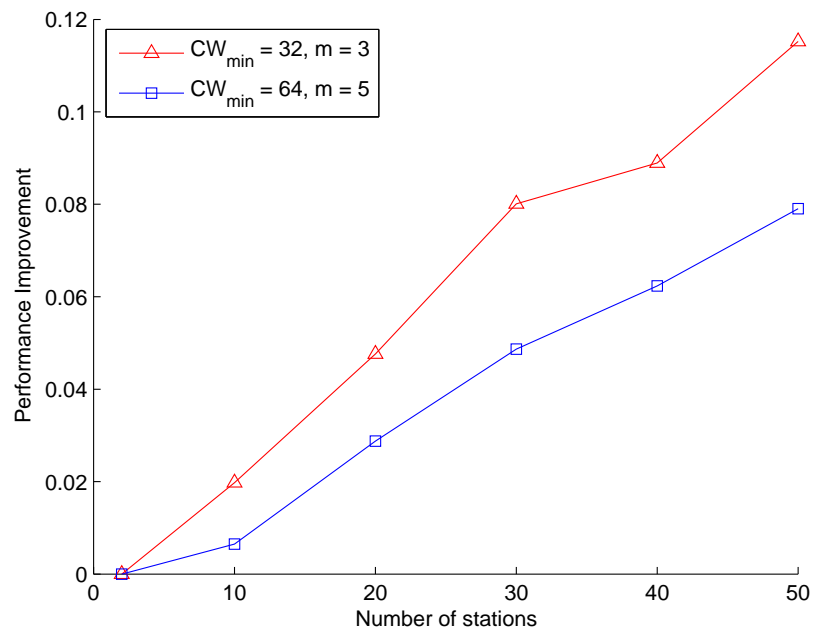


Figure 6.1: EBEB Performance Improvement over BEB

Increasing CW_{min} and/or m creates more space for randomness, the number of collisions are reduced for both schemes and hence the performance gain of EBEB over BEB is relatively less. In other words, as CW_{min} and/or m increase, performance of BEB tends to EBEB. This performance gain comes at the cost of higher delay, as the stations, on an average spend more time waiting before transmitting/retransmitting. This is corroborated from drop in performance gain: 12% for $CW_{min} = 32, m = 3$ to 8% $CW_{min} = 64, m = 5$ for $n = 50$.

EBEB essentially reduces the average number of collisions relative to BEB and hence provides a better Channel Utilization. This improvement in Channel Utilization can be translated to raw throughput or increase in system capacity.

EBEB is not adhered to any particular enhancement of IEEE 802.11 standard or it can be applied to all IEEE 802.11 enhancements. EBEB stations can coexist with BEB stations, which makes it very attractive to adopt for implementation.

6.2 Future Work

In this thesis, the performance comparison of EBEB versus BEB under saturated conditions was evaluated. However, under unsaturated conditions, this performance remains to be evaluated. This analysis will provide more insight into, viability of adopting EBEB over BEB.

Additionally, in this thesis, it is assumed that all the non-AP STAs and AP STA participating, have either EBEB scheme or BEB scheme only. A scenario containing mix of BEB and EBEB stations, still remains to be evaluated. It is highly likely that EBEB STAs in this scenario may be starved, as BEB stations tend to aggressively reach for the channel when compared to EBEB stations.

The average error in simulation results was about 5%. There may be a scope to minimize this error, by improving on the thread synchronization.

Appendix A: Pseudocode

A.1 The BEB Scheme

A.1.1 A BEB Non-AP STA

```
SET  $RET \leftarrow 0$  {RET: Retransmission number}
SET  $DIFS$ ,  $SLOT$  and  $RTO$ 
while  $MSG\_SENT < MAX\_MESSAGES$  do
  if A new Packet at HOL then
    if Channel is BUSY then
       $BO \leftarrow 2^{RET} * (CW_{min} - 1) * SLOT$  {BO: Back Off Time}
      repeat
        if Channel is IDLE then
          Sleep for a  $SLOT$ 
        else
          DEC  $BO$ 
        end if
      until back off time expires
    end if
    Sleep for  $DIFS$ 
    TX MSG
    Log TX TIME, STA ID, MSG ID
    Sleep for  $RTO$ 
    if ACK received for MSG ID then
      RESET  $RET$ 
      Log ACK RX TIME, STA ID, MSG ID
      INC  $MSG\_SENT$ 
    else
```

```
    if  $i < MAX\_BACKOFF$  then
        INC RET
    end if
end if
else
    Sleep arbitrary time
end if
end while
```

A.1.2 The BEB AP STA

```
SET SIFS and SLOT
loop
    if no new MSG then
        Sleep arbitrary time
    else
        Get MSG from QUEUE {FIFO QUEUE}
        Get MSG ID and STA ID from Header
        Log RX TIME, STA ID and MSG ID
        Prepare ACK
        repeat
            Sleep SLOT
        until CHANNEL is IDLE
        Sleep SIFS
        TX ACK
        Log ACK TX TIME, STA ID, MSG ID
    end if
end loop
```

A.2 The EBEB Scheme

A.2.1 An EBEB Non-AP STA

```
SET RET ← 0
SET DIFS, SLOT and RTO
while MSGSENT < MAX_MESSAGES do
  if A new Packet at HOL then
    if Channel is BUSY then
       $BO \leftarrow 2^{RET} * (CW_{min} - 1) * SLOT$ 
      repeat
        if Channel is IDLE then
          Sleep for a SLOT
        else
          DEC BO
        end if
      until back off time expires
    end if
    Sleep for DIFS
    TX MSG
    Log TX TIME, STA ID, MSG ID
    Sleep for RTO
    if ACK received for MSG ID then
      DEC RET
      Log ACK RX TIME, STA ID, MSG ID
      INC MSGSENT
    else
      if  $i < MAX\_BACKOFF$  then
        INC RET
```

```
        end if
    end if
else
    Sleep arbitrary time
end if
end while
```

A.2.2 The EBEB AP STA

```
SET SIFS and SLOT
loop
    if no new MSG then
        Sleep arbitrary time
    else
        Get MSG from QUEUE
        Get MSG ID and STA ID from Header
        Log RX TIME, STA ID and MSG ID
        Prepare ACK
        repeat
            Sleep SLOT
        until CHANNEL is IDLE
        Sleep SIFS
        TX ACK
        Log ACK TX TIME, STA ID, MSG ID
    end if
end loop
```

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Curriculum Vitae

Vikram Kamath received Bachelor of Engineering degree in Electronics and Telecommunication Engineering from Atharva College of Engineering, University of Mumbai, Mumbai, Maharashtra, India, in 2003. He worked as a Software Developer at Infosys Technologies Limited, India, between 2003 - 2006. He was a Graduate Research Assistant at the C4I Center, Department of Computer Science, George Mason University, 2007 - 2008. He has also been affiliated to Communications and Networking Laboratory, Department of Electrical and Computer Engineering, George Mason University, 2007 - 2008 for his Masters Thesis Project.