12-1998

The Simulation, Modeling and Analysis of Wireless Local Area Networks Supporting the IEEE 802.11 Standard

Jaikwan Joo

Recommended Citation

Joo, Jaikwan, "The Simulation, Modeling and Analysis of Wireless Local Area Networks Supporting the IEEE 802.11 Standard" (1998). *Theses and Dissertations*. 5218.
https://scholar.afit.edu/etd/5218

AFIT/GCS/ENG/98D-01

THE SIMULATION, MODELING AND ANALYSIS OF WIRELESS LOCAL AREA NETWORKS SUPPORTING THE IEEE 802.11 STANDARD

THESIS

Jaikwan Joo
Major, ROK Air Force

AFIT/GCS/ENG/98D-01

AFIT/GCS/ENG/98D-01

THE SIMUATION, MODELING AND ANALYSIS OF WIRELESS LOCAL AREA NETWORKS SUPPORTING THE IEEE 802.11 STANDARD

THESIS

Presented to the faculty of the Graduate School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science

Jaikwan Joo, B.S.
Major, ROK Air Force

December, 1998

Approved for public release; distribution unlimited

AFIT/GCS/ENG/98D-01

THE SIMUATION MODELING AND ANALYSIS OF WIRELESS LOCAL AREA NETWORKS SUPPORTING THE IEEE 802.11 STANDARD

Jaikwan Joo

Major, R.O.K.A.F

Approved:

Chairman — 24 Nov 98 date

Member — 24 Nov 98 date

Barry Mullins
Member — 24 Nov 98 date

Acknowledgments

I would like to thank a number of people who have helped with this effort. First of all, Major Richard A. Raines, my thesis advisor, showed me a right way and enormous advice with patient. Major Michael A. Temple and Major Barry E. Mullins, my thesis committee, also provided me a special guidance and also assistance in developing the ideas for this thesis. Lt. Col. David M. Gallagher, my academic advisor and my sponsor, helped me on adapting and scheduling my AFIT life.

Finally, I would like to thank my wife, Yunmi, and two daughters, Ayen and Sungyen, for their support and understanding.

Jaikwan Joo

Table of Contents

List of Figures

Number *Page*

List of Tables

Number *Page*

ABSTRACT

Research to improve the performance of the IEEE 802.11 has been ongoing since 1990. The focus of this research has investigated the use of the MAC (Medium Access Control) and Physical layers for improving throughput. An adaptive MAC protocol, CATER (Code Adapts To Enhance Reliability) is based on the proposed MAC standard for wireless local area networks (WLAN)-802.11.

IEEE 802.11 uses a fixed Pseudo-Noise (PN) code for spreading the information signal, implying a fixed process gain at the receiver. When the channel degrades, IEEE 802.11 offers only retransmissions at the MAC layer to contend with the corrupted medium. However, CATER allows communicating stations to reconfigure their transceivers to use a longer PN code after a prescribed number of failed retransmissions. The longer PN code increases the process gain of the receiver and reduces the error rate.

This thesis analyzes the performance of CATER as changing the factor: Start (the number of transmission before the channel is reconfigured) and Max (additional frame transmissions during reconfigure), PN code length, the number of station, and implementing Forward Error Correction (FEC). CATER provides better throughput for smaller Start and larger Max at a high bit error rate (10^{-3}).

When CATER uses a PN code length of 63, the throughput is increased by 101 percent at high bit error rate (BER). However, 802.11 is better than CATER at low BER ($<10^{-3}$).

As the number of stations is increased, the throughput is decreased, resulting from more stations contending for the channel to transmit the frames. When FEC is implemented with CATER, the throughput is improved by 156 percent at high BER ($>10^{-3}$).

1. Introduction

In recent years, there have been numerous research efforts to support the mobile communications. These efforts examined the employment of wireless media in the local area and utilization of high capacity wired media in the metropolitan and wide area environment.

In July 1990, the IEEE standard project group of 802.11 was formed to recommend an international standard for WLANs [Sta97]. The scope of 802.11 standard group was to develop Media Access Control (MAC) layer and Physical (PHY) layer standards for wireless connectivity of fixed, portable, and mobile stations within the local area. The 802.11 standard proposed that the physical layer to operated at 2.4 GHz Direct Sequence Spread Spectrum (DSSS), 2.4 GHz Frequency Hopping Spread Spectrum (FHSS), or diffused Infrared in the 850 to 950 manometer ranges. The MAC layer was proposed to be asynchronous and time bounded delivery of data frames. 802.11 was also envisioned to support to provide security and privacy for 802.11 compliant devices.

The Federal Communication Commission (FCC) opened the Industrial, Scientific, and Medical (ISM) bands to the unlicensed use of spread spectrum system. The FCC dictated the minimum process gain be 10 dB [Mul97]. To satisfy this requirement, the 802.11 standard proposes the use of an 11-chip Barker Code. In the 802.11standard, this PN code is fixed for all transmissions with no regard to channel performance.

In 1996, Mullins [Mul97] developed the protocol "Code Adapts To Enhance Reliability (CATER)", which has the ability to change the PN code length of DSSS to improve the throughput. CATER changes the PN code length of the two communicating stations from 11 chips to 63 chips if a frame continually fails transmission.

This thesis examines the throughput of CATER as several PN code lengths and several station configuration are modeled. Forward Error Correction (FEC) coding with CATER is also investigated.

This thesis is presented in five chapters. In the Chapter 2, we discuss the medium of wireless, DSSS, and the 802.11 draft standard in detail with focus on MAC layer. In Chapter 3, CATER algorithm is presented as well as the modeling of simulation of the protocol. Chapter 4 presents the analysis of the effects the different simulation factors have on the system throughput. Chapter 5 concludes this thesis by presenting areas for future works.

2. Background

2.1 Introduction

This chapter discusses principles and techniques associated with wireless communications and local area networks. Section 2.2 presents general information about wireless communications: frequency range categorization, wireless systems characteristics, and the trends of wireless communication. Spread spectrum technology is presented in Section 2.3. In this section, the general model of spread spectrum digital communications and the operation and the advantage of direct spread spectrum are discussed. The requirements of Wireless Local Area Network (WLAN) are presented in Section 2.4. The architecture as well as the physical and Medium Access Control (MAC) layers of IEEE 802.11 are also explained in this section. Section 2.5 deals with error control technologies. How Forward Error Correction (FEC) codes and block code operate as discussed in this section. Finally, Section 2.6 presents the summary of this chapter.

2.2 Wireless Communication

Since Gugliemo Marconi first demonstrated the use of radio for communications in 1897, the technologies of wireless communication have tremendously grown. Until recently, radio and satellite communication have dominated the wireless communication area. Examples of wireless communication are paging system, cordless telephone systems, Iridium satellite network (which is under construction, consists of 66 satellites, covers the globe and has voice and data services), cellular systems, and WLAN. Wireless communication allows the user to access the network at any time without regard to location or mobility.

2.2.1 Medium of transmission

Wireless communication uses the unguided medium. For unguided media, transmission and reception are achieved by means of an antenna. For transmission, the antenna radiates electromagnetic energy into the medium (air), and for reception, the antenna picks up electromagnetic wave from the surrounding medium.

There are three general ranges of frequency such as microwave, broadcast, and infrared. Microwave is in the range of about 2GHz to 40GHz. At these frequencies, highly directional beams are possible, and suitable for point-to-point transmission. Microwave is also used for satellite communications.

Broadcast is in the range of 30MHz to 1GHz, suitable for omnidirectional applications. Third range, Infrared covers from 300 GHz to 200,000 GHz. Infrared is useful to local point-to-point and multipoint applications within confined areas, such as a single room.

2.2.1.1 Microwave

Microwave systems use antenna with shapes such as a "dish". A typical size of this type of antenna is about 10 feet in diameter. Microwave antennas are usually located at heights well above ground level in order to extend the range between antennas and to be able to transmit over intervening obstacles. With no intervening obstacles, the maximum distance between antennas conforms to

$$d=7.14\sqrt{Kh} \qquad (2\text{-}1)$$

where d is the distance between antennas in kilometers, h is the antenna height in meters, and K is adjustment factor to account for the fact that microwaves are bent or refracted with the curvature of the earth and will propagate farther than the optical line of sight[Sta97].

The primary use for a microwave system is in long-haul telecommunication service, as alternatives to coaxial cable or optical fiber. The microwave facility requires far fewer amplifiers or repeaters than coaxial cable over the same distance, but requires line of sight transmission. Microwave is commonly used for voice and television transmission and short point-to-point link between buildings. These types of systems can be used for closed-circuit TV or as a data link between local area networks. Common transmission frequencies are in the range 2 to 40 GHz. The higher frequency used, the higher the potential bandwidth and therefore the higher the potential data rate. As with any transmission system, the main source of loss is attenuation. For the microwave, the loss can be express as

$$L=10\mathrm{Log}\left(\frac{4\pi d}{\lambda}\right)^2 \mathrm{dB} \tag{2-2}$$

where d is the distance between transmitter and receiver and λ is the wavelength, in the same units[Sta97]. Loss varies as the square of the distance. In contrast, for twist pair and coaxial cable, loss varies logarithmically with distance. Attenuation increases with rainfall, the effects of which become especially noticeable above 10 GHz. Another source of impairment is interference. With the growing popularity of microwave, transmission area overlap and interference is always a danger. The Federal Communication Commission (FCC) regulates the range in order to eliminate the interference.

2.2.1.2 Broadcast Radio

The principal difference between broadcast radio and microwave is that the former is omnidirectional and the latter is directional. Hence, broadcast radio does not require dish-shaped antennas, and the antennas need not be rigidly mounted to precise alignment.

Broadcast radio waves are less sensitive to attenuation from rainfall[Sta97]. According to Equation 2-2, the longer wavelength, the less attenuation. Because of the longer wavelength, radio suffers relatively less attenuation. A prime source of impairment for broadcast radio wave is multipath interference. Reflection from land, water and buildings create multiple transmission paths between antennas. This effect is frequently evident when TV reception displays multiple images as an airplane passes by.

2.2.1.3 Infrared

One important difference between infrared and microwave is that infrared does not penetrate walls. Thus, the security and interference problems encountered in microwave systems are not present. Furthermore, there is no frequency allocation issue with infrared, because no licensing is required [Sta97].

2.2.2 FDD and TDD

Wireless communication systems may be classified as simplex, half duplex, or full duplex. In simplex systems, communication is possible in only one direction. Half duplex radio systems allow two-way communication, but use the same radio channel for both transmission and reception. This means that at any given time, a user can only transmit or receive information. On the other hand, full duplex systems allow simultaneously radio transmission and reception between a subscriber and base station, by providing two simultaneously but separate channels (Frequency Division Duplex, (FDD)) or adjacent time slots on a single radio channel (Time Division Duplex, (TDD)). FDD provides simultaneous radio transmission channels for subscriber and base station, so that they both may constantly transmit while simultaneously receiving signals from one another. At the base station, a separate antenna is used to accommodate the two separate channels. At the subscriber unit, however, a single antenna is used for both transmission on and from the base station, and a device called a Duplexer is used inside the subscriber unit to enable the same antenna to be used for simultaneous transmission and reception. To facilitate FDD, it is necessary to separate the transmit and receive frequency by about 5 % of the nominal RF frequency[Sta97]. TDD uses the fact that it is possible to share a single radio channel in time, so that a portion of the time is used to transmit from the base station to the mobile, and the remaining time is used to transmit from the mobile to the base station.

Because TDD needs digital transmission formats, digital modulation, and is very sensitive to timing, only recently has it been used, and only for indoor or small area wireless application.

2.2.3 Trends in wireless communication

Since 1989, there has been enormous activity throughout the world to develop personal wireless systems that combine the network intelligence of today's PSTN (Public Switched Telephone Network) with modern digital processing and RF technology.

A world-wide standard, Future Public Land Mobile Telephone System (FPLMTS) - renamed the International Mobile Telecommunication 2000 (IMT-2000) in mid-1995 is being formulated by International Telecommunication Union (ITU). IMT-2000 is a globally compatible digital mobile radio system that will integrate paging, cordless, and cellular system, as well as Low Earth Orbit (LEO) satellites, into one universal mobile system. A total of 240MHz in the frequency band 1885MHz to 2025MHz and 2100 MHz to 2200 MHz has been targeted by the ITU World Administrative Radio Conference (WARC) in 1992. The types of modulation, speech coding, and multiple access scheme to be used in IMT-2000 are yet to be decided.

2.3 Spread Spectrum Technique

The spread spectrum technique was developed initially for military requirements. The essential idea is to spread the information signal over a wider bandwidth in order to make jamming and interception more difficult [Sta97].

Figure 2-1 represents the key characteristics of any spread spectrum system. Input is fed into a channel encoder that produces an analog signal with a relatively narrow bandwidth around some center frequency. This signal is further modulated using a sequence of seemingly random digits known as a pseudorandom sequence. The effect of this modulation is to significantly increase the bandwidth (spread the spectrum) of the signal to be transmitted. On the receiving end, the same digit sequence is used to demodulate the spectral signal. Finally, the signal is fed into a channel decoder to recover the data [Sta97].

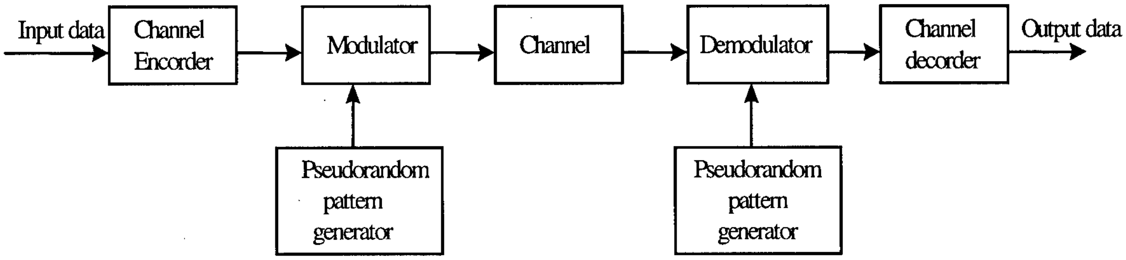


Figure 2-1 General Model of Spread Spectrum digital

Spreading the signal allows a spread spectrum system to operate with little interference to a conventional radio system. The signal is easier to hide from unauthorized or unfriendly systems. The possibility of jamming is reduced, and signal detection is more difficult, which leads to increase security. Spread spectrum offers selective addressing and code multiplexing. They can reduce the effects of multipath thereby increasing node mobility within an enclosed area such as an office. Multipath can be described as multiple copies of the same signal arriving at the receiver via different paths at slightly different times, potentially causing mutual interference [Mul97]. Although spread spectrum has many qualities, not all capabilities can be provided by one system configuration at one time.

A disadvantage of spread spectrum is that it requires increased bandwidth to accommodate the spread signal. Although spread spectrum offers a performance improvement in presence of other signals, it does not negate the corrupting effects of Gaussian noise[Sta97]. Spread spectrum systems are usually more expensive than traditional radio systems. Finally, because spread spectrum systems use the unlicensed ISM (Industry, Science, and Medical), operating parameters may limit system performance. Table 2-1 shows the frequency band and bandwidth for ISM.

The FCC regulation says that the transmitter's maximum peak output power into the antenna (6 dBi maximum antenna gain) is limited to less than 1 Watt and the processing gain must be at least 10 dB.

Spread spectrum capabilities are based on a direct implementation of Shannon's channel capacity formula, which is [Mul97]

$$C = W \log_2 \left(1 + \frac{S}{N}\right) \qquad (2\text{-}3)$$

where C is the channel capacity in bits per second, W is the bandwidth in hertz, N is noise power, and S is the signal power.

Table 2-1 ISM Frequency Bands

ISM Frequency Band(MHz)	**Availability Bandwidth(MHz)**
902 – 928	**26**
2400 – 2483	**83.5**
5725 – 5870	**125**

According to Equation 2-3, bandwidth requirements increase if channel capacity increases while channel noise and signal power remain unchanged. Channel bandwidth must increase if capacity remains the same but the channel becomes noisier (noise-to-signal power ratio increases). The tradeoff is bandwidth for noise and capacity.

There are two spreading techniques used by radio spread spectrum systems. These techniques are direct spread spectrum and frequency hopping. Because this research will only use direct sequence spread spectrum, frequency hopping is not discussed.

2.3.1 Direct Sequence Spread Spectrum (DSSS)

Under this scheme, each bit in the original signal is represented by multiple bits in the transmitted signal, known as a chipping code. The chipping code spreads the signal across a wider frequency band in direct proportion to the number of bits used. Therefore, a 10-bit chipping code spreads the signal across a frequency band 10 times greater than a 1 bit chipping code.

Direct sequence spread spectrum is to combine the digital information stream with the pseudorandom bit stream using an Exclusive-OR circuit. Figure 2-2 shows an example of a DSSS system. Note that an information bit of 1 inverts the pseudorandom bits in combination, while an information bit of 0 does not inverts the pseudorandom bits to be transmitted without inversion. The combination bit stream has the data rate of the original pseudorandom sequence, so it has wider bandwidth than the information stream. In Figure 2-2, the psueudorandom bit stream is clocked at four times the information rate.

The spectrum spreading achieved by the direct sequence technique is easily determined. For example, suppose the information signal has a bit width of T_b, which is equivalent to a data rate of $1/T_b$. In that case, the bandwidth of the signal, which depends on encoding technique, is roughly $2/T_b$. Similarly, the bandwidth of the pseudorandom signal is $2/T_c$, where T_c is bit width of pseudorandom input. The bandwidth of the combined signal is approximately the sum of the two bandwidth, or $2/(T_b+T_c)$. The amount of spreading that is achieved is a direct result of the data rate of the pseudorandom stream; the greater the data rate of the pseudorandom input, the greater the amount of spreading [Sta97].

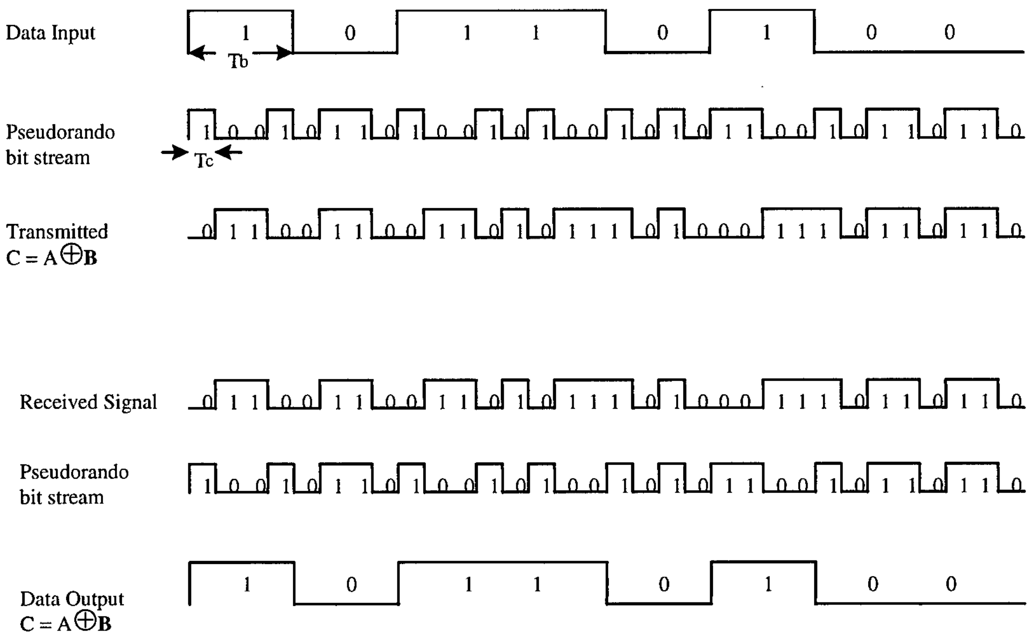


Figure 2-2 Example of Direct Sequence

2.3.1.1 Process Gain

Process gain is a measure of merit for spread spectrum systems and is defined as

$$G_p = \frac{BW_{RF}}{R_{Info}} \tag{2-4}$$

where BW_{RF} is the RF bandwidth and R_{info} is the data rate of information. For a DSSS system, the process gain is usually taken as [Mul97]

$$G_p = \frac{Chippingrate}{Datarate} \tag{2-5}$$

Assuming the system is symbol synchronous (one PN code sequence per data bit), the process gain is simply the number of chips used per data bit [Mul97]. The process gain is the form of a signal-to-noise improvement, which comes at the expense of channel capacity. Therein lies a critical feature of spread spectrum. If capacity can be sacrificed, an improvement can be achieved in the signal-to-noise ratio.

2.4 Wireless Local Area Network (WLAN)

As a result of advances in digital communications, portable computers, and semiconductor technology, the field of WLANs is expanding rapidly. WLAN are being studied as an alternative to the high installation and maintenance costs incurred by traditional additions, deletions, and changes experienced in wired LAN infrastructures. WLANs can be used as wired LAN extension, cross-building interconnect, nomadic access, and ad hoc network. WLANs must meet the same sort of requirements typical of any LAN, including high capacity, ability to cover short distances, full connectivity among attached stations, and broadcast capability.

There are two standards that are related to wireless LAN systems. These standards include two physical and link layer standards, IEEE 802.11 and European Telecommunication Standards Institute (ETSI) HIgh PErformance Radio LAN (HIPERLAN). HIPERLAN is designed to provide high speed (up to 20Mbps) over short distances (50 meters) using radio link between computers at dedicated frequency bands of 5.2 and 17.2GHz [Mul97].

WLANs are generally categorized according to the transmission technique that is used as shown in Table 2-2. This research only deals with IEEE 802.11 that uses Direct Sequence Spread Spectrum (DSSS).

2.4.1 The Requirements of WLAN

Users of wireless networks will want the same services and capabilities that they have commonly come to expect in wired networks. However, to meet these objectives, the wireless community faces certain challenges and constraints that are not imposed on their wired counterparts:

Frequency Allocation: Frequency band for particular uses must typically be approved and licensed.

Interference and Reliability: Interference in wireless communications can be caused by simultaneous transmission (i.e., collisions) by two or more sources sharing the same frequency band. Collisions are also caused by the "hidden terminal" problem, where a station, believing the channel is idle, begins transmission without successfully detecting the presence of a transmission already in progress. Interference is also caused by multipath fading, which is characterized by random amplitude and phase fluctuations at the receiver. The reliability of the communication channel is typically measured by the average bit error rate (BER). For packetized voice, packet loss rates on the order of 10^{-2} are generally acceptable, for uncoded data (BER of 10^{-5}).

Table 2-2 Comparison of Wireless LAN Technologies

	Infrared		**Spread spectrum**		**Radio**
	Diffused Infrared	**Direct Beam Infrared**	**Frequency Hopping**	**Direct Sequence**	**Narrow band Microwave**
Data Rate(Mbps)	1 - 4	1 - 10	1 - 3	2 - 20	5 - 10
Mobility	Stationary / Mobile	Stationary with LOS	Mobile	Stationary / mobile	
Range(ft)	50 - 200	80	100 - 300	100 - 800	40 - 130
Detectability	Negligible		Little		Some
Wavelength/ Frequency	λ = 800-900nm		ISM Band: 902-928 MHz 2.4 - 2.4835 GHz 5.725 - 5.85 GHz		18.825 - 19.205GHz or ISM band
Modulation Technique	OOK		GFSK	QPSK	FS / QPSK
Radiated Power	N/A		< 1W		25mW
Access Method	CSMA	Token Ring, CSMA	CSMA		Reservation ALOHA,CSMA
License required	No		No		Yes unless ISM

Security: A wireless network is more difficult to secure, since the transmission medium is open to anyone within the geographical range of a transmitter. Data privacy is usually accomplished over a radio medium using encryption. While encryption of wireless traffic can be achieved, it is usually at the expense of increased cost and decreased performance.

Power Consumption: The devices must be designed to be very energy-efficient, resulting in "sleep" mode and low-power displays, causing users to make cost versus performance and cost versus capability tradeoffs.

Mobility: System designs must accommodate handoffs between transmission boundaries and route traffic to mobile users.

Throughput: WLANs are currently targeted to operate at data rates between 1-20 Mbps. The IEEE 802.11 draft standard describes mandatory support for 1 Mbps WLAN with optional support at a 2 Mbps data transmission rate [CrF97].

2.4.2 IEEE 802.11 Wireless LAN

The IEEE 802.11 committee has been working since 1990 on the establishment of standard for wireless LANs. To create the standard, the committee makes use of the 2.4 GHz ISM band.

2.4.2.1 Architecture

There are primarily two topologies in the IEEE 802.11 standard, ad hoc and infrastructure. The basic service set (BSS) is the fundamental building block of IEEE 802.11 architecture. A BSS is defined as a group of stations that are under the direct control of single coordination function (i.e., a Distributed Coordination Function (DCF) or Point Coordination Function (PCF)) which is defined below. The geographical area covered by the BSS is known as the basic service area (BSA), which is analogous to a cell in a cellular communication network. An ad hoc network is a deliberate grouping of stations into a single BSS for the purpose of internetworked communication without the aid of an infrastructure network. Figure 2-3 is an illustration of an independent BSS (IBSS), which is the formal name of an ad hoc network in the IEEE 802.11 standard. Any station can establish a direct communication session with any other station in the BSS, without the requirement of channeling all traffic through a centralized access point (AP).

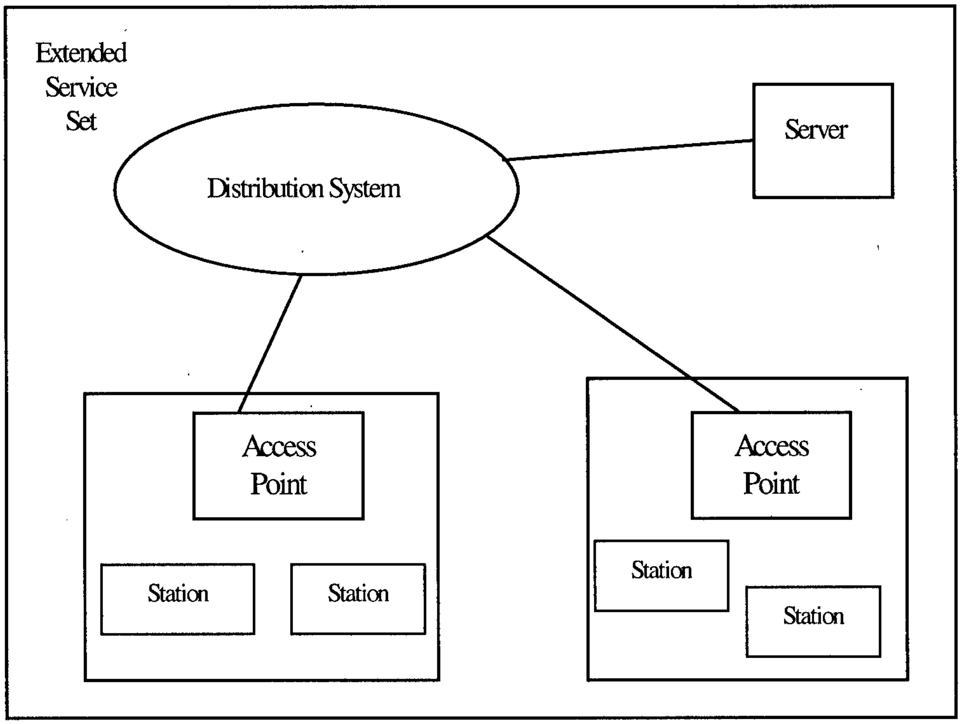


Figure 2- 3 IEEE 802.11 Architecture Infrastucture

Infrastructure networks are established to provide wireless users with specific service and range extension. Infrastructure networks are established using APs. The AP supports range extension by providing the integration points necessary for network connectivity between multiple BSSs, thus forming an extended service set (ESS). The ESS has the appearance of one large BSS to the logical link control (LLC) sublayer of each station (STA). The ESS consists of multiple BSSs that are integrated together using a common distribution system (DS). The DS can be thought of as a backbone network that is responsible for MAC-level transport of MAC service data units (MSDU). An ESS can also provide gateway access for wireless users into a wired network such as the Internet. This is accomplished via a device known as a portal. The portal is a logical entity that specifies the integration point on the DS where the IEEE 802.11 network integrates with a non-IEEE 802.11 network.

2.4.2.2 Physical Layer

The IEEE 802.11 draft specification calls for three different physical layer implementations: frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS), and Infra Red (IR). The FHSS utilizes the 2.4 GHz ISM band (i.e., 2.4-2.4835 GHz). In the United States, a maximum of 79 channels is specified in hopping set. The first channel has a center frequency of 2.402 GHz, and all subsequent channel are specified 1MHz apart. The FCC for the 2.4 GHZ ISM band mandates the separation of 1 MHz separation. Three different hopping sequence sets are established with 26 hopping sequences per set. Different hopping sequences enable multiple BSSs to coexist in the same geographical area, which may become important to alleviate congestion and maximize the total throughput in a single BSS. The reason for having three different sets is to avoid prolonged collision periods between different hopping sequences in a set [CrF97].

The DSSS also uses the 2.4 GHz ISM frequency band, where the 1 Mb/s basic rate is encoded using differential binary phase shift keying (DBPSK), and a 2Mb/s enhanced rate uses differential quadrature phase shift keying (DQPSK). The spreading is done by dividing the available bandwidth into 11 subchannels, each 11 MHz wide, and using an 11-chip Barker sequence to spread each data symbol. The maximum channel capacity is (11 chips/symbol)/(11MHz) = 1Mb/s if DBPSK is used. Overlapping and adjacent BSSs can be accommodated by ensuring that the center frequencies of each BSS are separated by at least 30MHz.

The IR specification identifies a wavelength range from 850 to 950 nm. The IR band is designed for indoor use only and operates with nondirected transmissions. The IR specification was designed to enable station to receive line-of-sight and reflected transmissions. Encoding of the basic access rate of 1Mb/s is performed using 16-pulse position modulation (PPM), where 4 data bits are mapped to 16 coded bits for transmission. The enhanced access rate (2Mb/s) is performed using 4-PPM modulation, where 2 data bits are mapped to 4 coded bits for transmission.

2.4.2.3 Medium Access Control Sublayer

The MAC sublayer is responsible for the channel allocation procedures, protocol data unit (PDU) addressing, frame formatting, error checking, and fragmentation and reassembly. The transmission medium can operate in contention period (CP) and contention free period (CFP). During the CFP, medium usage is controlled by the AP, thereby eliminating the need for stations to contend for channel access. IEEE 802.11 supports three different types of frames: management, control, and data. The management frames are used for station association and disassociation with the AP. This provides timing and synchronization, and authentication and deauthentication information. Control frames are used for handshaking during the CP, for positive acknowledgments during the CP, and to end the CFP. Data frames are used for the transmission of data during the CP and CFP, and can be combined with polling and acknowledgment during the CFP.

2.4.2.3.1 Distributed Coordination Function

The DCF is the fundamental access method used to support asynchronous data transfer on a best effort basis. As Figure 2-4 shows, all station must support the DCF. The DCF operates solely in the ad hoc network, and either operates solely or coexists with PCF in infrastructure network.

The DCF is located on top of the physical layer and supports contention services. Contention services imply that each station with an MPDU queued for transmission must contend for access to the channel for all subsequent frames. Contention services promote fair access to the channel for all stations.

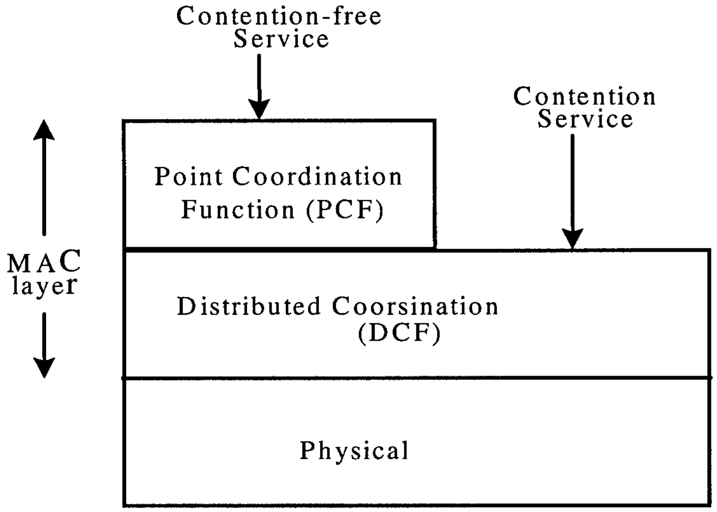


Figure 2-4 IEEE 802.11 Protocol Architecture

The DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA). CSMA/CD (Carrier Sensing Multiple Access with Collision Detection) is not used because a station is unable to listen to the channel for collisions while transmitting. In IEEE 802.11, carrier sensing is performed at both the air interference, referred as physical carrier sensing, and at the MAC sublayer, referred as virtual carrier sensing. Physical carrier sensing detects the presence of stations by analyzing all detected packets, and also detects activity in the channel via relative signal strength from other sources.

A source station performs virtual carrier sensing by sending MPDU duration information in the header of request to send (RTS), clear to send (CTS), and data frames. An MPDU is a complete data unit that is passed from the MAC sublayer to the physical layer. The duration field indicates the amount of time (in microseconds) after the end of the present frame the channel will be utilized to complete the successful transmission of the data or management frame. The stations in the BSS use the information in the duration field to adjust their network allocation vector (NAV), which indicates the amount of time that must elapse until the current transmission session is complete and the channel can be sampled again for idle status. The channel is marked busy if either the physical or virtual carrier sensing mechanism indicates the channel is busy.

Priority access to the wireless medium is controlled through the use of interframe space (IFS) time interval between the transmission of frames. The IFS intervals are mandatory periods of idle time on the transmission medium. There are three IFS known as short IFS, point coordination function IFS (PIFS), and DCF-IFS (DIFS). The order of IFS length is SIFS, PIFS, and DIFS. SIFS has the highest priority access among the IFS. For the basic access method, when a station senses the channel is idle, the station waits for a DIFS period and gets the channel. If the channel is still idle, the station transmits an MPDU. The receiving station calculates the checksum and determines if the packet was received correctly. Upon the receipt of a correct packet, the receiving station waits a SIFS interval and transmits a positive acknowledgment (ACK) back to the source station.

Figure 2-5 is a timing diagram illustrating the successful transmission of a data frame, when the data frame is used to let all station in the BSS know how long the medium will be busy. All stations hearing the data frame adjust their NAV based of the duration field value, which includes the SIFS interval and the ACK following the data frame.

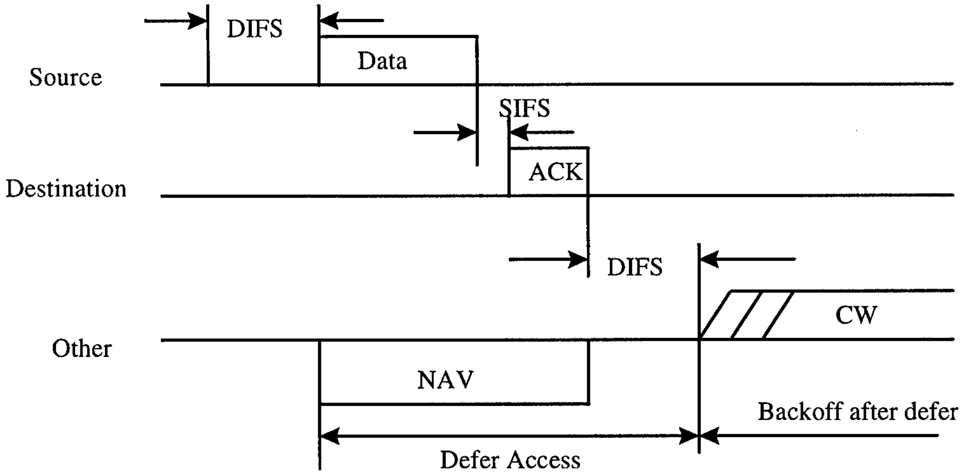


Figure 2-5 Transmission of an MPDU without RTS/CTS

RTS and CTS control frames can be used by a station to reserve channel bandwidth prior to the transmission of an MPDU and to minimize the amount of bandwidth wasted when collisions occur. RTS and CTS control frames are relatively small (RTS is 20 octets and CTS is 14 octets) when compared to maximum data frame size (2346 octets). The source station (after successfully contending for channel) first transmits the RTS control frame with a data or management frame queued for transmission to a specified destination station. All stations in the BSS hear the RTS packet, read the duration field and set their NAVs accordingly. The destination station responds to RTS packet with a CTS packet after an SIF idle period has elapsed. Stations hearing the CTS packet look at the duration field and again update their

NAV. Upon successful reception of the medium is stable and reserved for successful transmission of the MPDU. Figure 2-6 illustrates the transmission of an MPDU using the RTS/CTS.

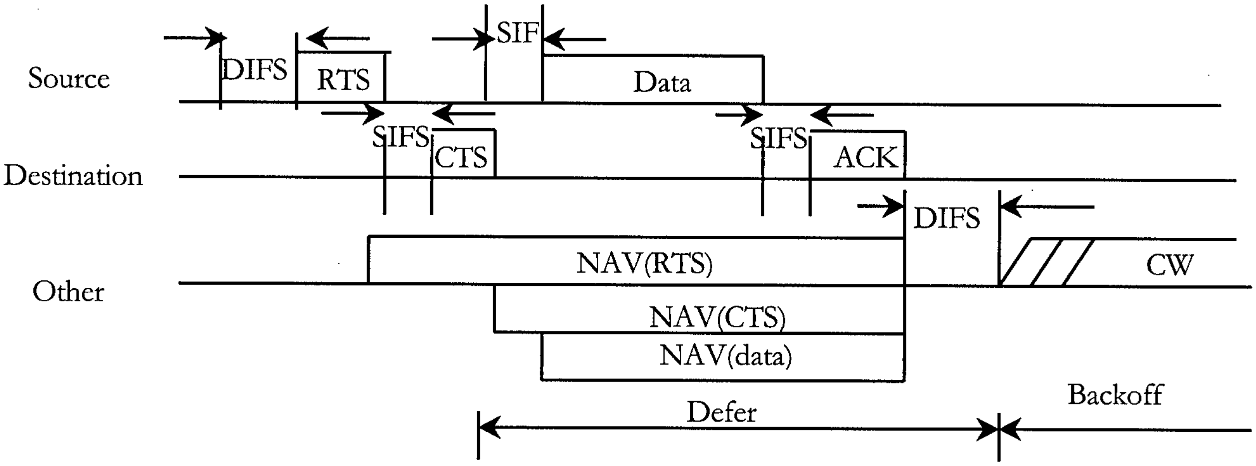


Figure 2-6 Transmission of an MPDU with RTS/CTS

The collision avoidance portion of CSMA/CA is performed through a random backoff procedure. If a station with frame to transmit initially senses the channel to be busy, then the station waits until the channel becomes idle for a DIFS period, and the compute a random backoff time. For IEEE 802.11, time is slotted in time periods that correspond to a slot_time. Unlike Slotted Aloha, where the slot time is equal to the transmission time of one packet, the slot_time used in IEEE 802.11 is much smaller than an MPDU and is used to define the IFS intervals and determine the backoff time is an integer value that corresponds to a number of time slots. Initially, the station computes a backoff time in the range 0-7. After the medium becomes idle following a DIFS period, stations decrement their backoff timer until the medium becomes busy again or the timer reaches zero. When the timer is finally decremented to zero, the station transmits its frame. If two or more stations decrement to zero at the same time, a collision will occur, and each station will have to generate a new backoff time. The backoff time grows as $\lfloor 2^{(2+i)} \bullet ranf() \rfloor$ * Slot_Time, where i is the number of consecutive times a station attempts to send an MPDU, ranf() is a uniform random variation in (0,1). The idle period after a DIFS period is referred to as the contention window (CW). The advantage of this channel access method is that it promotes fairness among stations, but its weakness is that it probably could not support time-bounded services. With DCF, there is no mechanism to guarantee minimum delay to stations supporting time-bounded services.

2.4.2.3.2 Point Coordination Function

The PCF provides contention-free (CF) frame transfer. The PCF relies on the point coordinator (PC) to perform polling, enabling polled stations to transmit without contending for the channel. The AP within each BSS performs the function of the PC.

The PCF repetition interval (CFP_Rate) is used to determine the frequency with which the PCF occurs. Within a repetition interval, a portion of the time is allotted to contention-free traffic, and the reminder is provided for contention-based traffic. The CFP repetition interval is initiated by beacon frame, where the AP transmits the beacon frame. One of its primary functions is synchronization and timing. The maximum size of the CFP is determined by the manageable parameter CFP_Max_Duration. The minimum value of CFP_Max_Duration is the time required to transmit two maximum-size MPDUs, including overhead, the initial beacon frame, and the CF_End frame. The maximum value of CFP_Max_Duration is the CFP repetition minus the time required to successfully transmit a maximum size MPDU during the CP (which includes the time for RTS/CTS handshaking and the ACK). It is up to the AP to determine how long to operate the CFP during any given repetition interval. If traffic is very light, the AP may shorten the CFP and provide the reminder of the repetition for the DCF. If previous DCF traffic carry over into current interval, the PCF is shortened.

Figure 2-7 shows coexistence of the PCF and DCF. At the beginning of each CFP repetition interval, all stations in the BSS update their NAV to the maximum length of the CFP. At the start of the CFP, PC senses the medium. If the medium remains idle for PIFS interval, the PC transmits a beacon frame to initiate the CFP. The PC starts a CF transmission a SIFS interval after the beacon frame is transmitted by sending a CF-Poll(no data), data or data + CF-Poll frame. The PC can immediately terminate the CFP by transmitting a CF-End frame. If the station in BSS receives a CF-Poll (no data) frame from the PC, the station can respond to the PC after a SIFS idle period, with a CF-ACK (no data) or a data + CF_ACK frame. If the PC receives a data + CF-ACK frame from station, the PC can send a data + CF-ACK + CF-Poll frame to a different station, where the CF-ACK

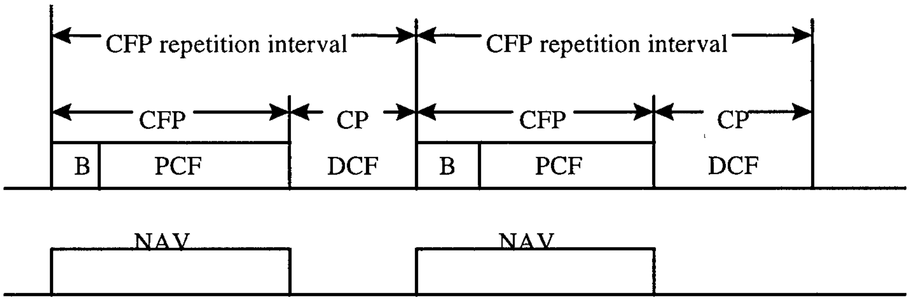


Figure 2-7 Coexistence of the PCF and DCF

portion of the frame is used to acknowledge receipt of the previous data frame. If the PC transmits a CF-poll (no data) and destination station does not have a data frame to transmit, the station sends a Null Function (no data) frame back to the PC.

Figure 2-8 represents the transmission of frames between the PC and a station, and vice versa. If the PC fails to receive an ACK for a transmitted data frame, the PC waits a PIFS interval and continues transmitting to the next station in the polling list.

After receiving the poll from the PC, the station may choose to transmit a frame to another station in the BSS. When the destination station receives the frame, a DCF ACK is returned to source station, and the PC waits a PIFS interval following the ACK frame before transmitting any addition frames.

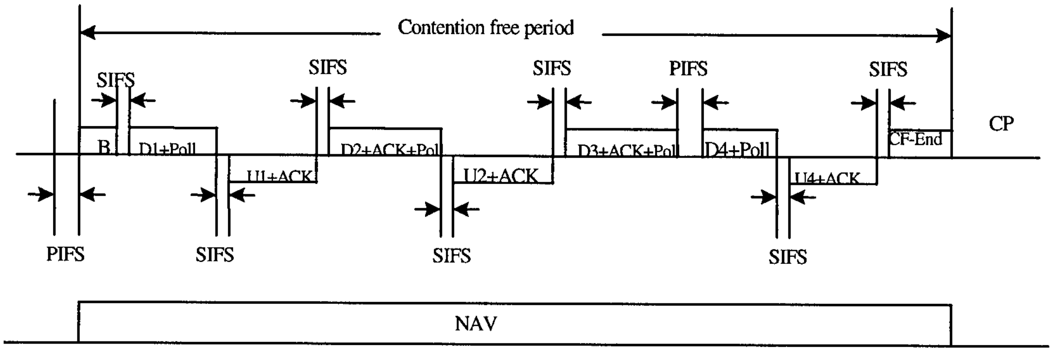


Figure 2-8 PC to Station Transmission

Figure 2-9 illustrates station-to-station frame transmission during the CFP. The PC may also choose to transmit a frame to an non-CF-aware station. Upon successful receipt of the frame, the station would wait a SIFS interval and reply to the PC with a standard ACK frame.

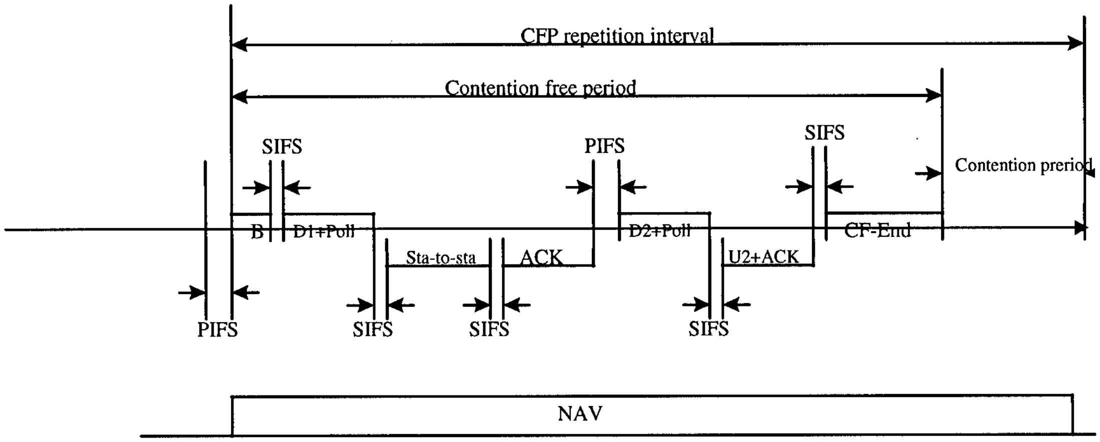


Figure 2-9 Station to Station Transmission

2.5 Error Control

There are two types of error control strategy: FEC (Forward Error Correction) and ARQ (Automatic Repeat Request). Error control for a one-way system must be accomplished using FEC, that is, by employing error-correcting codes that automatically correct errors detected at the receiver. ARQ is two-way system, when errors are detected at the receiver, a request is sent for the transmitter to repeat the message, and this continues until the message is received correctly.

There are two types ARQ systems: stop-and–wait ARQ and continuous ARQ. In the stop-and-wait ARQ, the transmitter sends a code word to receiver and waits for positive (ACK) or negative (NAK) acknowledgment from the receiver. If ACK is received (no error detected), the transmitter sends the next code. If NAK is received (errors detected), it sends the preceding code word. When the noise is persistent, the same code word may be retransmitted several times before it is correctly received and acknowledged. With continuous ARQ, the transmitter sends code words to the receiver continuously and receives acknowledgments continuously. When a NAK is received, the transmitter begins a retransmission. It may back up to the code word in error and resend that words plus the word that follows it (go-back-N ARQ). Alternatively, the transmitter may send only those code words that are acknowledged negatively (selective-repeat ARQ). Selective-repeat ARQ is more efficient than go-back-N ARQ, but requires more logic and buffering. When higher transmission rate and longer round trip delay and full duplex channels, continuous ARQ is used.

The major advantage of ARQ is that error detection requires much simpler decoding equipment than error correction. Also, ARQ is adaptive in the sense that information is retransmitted only when error occur. On the other hand, when the channel error rate is high, retransmission must be sent too frequently, the throughput of ARQ is lower than FEC. The combination of FEC for the most frequent error patterns and ARQ for less likely error pattern is more efficient than ARQ alone.

2.5.1 Forward Error Correction (FEC)

There are many categories of FEC: block codes, cyclic codes, Reed Solomon codes, and convolutional codes. Each type is briefly described below.

In general, block codes break the data stream up into k-bit blocks, and (n-k) check bits are added to these blocks. This is referred to as (n, k) block code. An encoder outputs a unique n-bit code for each of the 2^k possible input k-bit blocks. For example, a (15,11) code has 15 bit code words, 4 bits of which are parity bits and reminder data bits.

Cyclic codes are also block codes, but the code words are simple lateral shifts of one another. For example, take the code word $c=(c_1, c_2, c_3, \dots c_n)$, then $(c_2, c_3, \dots c_n, c_1)$

and $(c_3, \dots c_n, c_1, c_2)$ are also codewords. This structure enables cyclic code to correct larger blocks of errors than non-cyclic block codes. Cyclic codes are quite easy to implement and use the shift register. The number of shift register bits is equal to the number of parity bit (n-k).

Reed Solomon codes are a subset of BCH (Bose-Chaudhuri-Hocquenghem) cyclic code which are designed to provide multiple error correction. Convolutional codes operate on a sliding sequence of data bits in order to generate the code stream of bits.

2.5.1.1 Block Codes

In the block coding, this binary information sequence is segmented into message blocks of fixed length. Each message block consists of **k** information digits. There are a total of 2^k distinct messages. The encoder transforms each input message **u** into binary n-tuple **v** (code word or code vector) with n > k. Generator matrix (G) is needed to transform message into code word. G is k x n matrix as follows.

$$G = \begin{bmatrix} g_0 \\ g_1 \\ \cdot \\ \cdot \\ \cdot \\ g_{k-1} \end{bmatrix} = \begin{bmatrix} g_{00} & g_{01} & g_{02} & \cdot & \cdot & \cdot & g_{0,n-1} \\ g_{10} & g_{11} & g_{12} & & & & \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ g_{k-1,0} & g_{k-1,1} & g_{k-1,2} & \cdot & \cdot & \cdot & g_{k-1,n-1} \end{bmatrix}$$

Where $g_i = (g_{io}, g_{i1}, \dots\dots, g_{i,n-1})$ for $0 \le i \le k$. If $u = (u_1, u_2, \dots, u_{k-1})$ is the message to be encoded, the corresponding code word can be follows:

$$V = u \bullet G = (u_1, u_2, \ldots\ldots, u_{k-1}) \bullet \begin{bmatrix} g_0 \\ g_1 \\ \cdot \\ \cdot \\ \cdot \\ g_{k-1} \end{bmatrix} = u_0 g_0 + u_1 g_1 + \ldots\ldots + u_{k-1} g_{k-1}$$

For example, when given the matrix G, if we encode message (1011) to code word.

$$G = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$V = [1011] \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} = (1\ 0\ 0\ 1\ 0\ 1\ 1)$$

Code word is 1001011.

Code word is sent to receiver. The receiver will receive vector r, r = v + e, where e is error vector. If the presence of errors is detected, the decoder will take action to locate the errors and correct them. When r is received, the decoder computes the following (n-k)-tuple:

$s = r \bullet H^T = (s_0, s_1, \ldots, s_{n-k-1})$ which is called the syndrome of r. Then s = 0 if only if r is a code word, and $s \neq 0$ if only if r is not a code word. Therefore, when $s \neq 0$, we know that r is not a code word and the presence of errors has been detected. It is possible that the errors in certain error vector are not detectable (i.e., r contains errors but $s = r \bullet H^T = 0$). It can be happen when the error pattern e is identical to a non zero code word. Since there are

2^k-1 nonzero code words, there are 2^k-1 undetectable error patterns. When an undetectable error pattern occurs, the decoder makes a decoding error.

$s = r \bullet H^T = (v + e) H^T = v H^T + e H^T$. Because $v H^T = 0$, $s = e H^T$.

$$\text{For example, } H = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \end{bmatrix} \text{ from the matrix G.}$$

$$H^T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix}$$

Let v = (1001011) be the transmitted code word and r =(1001001) be the receive vector.

$$s = r \bullet H^T = [1001001] \bullet \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix} = (1\ 1\ 1)$$

Next, the receiver lookups the syndrome table to find error vector. Table 2-3 is shown the syndrome table. In this table, Syndrome of (111) is associated with error vector (0000010). So, code word will be $V^* = r + e = (1\ 0\ 01\ 0\ 0\ 1) + (0\ 0\ 0\ 0\ 0\ 1\ 0) = (1\ 0\ 0\ 1\ 0\ 1\ 1)$.

Table 2-3 Syndrome Table of Code word (001011)

Syndrome	Error Vector
000	0000000
001	0010000
010	0100000
011	0000100
100	1000000
101	0100000
110	0001000
111	0000010

2.6 Summary

This chapter discussed the wireless communication issues. An overview of wireless communication was provided with emphasis on the frequency. Direct Sequence Spread Spectrum technology was presented next. DSSS offers an effective means to improve the channel reliability of the wireless communication. WLANs were presented next. The requirements of WLANs and major aspect of 802.11 were presented including the distributed coordination foundation wireless medium access control and the physical layer specification.

Finally, the error control such as ARQ and FEC was presented. It contained how the block codes, one of FEC schemes, operate.

3. Methodology

3.1 Introduction

In order to improve the throughput of wireless LANs, many methods have been developed in this area. According to the 802.11, Wireless LANs are implemented with spread spectrum technology, which have the characteristics to increase the process gain as changing spread spectrum parameter (PN code).

The protocol, CATER (Code Adapts To Enhance Reliability) developed by [Mul97] use these characteristics. In this research, this protocol will be used as main topic. The protocol monitors network performance at MAC sublayer and dynamically changes spread spectrum parameters at the physical layer to increase process gain when needed [Mul97]. This chapter presents the objectives of this research, operating assumptions, the algorithm of CATER, and the simulation construction.

3.2 The objectives

The objective of this thesis is to analyze the throughput of the wireless LAN as the PN code is changed and as the number of stations is changed. In addition, when Forward Error Correction (FEC) is implemented with this protocol, the throughput will be analyzed.

3.3 Assumptions

3.3.1 Network Topology

The stations are fully meshed in a bus-style topology. That is, all stations can transmit and receive to and from each other. This does not consider temporary fade or degradation in the link between two stations. The hidden terminal problem is not considered.

3.3.2 Capture

Without capture, if the collision occurs, all colliding frames are destroyed beyond recovery.

3.3.3 Number of stations

This research uses 10 stations, 15 stations and 20 stations for investigating the performance. These values are chosen due to the fact LANs typically have a small number of stations.

3.3.4 Power Considerations

Since the wireless LAN depends on the battery, power consumption is always of concern. For the purposes of this research, power is assumed to be available.

3.3.5 Distributed Foundation Wireless Medium Access Control (DFWMAC)

DCF is used specially in this research. PCF is not addressed. That is, this research considers the ad hoc network instead of an infrastructure network.

3.3.6 Transmission Mode

Since LANs typically have bursty traffic, a packet switching mechanism is used.

3.3.7 Addressing Mode

This supports the modified unicast transmissions. All stations transmit to the station with next highest address; the last station transmits to the lowest numbered station. For example, if the number of station is 5, station 0 transmits to station 1, 2 to 3, 3 to 4, and 4 to 0.

3.3.8 Propagation Delay

Since wireless stations are in close proximity to each other, propagation delay of the radio signal is negligible. Therefore, delay is assumed to be 0.

3.3.9 Packet Generation Rates

Each station uses a Poison process to create the packets.

3.3.10 Frame Length

Frame length is fixed at 8000 bits.

3.3.11 System Queue

All system queues are FIFO. Each station is with a finite capacity queue (10 frames) within MAC layer.

3.3.12 PN code Sequence

IEEE 802.11 specified the use of the 11 chip Barker sequence:

+1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1

This research alters the spread sequence during a session. Each station changes the PN Code such as 11 to 49, 11 to 63, and 11 to 94.

3.3.13 Modulation Format and Channel Data Rates

802.11 supports Differential Binary Phase Shift Keying (DBPSK) modulation that provides a 1Mbps data rate and Differential Quardrature Phase Shift Keying (DQPSK) modulation that provides a 2 Mbps. This research addresses only DBPSK format.

3.3.14 Forward Error Detection and Correcting

In this research, a simple method of FEC, Linear Block Codes is used. Since there are 32 bits-CRC fields in 802.11, the capability of FEC is 2.6 bit errors in frame. [If n (code words) is 8191 and when k (information bits) is 8178 and n-k is 13, t (correction capability) will be 1. So, 32 (CRC bit) / 13 = 2.6]. The processing time of detection and correction is set to 0.

3.4 CATER (Code Adapts To Enhance Reliability)

CATER is a protocol that attempts to improve the throughput for the wireless LAN standard. As described in the previous chapter, DSSS is used to improve the throughput of channel by making the PN code larger. CATER uses a similar approach.

CATER attempts to make the link between two computers more reliable. It is built into the MAC sublayer by dynamically varying the PN code length of frame transmission. CATER is built on and expands 802.11's capabilities. CATER changes the PN code length of two communicating stations from 11 chips to more chips if a frame continually fails transmissions. Reconfiguring PN code lengths is done on a per station pair base. Changing to longer PN codes allows for lower BER, but the effective data rate decreases. For example, assuming a fixed chipping rate of 11.264 million chips per second (Mcps), a PN code of 11 chips results in a data rate of 1.024 Mbps (11.264 Mcps/11). If the PN code is changed to 63 chips, the corresponding data rate is 187kbps (11.264 Mcps/63).

3.4.1 Setting to Reconfigure Status

If a link continually experiences an unacceptable BER using 11 chips, CATER reconfigures the communicating stations to use longer chips. There are several parameters used in CATER: Reconfigure ACK Time-Out, Reconfigure ACK, Max Additional Frames to Transmit During Reconfigure, Data Not Received. Start Reconfigure Limit (hereafter called Start) is used for the control when a link between two stations should be reconfigured. If this parameter is set to 2, two failed frames are permitted before the source station initiates the reconfigure protocol.

If station A experiences two failed sent frames to station B, station A does not retransmit that frame again. Instead, it transmits a short reconfigure request frame to station B and changes PN code to a longer code. If station B received a reconfigure request frame, station B transmits a Reconfigure ACK to station A and changes the PN code to longer code. Otherwise, if station A does not receive the reconfigure ACK frame from station B by Reconfigure ACK Time-Out, the PN code is reverted to 11.

After reconfigure, station A tries to send the frame to station B as many as Max Additional Frames to Transmit During Reconfigure and then changes to 11 chips. If it is failed as Reconfigure Transmit Limit in station A, it should be changed to 11 chips. If station B does not receive the frames for Data Not Received, the PN code changes to 11 chips.

3.4.2 Algorithm

3.4.2.1 Process Packet Transmission Request from TCP/IP

As shown in Figure 3-1, this function accepts a packet from TCP/IP or higher level in the OSI model, converts the packet to an 802.11-compliant frame and transmit the frame. The first step is accepted the frame from TCP/IP by MAUNUTDATA.request. As soon as a packet is received, the protocol makes the packet suitable for 802.11-compliant frame.

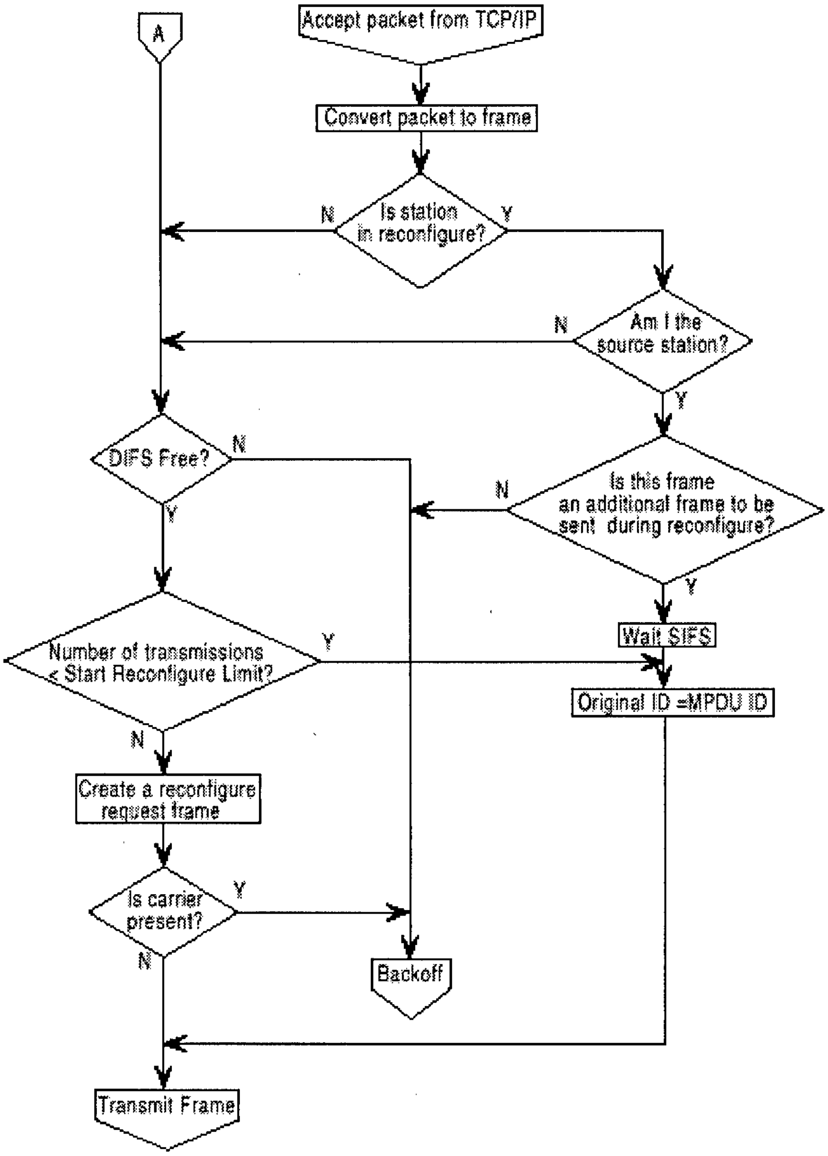


Figure 3-1 Process Packet Transmission Request From TCP/IP [Mul97]

The protocol determines if the station is in reconfigure, if so, the protocol determines if this station is the source station during the reconfiguration. If it is, the protocol determines if this frame is one of the additional frames to be sent during reconfiguration. If so, the frame is sent to the Transmit Frame function after a SIFS period has elapsed and the MAC Protocol Data Unit (MPDU) ID is recorded.

If the station is not the source station in a reconfigure connection, the station must check to see if the channel has been idle for at least DIFS. If it is not, the frame is sent to the Backoff function.

If the number of transmissions for this frame is less than the Start Reconfigure Limit parameter, the frame is sent to the Transmit Frame function after recording the MPDU ID. If the Start Reconfigure Limit has been exceeded, a reconfigure request frame is created for transmission to the destination station while storing the original data frame in a buffer. If a carrier is not present, the frame is sent to the Transmit Frame function. If a carrier is present, the frame is sent to the Backoff function.

3.4.2.2 Transmit Frame

The Transmit Frame function, shown in Figure 3-2 is responsible for transmitting a frame onto the channel. If a data timer is set on this station, then cancel the data timer and change the PN code to 11. If the data timer is not set on, it is not reconfigure status. The next step is to increment the number of transmission attempts for this frame. If the frame to transmit is a reconfigure ACK, change the PN code to 63. If not, send the frame to the physical layer without changing the PN code length. After the frame is transmitted, according to the frame type, each timer is set to; data frame to ACK timer, reconfigure request to reconfigure ACK timer, reconfigure ACK to data timer and change the station PN code length to 63. If there are no additional frame to receive during reconfigure, station change the PN code to 11 chips.

3.4.2.3 Accept Frame From Channel

As shown in Figure 3-3, this function is responsible for routing the incoming frame from channel to the proper function. If the incoming frame is a data frame, the station compares the MPDU ID against the last received MPDU ID. The station discards the frame if two numbers matches. If not, the station stores the MPDU ID in the MPDU ID cache for future comparison, sends the data frame to TCP/IP and then cancel the data timer if set. The station creates an ACK frame for their data frame and sends it to Transmit Frame after waiting SIFS. If the frame is an ACK, station compares the MPDU ID of ACK frame against the stored MPDU ID. Theses two numbers should match indicating this ACK is for the last data frame. If there are no additional frame to send during a reconfigure period, the station changes the PN code length to 11 chips and sends confirmation to TCP/IP. The station requests the next packet for transmission from the MAC buffer and sends it to Accept Packet From TCP/IP for processing.

When a reconfigure request frame is received, the station reads the number of additional frames to be sent during the reconfigure period.

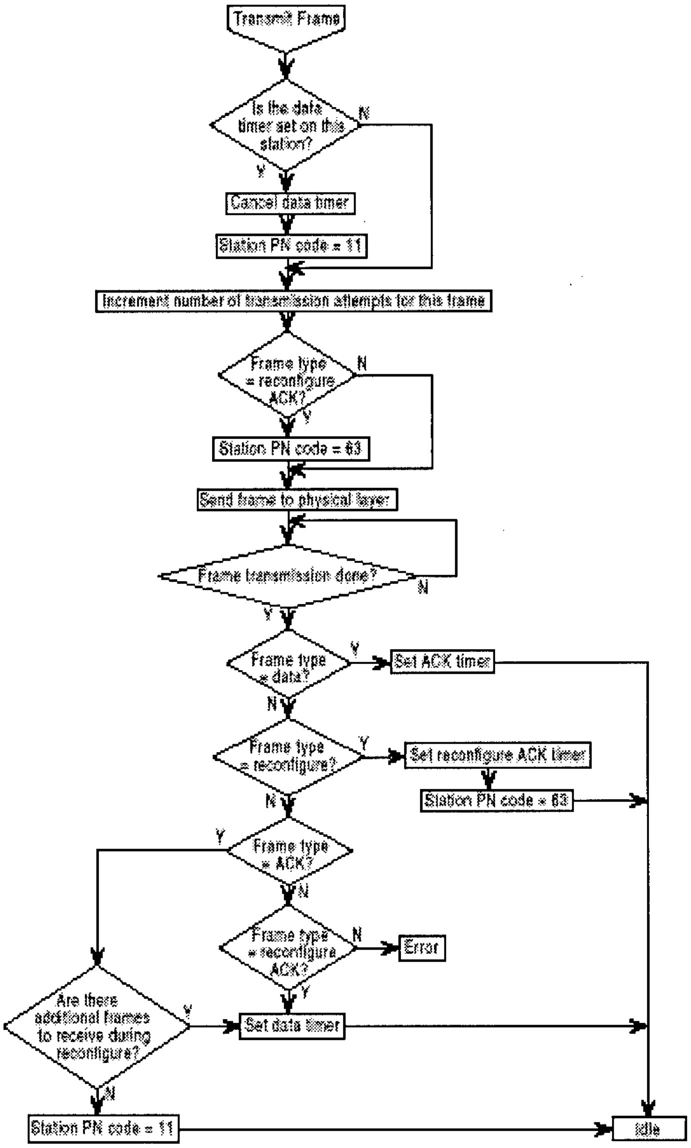


Figure 3-2 Transmit Frame Function [Mul97]

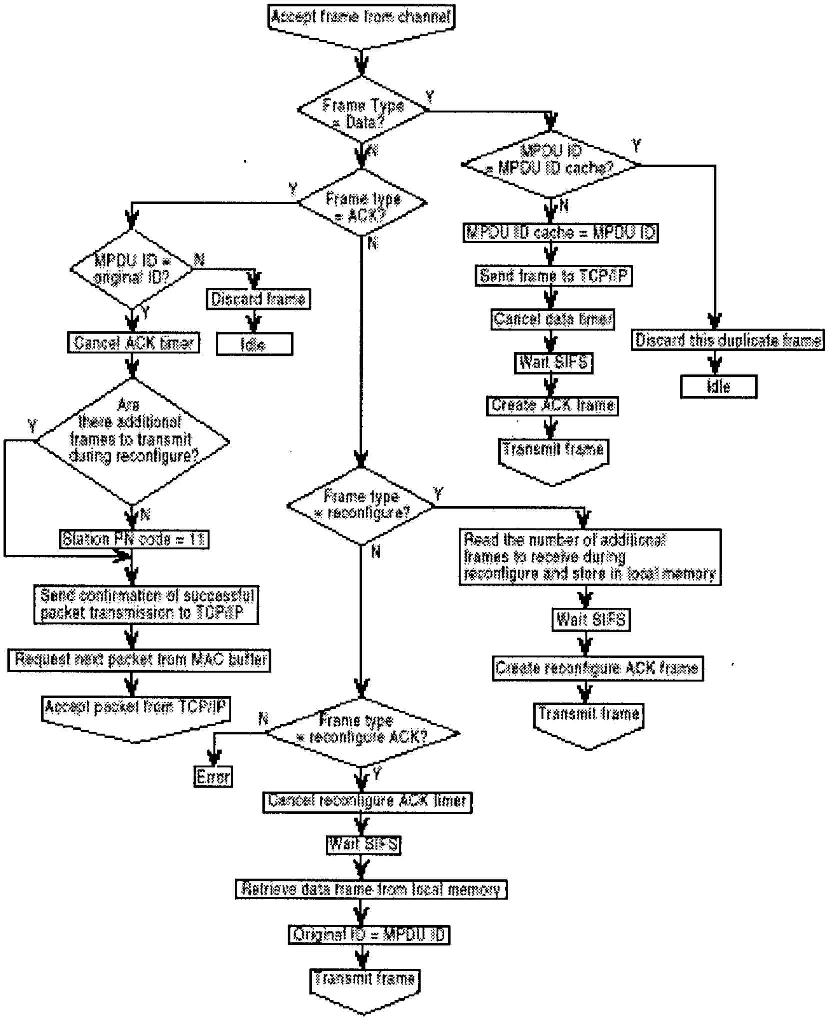


Figure 3-3 Accept Frame From Channel [Mul97]

When reconfigure ACK is received, the station cancels the reconfigure ACK timer, waits for SIFS, retrieves MPDU ID, sends the data frame from local memory, reads the MPDU ID, and sends the data frame to the Transmit Frame function.

3.4.2.4 Backoff

Backoff (Figure 3-4) controls the exponential backoff mechanism. If the total number of transmissions plus the total number of reconfigure request frame for the frames exceed the retransmission limit, an excessive retransmission is declared. If the limit is not exceed, the station computes the backoff time for the frame and starts the timer when the medium has been idle for at least DIFS. The station stops the timer each time the medium is sensed busy and restarts it when the medium is clear for at least DIFS. When the backoff timer expires, the station sends the data frame to Accept Packet From TCP/IP.

3.4.2.5 Service MAC Timers

Figure 3-5 illustrates the Service MAC Timer function. After the ACK timer expires, the protocol checks if the station is in reconfigure status and if the number of reconfigured transmissions of data frame is less than Reconfigured Transmission Limit and if this is not an additional frame sent during reconfigure and if the carrier is not present. If it is, station sends the frame to Transmit Frame after recording the MPDU ID. If it is not, station changes the PN code length to 11 chips and then sends the frame to Backoff. If Reconfigure ACK timer is expired, the PN code length is change to 11 chips and the data frame is sent to Backoff. If Data timer is expired, the PN code length is changed to 11 chips.

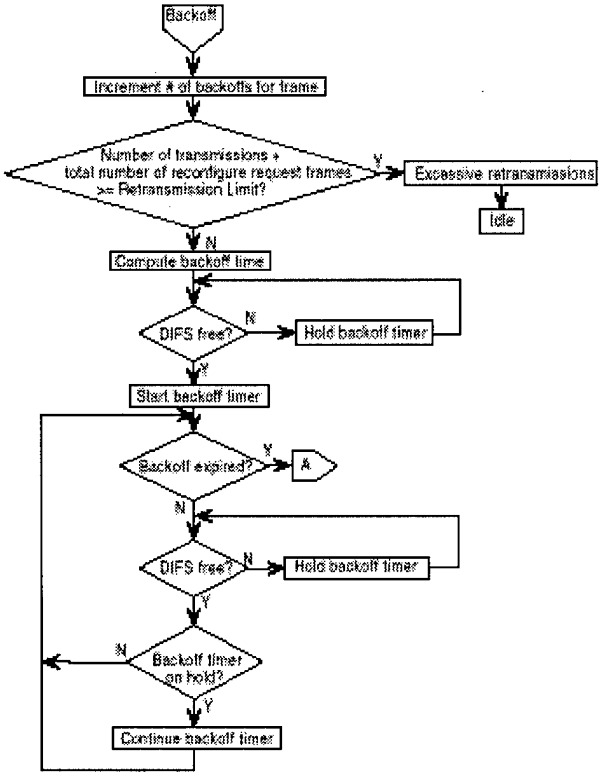


Figure 3-4 Backoff [Mul97]

3.5 Simulation

This research uses Designer version 3.6 tool by Comdisco System, Inc. for the simulation study. The network system is modeled at system level and system is made by components, and further decomposed into lower level components.

3.5.1 Data Structure

The data structures traverse the simulation model much the same way as actual data packets. This study uses data structure such as Frame, MA_DATA.req, MA_DATA.ind, and

MA_DATA.con. The 802.11 frame types can be either data, ACK, Reconfigure, or ReconfigureACK.

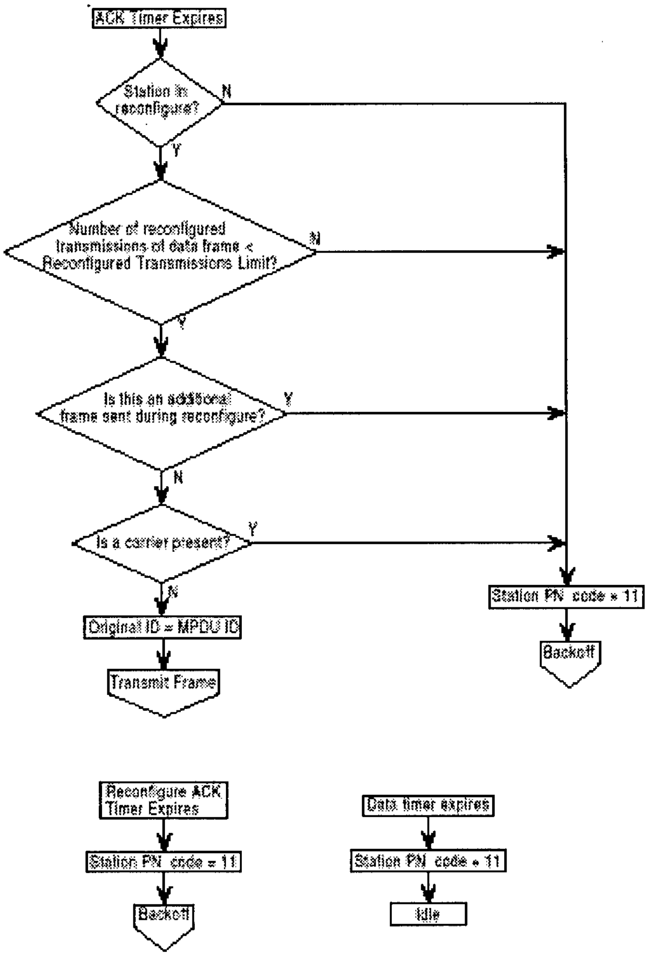


Figure 3-5 Service MAC Timer [Mul97]

Table 3-1 lists the frame structure. The frame is the only structure exchanged between stations. The ROOT-OBJECTION data type allows the insertion of any other structure within the field. The 802.11 frame types can be either Data, ACK, Reconfigure or Reconfigure ACK.

Table 3-2 lists the fields in MA_DATA.req data structure, which models the service primitive request from the logical link control (LLC) sublayer to the MAC sublayer requesting a packets be sent. Table 3-3 lists the fields in the MA_DATA.ind data structure, which models the service primitive indication from the MAC sublayer to LLC sublayer indicating the receipt of a frame. Table 3-4 lists the fields in the MA_DATA.conf data structure, which models the service primitive confirmation from the MAC sublayer to LLC sublayer of source station conveying the status of the last transmission attempt.

3.5.2 Wireless LAN Simulation model

The 10-station model is a system and is shown in Figure 3-6. There are 3 station models such as 10, 15, and 20. It is decomposed of wireless station (wireless workstation component) running CATER and sharing the same channel called Channel Memory. The station transmits frames to Channel Memory where all other stations immediately sense the new arrival and retrieve the frame.

3.5.2.1 Wireless workstation component module

Each wireless workstation, (shown in Figure 3-7), has an 802.11 MAC and packet generator (Traffic Source) used to transmission requests from the LLC Sublayer. Upon initialization, the Traffic Source starts generating packets for transmission following a Poison distribution. When a packet is generated, it is sent to the 802.11 MAC where it attempts to contend for the channel and transmit the packet. Regardless of its success, the 802.11 MAC reports its transmission status back to traffic source.

Table 3-1 Frame Data Structure

Field	Data Type
Source Address	Integer
Destination Address	Integer
Data	ROOT-OBJECT
Data Length(in bits)	Integer
Frame Length(in bits)	Integer
Frame Generation Time	Real
Initial Transition Time	Real
Number of Transimission	Integer
Number of Backoff	Integer
MAC Protocol Data Unit ID	Integer
Last Time Transmitted	Real
Frame Type	802.11 Frame Type
Collision	Integer
Reconfigure Attempts	Integer
Total Reconfigure Frames	Integer
PN Code Length	Integer
Data Generation Time	Real
Additional Frames to Transmit During	Integer

Table3-2 MA_DATA.req Data Structure

Field	Data Type
Source Address	Integer
Data	ROOT-OBJECT
Destination Address	Integer
Length	Integer

Table 3-3 MA_DATA.ind Data Structure

Field	Data Type
Source Address	Integer
Data	ROOT-OBJECT
Destination Address	Integer
Length	Integer
Reception Statue	MAC-Reception Status

Table 3-4 MA_DATA.con Data Structure

Field	Data Type
Transmit Status	MAC-Transmit-Status
Data Time Generation Time	Real

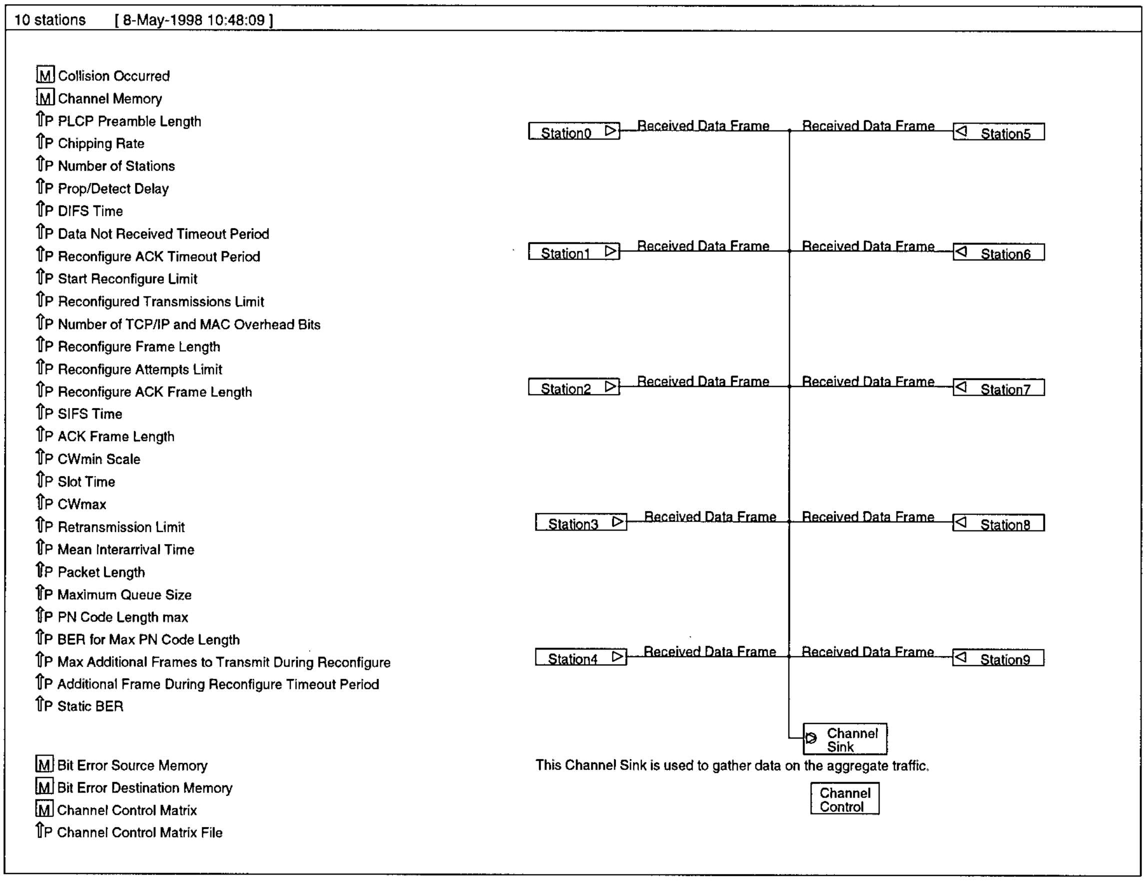
3.5.2.2 MAC module

802.11 MAC module consists of Control, Transmit and Accept Frame From Channel.

3.5.2.2.1 Control module

The Control module, shown in Figure 3-8, is responsible for the overall timing of the 802.11 MAC. The Discriminate Type block routes incoming frames to the appropriate output port based on the frame type field. The Data Received block compares the incoming data frames against data frames previously received by this station. Duplicate data frames are discarded. Data Received also cancels the data timer and then requests ACK transmission. Transmit ACK accepts an incoming frame and generates an ACK frame to send back to the source station. ACK Received accepts the ACK frame and verifies it is for the data frame last sent from this station.

Transmit Reconfigure ACK accepts a reconfigure frame. It then reads the Additional Frames to Transmit During Reconfiguration field and store this number in memory.


10 stations [8-May-1998 10:48:09]

This Channel Sink is used to gather data on the aggregate traffic.

Figure 3-6 Designer 10 Station System Model

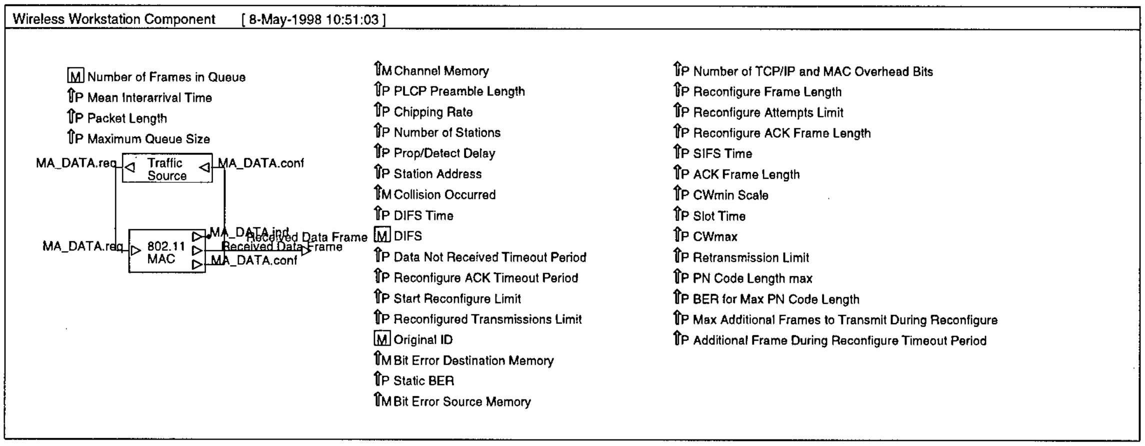


Figure 3-7 The Wireless Workstation Module

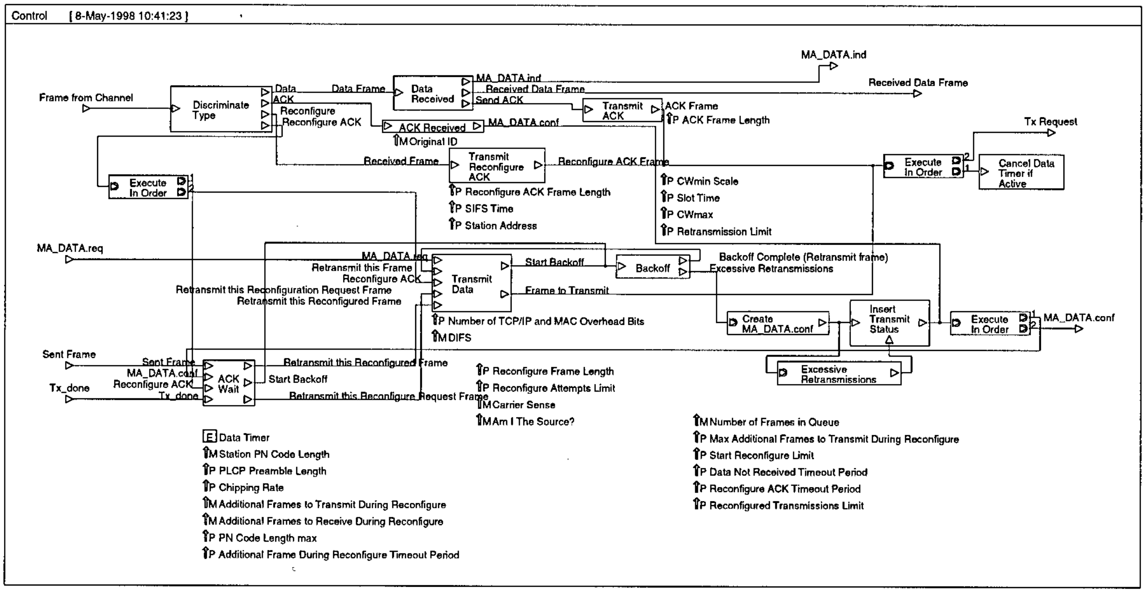


Figure 3-8 The Control Module

Transmit Data module (Figure 3-9) implements most of the reconfigure protocol. There are two possible outcomes from this module—transmit the data or reconfigure frame and send the data to Backoff. MA_DATA.req input accepts this primitive type from Traffic Source and converts it to a frame via the Convert MA_DATA.req to frame module. If the station is not in reconfigure (In Reconfigure?), it determines if DIFS has elapsed. If not, data frame is sent to Backoff. If DIFS has elapsed, Transmit Data determines whether to initiate CATER by comparing the number of transmissions for that frame against Start Reconfigure Limit. If it is determined that the station should be reconfigured, the data frame is sent to Reconfigure Control; otherwise, the data frame is sent to Transmit after MAC Protocol Data Unit (MPDU ID) is recorded.

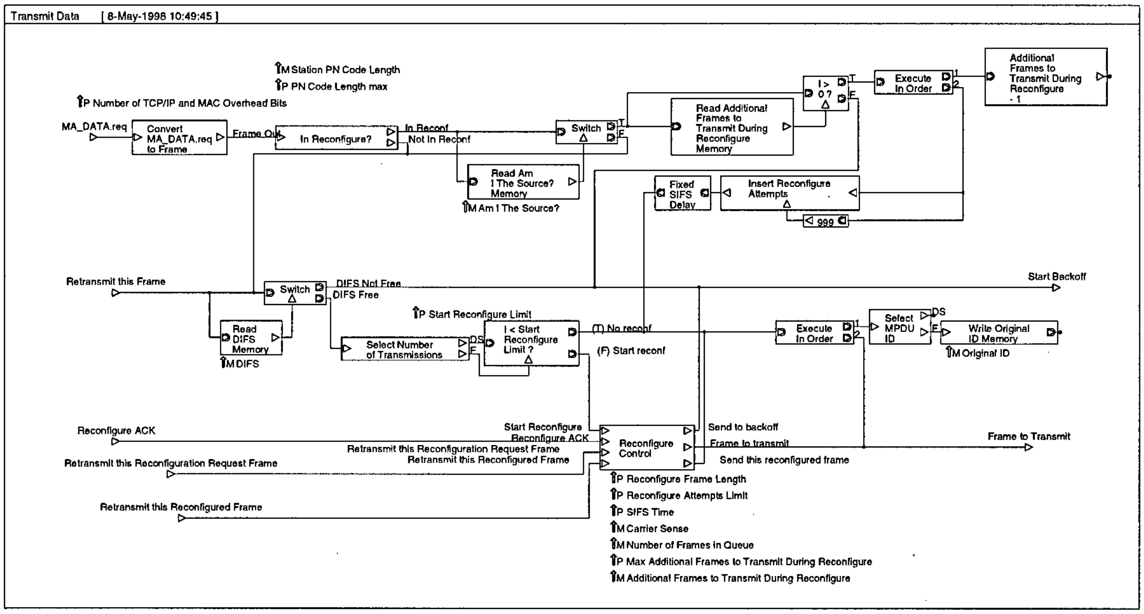


Figure 3-9 Transmit Data

Assuming the station has been reconfigured and it is the source station, an additional frame is sent to Transmit after a SIF delay and MPDU ID is recorded.

The Reconfigure Control function is shown in Figure 3-10. This module creates a reconfigure frame via Create Reconfigure and verifies the maximum number of reconfigure attempts Limit parameter. If this limit has been exceeded, the data frame is sent to Backoff after the Total Reconfigure field is updated. If the limit is not exceeded, the medium is once again sensed for a carrier. Assuming the carrier is not present, Reconfigure frame is sent to Transmit; else, the data frame is sent to Backoff with total reconfigure frame field updated. The Backoff module accepts a data frame and first increments the number of backoff attempts. The ACK Wait module controls most of timeout function of protocol as well as a PN code length selection.

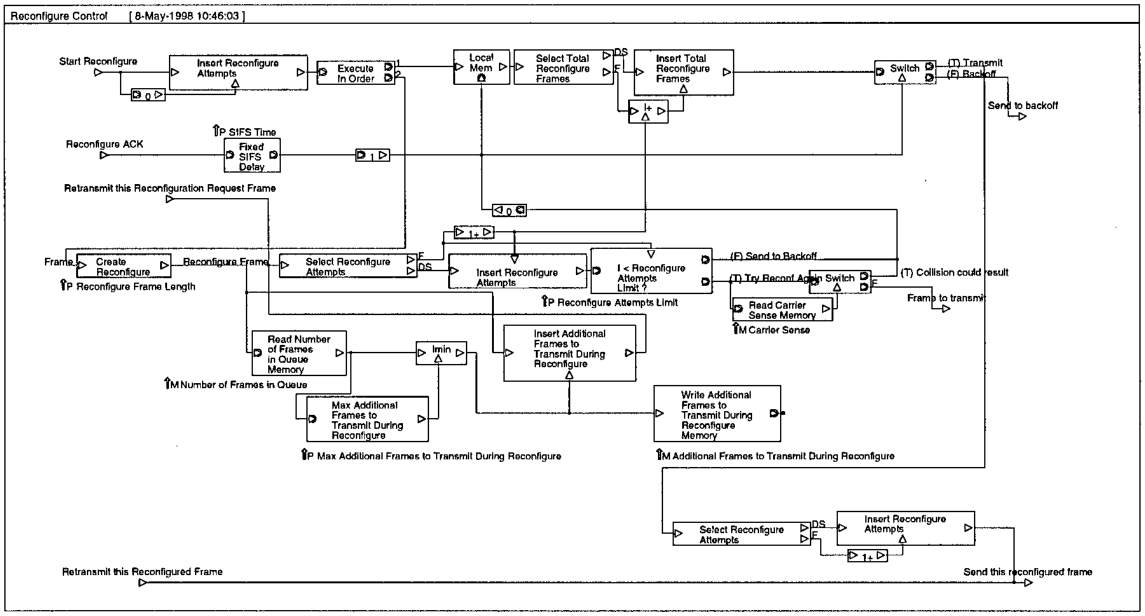


Figure 3-10 Reconfigure Control

3.5.2.2.2 Transmit Module

The Transmit module, shown in Figure 3-11, is responsible for the actual transmission of a frame onto the channel. This module accepts the frame from the Tx_req port, updates its transmission time fields, increments the number of transmission field, and sends the frame to Control via the Sent Frame port.

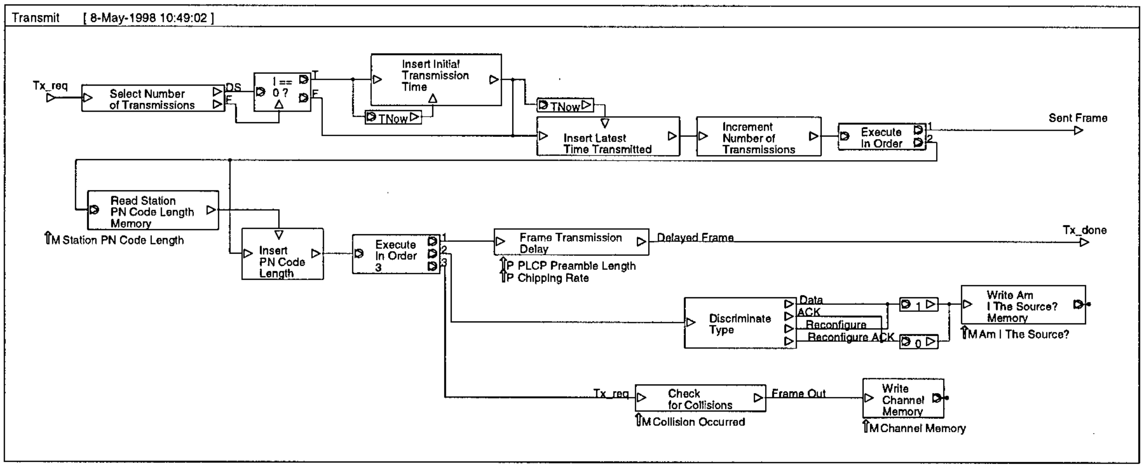


Figure 3-11 Transmit Module

The Check for Collision module compares the contents of Channel Memory versus the frame about to be sent. If both frames have the same transmission time, a collision has occurred.

3.5.2.2.3 Accept Frame from Channel module

The Accept Frame from Channel module, shown in Figure 3-12, is responsible for discarding frame received from the channel that have either collided or contain errors. Carrier Sense and DIFS Control is responsible for determining when carrier is sensed on the channel and when DIFS time has elapsed.

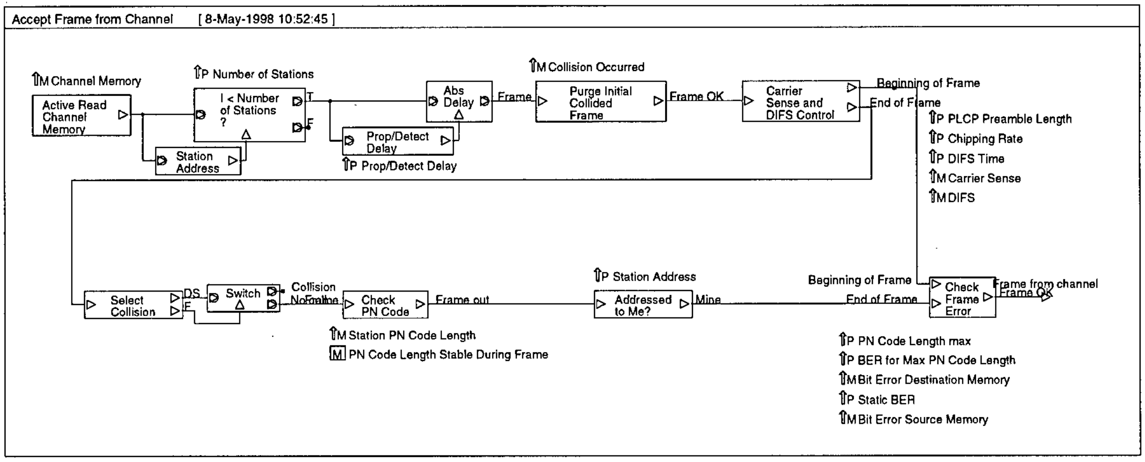


Figure 3-12 Accept Frame From Channel

Check Frame Error (Figure 3-13) determines if an error has occurred within the received frame. It has two mode of operation – Static BER and Dynamic BER. If the static case, a binomial distribution is used to determine if an error has occurred within the frame. The module Binomial Regen accepts two values; they are the numbers of bits in the frame and the BER. The BER is either the static BER parameter if PN length is set to 11, or the BER for Max PN Code length.

In this module, the FEC is implemented. If the capacity of FEC is 2 bits in a frame, the parameter, Number of Errors should be set to 2.

3.6 Simulation Parameters

3.6.1 Stop Time

Stop time is when to stop the simulation. It is found that a stop time of 51 seconds provides the best between accuracy and computing resources utilization [Mul97].

3.6.2 CW_{min}

Contention windows used to determine the maximum number of slots a station should backoff after a collision. CW_{min} is the size of window before a backoff occurs and is set to 31 in accordance with 802.11 [Mul97].

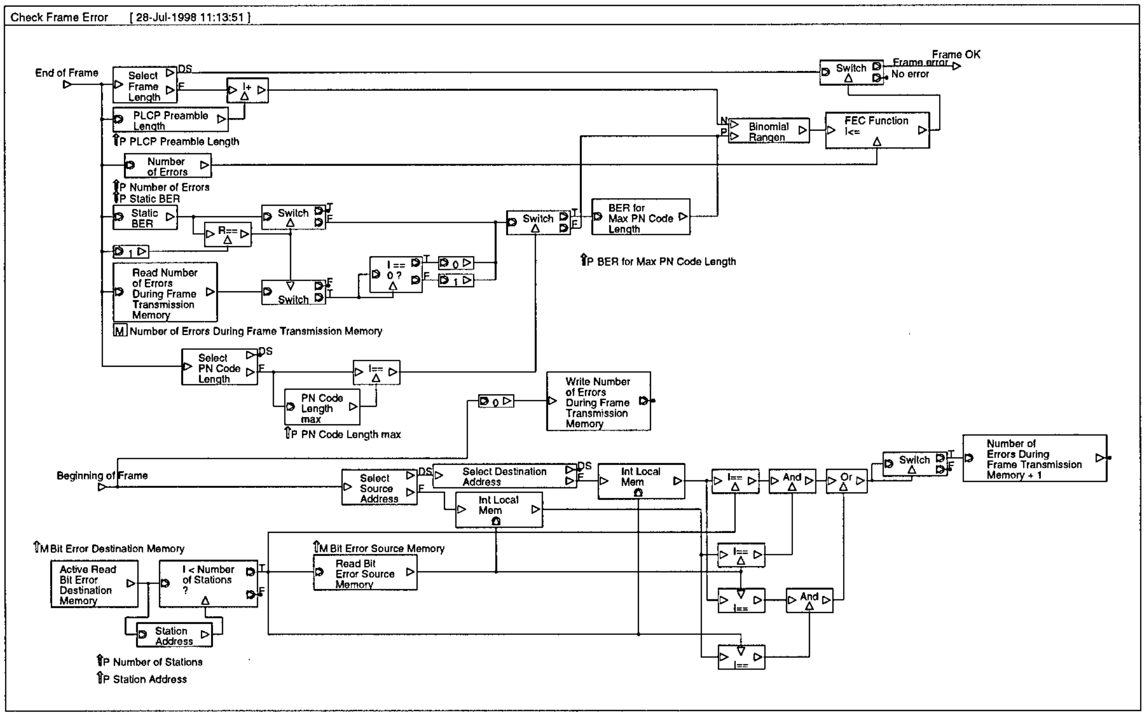


Figure 3-13 Check Frame Error

3.6.3 CW_{min} Scale

This parameter is used to calculate the contention window size for successful backoff of a data frame. As specified by 802.11, the contention window is 31, 63, 127 and 255. The following formula finds the power of 2 that result in CW_{min}:

$$\mathrm{CW_{min}\,Scale} = \left(\frac{\log(CW_{\min}+1)}{\log 2}\right) - 1$$

3.6.4 $\mathrm{CW_{max}}$

This is the largest size of the contention window and is set to 255 as directed by 802.11 [Mul97].

3.6.5 Number of Stations

This is the number of stations in ad hoc network. Simulation uses 10, 15, and 20.

3.6.6 Retransmission Limit

This parameter determines when the MAC protocol stops its attempts to retransmit a frame. Because 802.11 did not decide the value, 15 of IEEE 802.3 (CSMA/CD) is used [Mul97].

3.6.7 Max Queue Size

This is the maximum size of FIFO queue awaiting transmission at the MAC-layer. It is set to 10.

3.6.8 PN Code max

Simulation uses PN Code max such as 49, 63, and 94.

3.6.9 PN Code min

When the station is not reconfigured, it transmits using the minimum PN code length of 11 chips.

3.6.10 Chipping Rate

This is set to 11.264 (Mcps). Because 802.11 is designed to provide 1 Mbps and uses the 11 chip Barker Code.

3.6.11 PLCP Preamble Length

According to 802.11, it is set to 192 bits.

3.6.12 ACK frame length

Because IEEE 802.11 specifies 112 bits, it is set to 112.

3.6.13 Packet length

It is set to 8000 bits. This value corresponds to roughly half of 802.11's maximum of 2312 bytes [Mul97].

3.6.14 Prop/Detection Delay

For the ad hoc network configuration, because maximum distance is less than 300m and comparing the speed of light, this value is negligible. This value is set to 0.

3.6.15 Slot Time

This parameter is set to 50 microseconds as specified by the 802.11 standard.

3.6.16 SIFS Time

SIFS Time is set equal to Slot Time.

3.6.17 DIFS Time

This parameter is set to three times the SIFS Time.

3.6.18 Start Reconfigure Limit

This determines when the adaptive protocol is initiated. If this value is set to any value above Retransmission Limit, it is not able to reconfigure the channel.

3.6.19 Reconfigure Transmissions Limit

This determines how many times a reconfigured frame is sent. It is set to 2, because too many retransmissions waste the bandwidth.

3.6.20 Reconfigure Frame Length

This is the length of the frame sent from the source station to attempt a link reconfiguration. It is set to 160 bits, because RTC and CTS frame to reserve the channel are 160 bits.

3.6.21 Reconfigure Attempts Limit

This is a parameter used during the initial development of the adaptive protocol. It is set to 1 for eliminating the waste of channel bandwidth.

3.6.22 Reconfigure ACK Frame Length

This is set to 112 bits per the 802.11 standard.

3.6.23 Reconfigure ACK Timeout Period

This determines how long the source station is to wait before declaring the reconfigure frame a failure.

$$(2 * SIFTime) + \frac{\mathrm{Re}\,configureACKFrameLength + PLCP\,\mathrm{Pr}\,eambleLength}{\left(\dfrac{ChippingRate}{PNCodeLength\,\mathrm{max}}\right)}$$

3.6.24 Additional Frame During Reconfigure Time Period

This determines when a destination station should consider the reconfiguration a failure.

$$(2 * SIFTime) + \frac{\beta}{\left(\dfrac{ChippingRate}{PNCodeLength\,\mathrm{max}}\right)}$$

Where

$\beta =$ Packet Length + Number of TCP/IP and MAC Overhead bits + PLCP Preamble Length

3.6.25 Max Additional Frame to transmit During reconfigure

This determines how many additional frames to transmit after the original data frame during a reconfigure period.

3.6.26 BER for PN code length

This is the BER used during periods when maximum PN code length is used.

3.6.27 Data Not Received Timeout Period

This determines when the destination station should consider the reconfigure following a failure.

$$(2 * SIFTime) + \mathrm{Re}configuredTransmissionLimit * \left(\frac{\beta}{\rho} + (2 * SIFTime) \right)$$

β = Packet Length + Number of TCP/IP and MAC Overhead bits + Reconfigure ACK Frame Length + (2 * PLCP Preamble Length)

$$\rho = \frac{ChippingRate}{PNCodeLength\,\mathrm{max}}$$

3.6.28 Best Service Time

This parameter defines the best possible time that a frame can be served by the MAC function.

$$\text{DIFS Time} + \text{SIF Time} + \frac{\beta}{\rho}$$

β = Packet Length + Number of TCP/IP and MAC Overhead bits + Reconfigure ACK Frame Length + (2 * PLCP Preamble Length)

$$\rho = \frac{ChippingRate}{PNCodeLength\,\mathrm{max}}$$

3.6.29 Number of TCP/IP and MAC Overhead Bits

It is set to 592. Because TCP/IP has 320 bits and 802.11 adds another 272 bits.

3.6.30 Mean Interval Time

The packet-generating rate is determined by this parameter.

$$\frac{(BestServiceTime * NumberofStations)}{Load}$$

3.6.31 Number of Errors

This is the number of errors in frame.

3.6.32 Global Seed

This is used by all random number generators within the simulation. This research uses 5 global seeds. At least 5 global seeds are required to obtain confidential interval for aggregate throughput [Mul97].

3.7 Summary

In this chapter, the objective of this thesis and assumptions were presented. The algorithm for CATER as well as the model construction were explained. In next chapter, the simulation result and analysis are discussed.

4. Results and Analysis

4.1 Introduction

This chapter presents the results and analysis of the throughput as the simulation factors Start and Max are changed. Additional observations on the throughput are made while varying the PN code length, the number of stations, and implementation of FEC.

4.2 Aggregate Throughput

The aggregate throughput is a common metric for measuring system performance for a network. This research attempts to maximize the aggregate throughput by changing PN code length and the number of station while at the same time, implementing Forward Error Correction (FEC) into the system. The environment of Bit Error Rate (BER) is static and dynamic. As shown by Mullins [Mul97], because static and dynamic BER presented the same result, only static BER is investigated in this research. There are two independent variables: BER and Load. The analysis of throughput is made by examining the effects caused by changes in value of these variables.

This effort selects the number of stations (10, 15, 20) and the number of PN code lengths (49, 63, 94). This simulation investigation contains the following levels of variation: 5 BER levels, 5 system Load levels, 4 levels of Start, 4 levels of Max, 3 levels of FEC and 5 global seeds. This yields 54,000 simulation runs.

The protocol reconfigures a link between two stations only when frames are lost due to bit errors and not collisions. To prevent reconfiguring due to collisions, CATER should not initiate reconfiguration until several attempts (Start) are made to resolve collision using 802.11-backoff mechanism. However, attempting too many retransmissions wastes the channel bandwidth. A larger value of Start increases the time before a link is reconfigured. Also, a larger value of Max allows more frames to be sent during reconfigured periods thereby increasing the delay time. To maximize the throughput, the balance is needed.

CATER improves the throughput performance at higher BER ($>10^{-3}$), while 802.11 is better at the lower BER. This effects come from protocol overhead, which consists of transmissions of management frames (e.g., reconfigure request frame) and decreases the data rate of a reconfigure link to a longer PN code length.

4.2.1 Throughput as Start and Max changes

Table 4-1 and 4-2 show the performance of the protocol over values of Start and Max. If Start is set to 5 and Max is set to 0, the protocol (CATER) will initiate after 5 failed frames and will only send one frame after the link is reconfigured. Table 4-1 illustrates that the larger value of Max is better at the high BER (10^{-3}). However, at the low BER ($< 10^{-3}$), Start=9 and Max=0 is best and next is 3, 6, and 9. At low BER ($< 10^{-3}$), the throughput of CATER is worse than 802.11 due to protocol overhead – reconfiguring the link too early and wasting bandwidth by utilizing the channel with additional frames sent during reconfiguration. If two reconfigured stations occupy the channel, other stations are holding frames for transmission in backoff. Table 4-2 shows the value of best throughput as the factors, Start and Max are varied. When BER is higher than 10^{-3}, the configuration is 3 of Start and 9 of Max. When lower than 10^{-3}, it is 9 of Start and 0 of Max.

Table 4-1 Max Order of Best Throughput

10 stations, PN =49, Max Order

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	almost same	almost same
9	9,6,3,0	9,6,3,0	0,3,6,9	same	same

10 stations, PN =63, Max Order

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	Almost same	almost same
9	9,6,3,0	9,6,3,0	0,3,6,9	same	same

10 stations, PN =94, Max Order

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	Almost same	almost same
9	9,6,3,0	9,6,3,0	0,3,6,9	same	same

Table 4-2 Best Throughput of Changing the BER

10 stations, PN=49

Start \ BER	0.01	0.001	0.0001	0.00001	0.000001
802.11	-	0.000156	**0.261462**	**0.407969**	**0.418187**
3	**0.025956**	**0.068800**	0.152869	0.384519	0.402025
5	0.019281	0.062088	0.208619	0.406356	0.416981
7	0.013000	0.055431	0.237856	0.407756	0.417844
9	0.008650	0.047719	0.252156	**0.407969**	**0.418187**

10 stations, PN=63

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	**0.261462**	**0.407969**	0.418187
3	**0.081469**	**0.121806**	0.196338	0.390381	0.4051
5	0.069419	0.117362	0.230831	0.406412	0.417387
7	0.057381	0.112737	0.246225	0.4079	0.417994
9	0.044781	0.108587	0.252975	0.4079	**0.418225**

10 stations, PN=94

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	**0.261462**	**0.407969**	**0.418187**
3	**0.072331**	**0.095031**	0.169519	0.382619	0.397875
5	0.066369	0.093331	0.218937	0.405606	0.417237
7	0.059981	0.090844	0.242531	0.407631	0.418031
9	0.050875	0.088775	0.253863	**0.407969**	**0.418187**

4.2.2 Throughput as the PN Code changes

As Chapter 2 presented, as the length of the PN code is increased, the BER is increased, but the data rate is decreased. This is tradeoff between BER and Data Rate. For maximizing the throughput, this research uses three PN code lengths as shown Table 4-3.

Table 4-3 PN code length and BER

PN code Length	BER	Data Rate
11	10^{-2}	1,024 kbps(1 Mbps)
49	10^{-4}	229 kbps
63	10^{-5}	187 kbps
94	10^{-7}	119 kbps

If the system is not in reconfigure, it uses only a PN code length of 11. But, if the PN code length is set to 49 and system changes to reconfigure, the system uses for the PN code length. Figure 4-1 shows the best performance is at 63 of PN code and next is 94, 49 at BER = 10^{-2} and 10^{-3}. At low BER, the result is almost same result. This means system did not reconfigure the channel, because there are not many retransmissions (low BER): system uses only 11 PN code length.

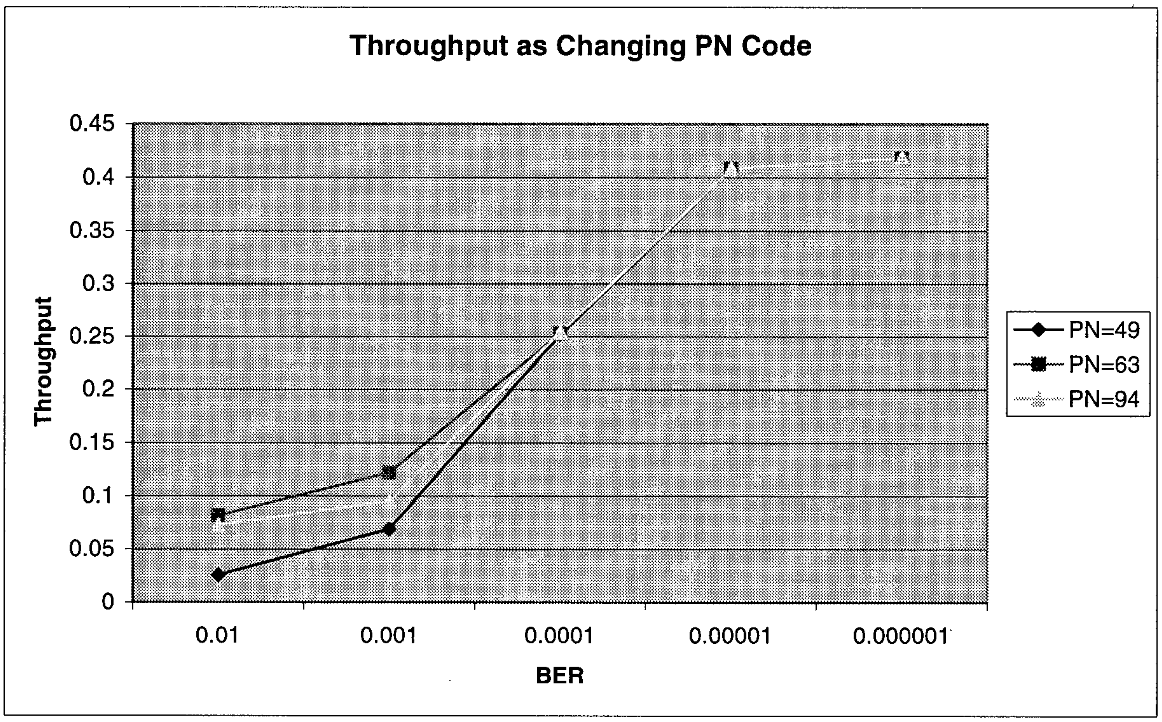


Figure 4-1 Throughput as Changing PN Code with 10 Stations

4.2.3 Effects on Throughput due to Node Increases

Figure 4-2 presents the results as a function of the number of stations. As the number of stations is increased, the throughput is decreased. This is due to the fact that contention for the channel is increased as the number of station increases, more stations are requested to wait (backoff). The increased number of backoffs reduces the system throughput.

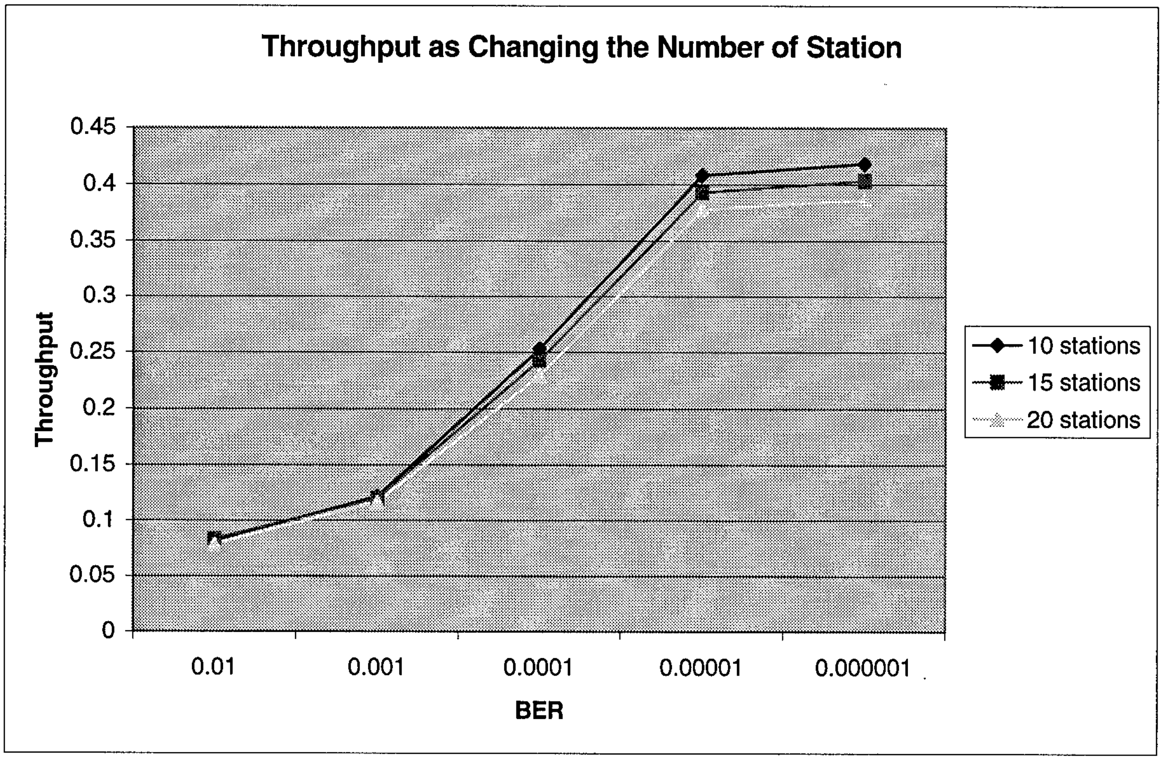


Figure 4-2 Throughput as Changing the Number of Station when PN Code is 63

4.2.4 Effects on throughput due to FEC implementation

Because standard 802.11 has a 32 bit CRC field in the frame, the correcting capacity of the FEC is approximately 2.6 bits per frame. The 2.6 bit of FEC capability means errors less than 2.6 bits in a frame can be corrected. If the BER is 10^{-3}, the average error in a frame is one in 1,000. In case of 10^{-4}, there is one in 10,000 in a frame. The length of the modeled frame is 8,000 bits. So, when BER is 10^{-3}, the average number of errors in a frame is 8 bits.

Figure 4-3 shows that the throughput at high BER ($>10^{-3}$) is not better than when the BER is 10^{-4}. This means a frame in high BER has greater than 2.5 bit errors. So, FEC function can not correct the frame. When BER is 10^{-4}, the function of FEC is best. This is the reason why the error in a frame is average 0.8 bit. However, at the low BER, there are no difference between FEC and with out FEC, because when the BER is low, there are not many frames to be corrected. When the system operates with a PN code length of 49 and encounters a high BER, the throughput drastically is improved. This is because the BER is 10^{-4} and data rate is higher than 63 and 49.

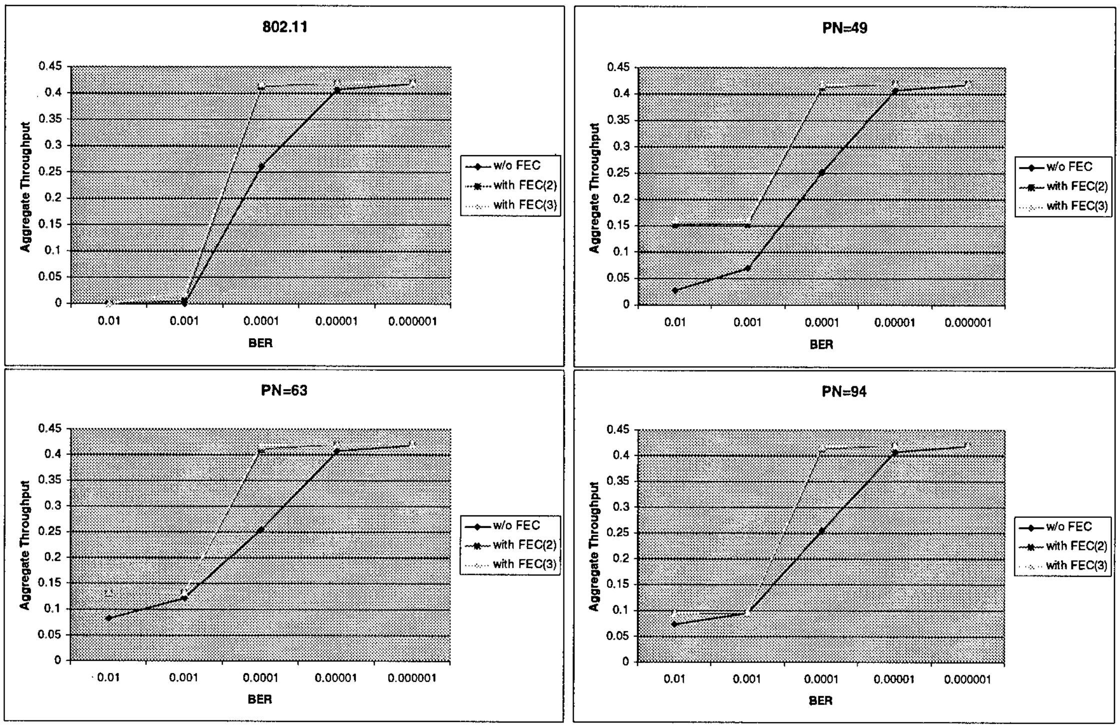


Figure 4-3 Best Throughput as Implementing the FEC

4.3 Summary

In this chapter, the simulation results and analysis were presented. The changes in throughput in resulting from changes in the factors were first discussed. Addition effects on throughput were shown that resulted from the change in PN code length, number of stations, and FEC implementation.

5. Conclusion

5.1 Conclusion

This research analyzes the performance of CATER protocol in several environments. The CATER protocol uses the characteristic of direct spread spectrum technology: longer PN code lengths increase the process gain of the receiver and reduces the error rate. This is tradeoff between BER and data rate. CATER allows communicating stations to reconfigure their transceiver to use a longer PN code after prescribed a number of failed retransmissions. CATER shows the performance of throughput is better at higher BER ($>10^{-3}$) while 802.11 is better at lower BER.

First, the throughput as Start and Max changed was investigated. When the system had a smaller Start and larger Max at higher BER ($>10^{-3}$), CATER produced the better throughput. However, at low BER, larger Start and smaller Max was better. Because there were too many retransmissions due to high BER, early reconfiguration and sending the additional frames during reconfiguration was better choice. At the low BER, reconfiguration did not help the system performance due to a few retransmissions.

Second, effects on throughput due to PN code change were examined. The protocol produced the best performance at a PN code length equal to 63. This result comes from the tradeoff between BER and data rate.

Third, effects on the throughput due to node increase were discussed. As the number of station was increased, the throughput decreased. This was due to the fact that contention for the channel was increased as the number of station increased. This caused more stations to wait (backoff). The increased backoffs reduced the system throughput.

Finally, effects on throughput due to FEC implementation were mentioned. When the BER was 10^{-4}, FEC performed best. When the BER was higher than 10^{-4}, there were numerous errors in a frame (>2.5 bits). Therefore, the FEC could not correct that frame. However, the frame with 10^{-4} BER has many frames that can be corrected. On the other hand, there are no difference between FEC and without FEC at low BER, because the BER is too low resulting in frame errors being correctable. Also, the FEC functioned best at a PN code length of 49, because it has low BER (10^{-4}) and data rate is higher than 63 and 94.

5.2 Future research

This thesis is based on the assumption that the system uses only DCF. Therefore, CATER is running over an ad hoc network. It is recommended that examining the impact of CATER on an infrastructure network configuration.

Appendix A. The Aggregate Throughput

Appendix A1. The Order of Max for best throughput

15 stations, PN =49, Max Order

Start \ BER	0.01	0.001	0.0001	0.00001	0.000001
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	same
9	9,6,3,0	9,6,3,0	0,3,6,9	same	same

15 stations, PN =63, Max Order

Start \ BER	0.01	0.001	0.0001	0.00001	0.000001
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
9	9,6,3,0	9,6,3,0	0,3,6,9	Almost same	same

15 stations, PN =94, Max Order

Start \ BER	0.01	0.001	0.0001	0.00001	0.000001
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
9	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9

20 stations, PN =49, Max Order

Start \ BER	0.01	0.001	0.0001	0.00001	0.000001
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
9	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	same

20 stations, PN =64, Max Order

Start \ BER	0.01	0.001	0.0001	0.00001	0.000001
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
9	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	almost same

20 stations, PN =94, Max Order

Start \ BER	0.01	0.001	0.0001	0.00001	0.000001
3	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
5	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
7	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9
9	9,6,3,0	9,6,3,0	0,3,6,9	0,3,6,9	0,3,6,9

Appendix A2. The Best Throughput with Changing BER

15 stations, PN=49

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	0.250788	0.393081	0.403178
3	0.027006	0.067281	0.143006	0.353281	0.376681
5	0.018681	0.059944	0.190906	0.387038	0.398519
7	0.012619	0.053606	0.222656	0.391831	0.402387
9	0.008725	0.048263	0.238619	0.392975	0.403216

15 stations, PN=63

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	0.250788	0.393081	0.403178
3	0.083331	0.119944	0.182681	0.364356	0.380756
5	0.070019	0.115131	0.219081	0.389	0.400762
7	0.058256	0.109981	0.234056	0.392781	0.402931
9	0.045275	0.1061	0.242744	0.392962	0.403169

15 stations, PN=94

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	0.250788	0.393081	0.403178
3	0.070425	0.092475	0.156537	0.342856	0.370131
5	0.063456	0.090569	0.201969	0.387362	0.398419
7	0.056313	0.088081	0.226913	0.392687	0.402856
9	0.046275	0.086006	0.239425	0.393344	0.403169

20 stations, PN=49

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	0.236556	0.377981	0.3865
3	0.025487	0.0668	0.135744	0.328781	0.357513
5	0.017963	0.058131	0.178994	0.367738	0.378919
7	0.012175	0.050913	0.208869	0.376094	0.384950
9	0.008281	0.044219	0.223881	0.376794	0.386319

20 stations, PN=63

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	0.236556	0.377981	0.3865
3	0.07815	0.116475	0.173369	0.336956	0.359719
5	0.065175	0.111137	0.203569	0.3698	0.38075
7	0.053581	0.106625	0.218494	0.375625	0.385713
9	0.040444	0.1016	0.228988	0.377644	0.386463

20 stations, PN=94

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.000156	0.236556	0.377981	0.3865
3	0.0683	0.089369	0.146731	0.312869	0.351981
5	0.060981	0.08665	0.186444	0.368419	0.377731
7	0.053369	0.084562	0.210787	0.376069	0.384494
9	0.044194	0.082775	0.223956	0.377325	0.386275

Appendix A3. The Best Throughput as Changing the Load

10 stations, PN=49

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.058276	0.153918	0.235206	0.304463	0.344256
3	0.065737	0.155337	0.224956	0.293794	0.294344
5	0.063856	0.167143	0.235863	0.305125	0.341338
7	0.062381	0.167325	0.241594	0.312119	0.348469
9	0.060325	0.165118	0.243925	0.313769	0.351544

10 stations, PN=63

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.058276	0.153918	0.235206	0.304463	0.344256
3	0.071388	0.191825	0.261438	0.330756	0.339687
5	0.070856	0.194662	0.266612	0.336331	0.37295
7	0.070837	0.190681	0.26755	0.336906	0.376262
9	0.070393	0.186394	0.265681	0.334938	0.375062

10 stations, PN=94

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.058276	0.153918	0.235206	0.304463	0.344256
3	0.071912	0.177062	0.245462	0.313481	0.309456
5	0.071525	0.186694	0.256294	0.325669	0.3613
7	0.072012	0.1854	0.261525	0.330944	0.369138
9	0.071262	0.182806	0.262769	0.331713	0.371119

15 stations, PN=49

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.05313	0.14775	0.230759	0.298069	0.326869
3	0.057844	0.149812	0.220519	0.281738	0.257344
5	0.056575	0.159575	0.228369	0.296563	0.314006
7	0.055262	0.160875	0.235612	0.302044	0.329306
9	0.0534	0.159322	0.23755	0.306712	0.334813

15 stations, PN=63

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.05313	0.14775	0.230759	0.298069	0.326869
3	0.062675	0.183638	0.256688	0.321563	0.306506
5	0.061987	0.1873	0.261694	0.331244	0.351769
7	0.061663	0.183244	0.262794	0.330925	0.359381
9	0.060956	0.180044	0.261344	0.32955	0.358356

15 stations, PN=94

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.05313	0.14775	0.230759	0.298069	0.326869
3	0.0625	0.168575	0.240344	0.290181	0.270825
5	0.062006	0.178887	0.248412	0.317637	0.334831
7	0.061506	0.178338	0.254294	0.322863	0.34985
9	0.060519	0.175538	0.255681	0.323825	0.352656

20 stations, PN=49

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.046094	0.140794	0.220862	0.292031	0.312194
3	0.047038	0.143537	0.21445	0.268131	0.241169
5	0.045588	0.151413	0.22155	0.290888	0.292306
7	0.044332	0.153625	0.226981	0.295538	0.312525
9	0.043407	0.15185	0.228294	0.298631	0.317312

20 stations, PN=63

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.046094	0.140794	0.220862	0.292031	0.312194
3	0.050313	0.174638	0.248419	0.307119	0.284181
5	0.049969	0.178219	0.250881	0.321863	0.3295
7	0.04915	0.1746	0.252306	0.324012	0.339969
9	0.048381	0.17065	0.251487	0.321731	0.342888

20 stations, PN=94

Start \ Load	0.1	0.3	0.5	0.7	0.9
802.11	0.046094	0.140794	0.220862	0.292031	0.312194
3	0.050169	0.160669	0.232625	0.275481	0.275481
5	0.04955	0.16885	0.239988	0.309719	0.312119
7	0.048756	0.169887	0.244131	0.315137	0.331369
9	0.048219	0.167481	0.245869	0.316681	0.336275

Appendix A4. The Best Throughput as Implementing FEC

10 stations, PN=49

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012391	0.414594	0.419322	0.419531
3	0.155654	0.157631	0.404456	0.410442	0.410122
5	0.148769	0.151027	0.414094	0.418363	0.418444
7	0.142247	0.144719	0.414653	0.419241	0.41945
9	0.135412	0.138811	0.414649	0.419379	0.419588

10 stations, PN=63

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012391	0.414594	0.419322	0.419531
3	0.131257	0.132604	0.401366	0.407276	0.407632
5	0.127115	0.128474	0.413519	0.418419	0.418356
7	0.123097	0.124793	0.414714	0.419312	0.419512
9	0.118779	0.121124	0.414767	0.419268	0.419306

10 stations, PN=94

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012391	0.414594	0.419322	0.419531
3	0.094642	0.09544	0.39199	0.399988	0.399882
5	0.092421	0.093507	0.41319	0.419013	0.418832
7	0.090175	0.091522	0.414691	0.419397	0.419606
9	0.087717	0.089644	0.414696	0.419397	0.419606

15 stations, PN=49

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012919	0.399959	0.404744	0.404825
3	0.1526	0.155229	0.382877	0.388755	0.387971
5	0.145496	0.147592	0.39728	0.402171	0.403018
7	0.138757	0.141683	0.39963	0.404452	0.404534
9	0.131539	0.135622	0.399595	0.404746	0.404828

15 stations, PN=63

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012919	0.399959	0.404744	0.404825
3	0.128904	0.130065	0.388083	0.382921	0.383234
5	0.124458	0.125612	0.396658	0.401158	0.401158
7	0.119925	0.121855	0.39938	0.404752	0.404834
9	0.115423	0.118375	0.399924	0.404746	0.404828

15 stations, PN=94

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012919	0.399959	0.404744	0.404825
3	0.092299	0.093971	0.365767	0.372321	0.371984
5	0.089763	0.090776	0.39488	0.400002	0.400352
7	0.08756	0.088944	0.399133	0.40454	0.404622
9	0.084795	0.08688	0.399941	0.404745	0.404826

20 stations, PN=49

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012122	0.383232	0.387947	0.388019
3	0.147669	0.151109	0.362076	0.367455	0.365939
5	0.140739	0.142865	0.379348	0.38328	0.383014
7	0.134146	0.1374	0.382386	0.386448	0.386466
9	0.127415	0.131647	0.38328	0.387885	0.38796

20 stations, PN=63

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012122	0.383232	0.387947	0.388019
3	0.124638	0.126013	0.355779	0.362435	0.362504
5	0.119785	0.121564	0.377967	0.382042	0.382292
7	0.115847	0.117599	0.382101	0.386482	0.386466
9	0.110962	0.114044	0.383196	0.387843	0.387925

20 stations, PN=94

Start \ BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
802.11	-	0.012122	0.383232	0.387947	0.388019
3	0.08874	0.090283	0.341553	0.350414	0.350654
5	0.086534	0.087741	0.37546	0.378823	0.37928
7	0.084084	0.085525	0.38212	0.38617	0.386222
9	0.081204	0.083445	0.383385	0.387969	0.388063

Appendix A5. The comparison between with FEC and without FEC

BER/PN	802.11		49		63		94	
	W/o FEC	FEC(2.5)	w/o FEC	FEC(2.5)	w/o FEC	FEC(2.5)	w/o FEC	FEC(2.5)
10^{-2}	-	-	0.02596	0.15565	0.08147	0.13126	0.07233	0.1526
10^{-3}	0.00016	0.01239	0.06880	0.15565	0.12181	0.13260	0.09503	0.15523
10^{-4}	0.26146	0.41459	0.25216	0.41465	0.25298	0.41477	0.25386	0.39960
10^{-5}	0.40797	0.41932	0.40797	0.41938	0.4079	0.41927	0.40797	0.40475
10^{-6}	0.41819	0.41953	0.41819	0.41959	0.41823	0.41931	0.41819	0.40483

Appendix A6. The throughput as Changing the PN Code

10 stations

BER\PN	49	63	94
10^{-2}	0.025956	0.081469	0.072331
10^{-3}	0.068800	0.121806	0.095031
10^{-4}	0.252156	0.252975	0.253863
10^{-5}	0.407969	0.4079	0.407969
10^{-6}	0.418187	0.418225	0.418187

15 stations

BER\PN	49	63	94
10^{-2}	0.027006	0.083331	0.070425
10^{-3}	0.067281	0.119944	0.092475
10^{-4}	0.238619	0.242744	0.239425
10^{-5}	0.392975	0.392962	0.393344
10^{-6}	0.403216	0.403169	0.403169

20 stations

BER\PN	49	63	94
10^{-2}	0.025487	0.07815	0.0683
10^{-3}	0.0668	0.116475	0.089369
10^{-4}	0.223881	0.228988	0.223956
10^{-5}	0.376794	0.377644	0.377325
10^{-6}	0.386319	0.386463	0.386275

Appendix A7. The throughput changing the number of stations (BER)

PN=49

BER\ Number of Stations	10	15	20
10^{-2}	0.025956	0.027006	0.025487
10^{-3}	0.068800	0.067281	0.0668
10^{-4}	0.252156	0.238619	0.223881
10^{-5}	0.407969	0.392975	0.376794
10^{-6}	0.418187	0.403216	0.386319

PN=63

BER\ Number of Stations	10	15	20
10^{-2}	0.081469	0.083331	0.07815
10^{-3}	0.121806	0.119944	0.116475
10^{-4}	0.252975	0.242744	0.228988
10^{-5}	0.4079	0.392962	0.377644
10^{-6}	0.418225	0.403169	0.386463

PN=94

BER\ Number of Stations	10	15	20
10^{-2}	0.072331	0.070425	0.0683
10^{-3}	0.095031	0.092475	0.089369
10^{-4}	0.253863	0.239425	0.223956
10^{-5}	0.407969	0.393344	0.377325
10^{-6}	0.418187	0.403169	0.386275

Appendix A8 The Throughput Changing the Number of Stations (Load)

10 stations as changing the PN code

Load \ PN	49	63	94
0.1	0.065737	0.071388	0.072012
0.3	0.167325	0.194662	0.186694
0.5	0.243925	0.26755	0.262769
0.7	0.313769	0.336906	0.331713
0.7	0.351544	0.376262	0.371119

15 stations as Changing the PN Code

Load \ PN	49	63	94
0.1	0.057844	0.062675	0.0625
0.3	0.160875	0.1873	0.178887
0.5	0.23755	0.262794	0.255681
0.7	0.306712	0.331244	0.323825
0.7	0.334813	0.359381	0.352656

20 stations as Changing the PN Code

Load \ PN	49	63	94
0.1	0.047038	0.050313	0.050169
0.3	0.153625	0.178219	0.169887
0.5	0.228294	0.251487	0.245869
0.7	0.298631	0.324012	0.316681
0.7	0.317312	0.342888	0.336275

PN=49

Load \ Stations	10	15	20
0.1	0.065737	0.057844	0.047038
0.3	0.167325	0.160875	0.153625
0.5	0.243925	0.23755	0.228294
0.7	0.313769	0.306712	0.298631
0.7	0.351544	0.334813	0.317312

PN=63

Load \ Station	10	15	20
0.1	0.071388	0.062675	0.050313
0.3	0.194662	0.1873	0.178219
0.5	0.26755	0.262794	0.251487
0.7	0.336906	0.331244	0.324012
0.7	0.376262	0.359381	0.342888

PN=94

Load \ Stations	10	15	20
0.1	0.072012	0.0625	0.050169
0.3	0.186694	0.178887	0.169887
0.5	0.262769	0.255681	0.245869
0.7	0.331713	0.323825	0.316681
0.7	0.371119	0.352656	0.336275

Bibliography

[CoR97] Luis M. Correia, Ramjee Prasad, "An Overview of Wireless Broadband Communications", *IEEE Communications Magazines*, pp 28-33, January 1997.

[CrF97] Brian P. Crow, Indra Widjaja, Jeong Geun Kim, Prescott T. Sakai, " IEEE 802.11 Wireless Local Area Network", IEEE Communication Magazine, pp 116-126, September 1997.

[Fla94] Alan Flatman, "Wireless LANs: developments in technology and standards", *Computing and Control Engineering Journal*, pp 219-224, October 1994.

[Fre91] Thomas A. Freeburg, " Enabling Technologies for Wireless in-Building Network Communications- Four Technical Challenges, Four Solutions", *IEEE Communication Magazine*, pp 58-64, April 1991.

[Gol94] Lee Goldburg, "MAC protocol: The key to robust wireless systems", *Electronic Design*, pp 63-74, June 1994.

[HoK97] Walter Honcharenko, Jan P. Kruys, David Y. Lee, Nitin J. Shah, "Broadhand Wireless Access", *IEEE Communications Magazine*, pp 20-26, January 1997.

[KoM95] Ryuji Kohno, Reuven Meidan, Laurence B. Milstein, " Spread Spectrum Access Methods for Wireless Communications", *IEEE Communications Magazine*, pp 58-67, January 1995.

[LaK96] Richard O. LaMaire, Arvind Krishna, and pravin Bhagwat, IBM James Panian, Ericsson Inc." Wireless LANs and Mobile Networking: Standards and Future Directions" *IEEE Communication Magazine*, pp 86-94, August 1996

[LiD94] Cees Links, Wim Diepstraten, Vic Hayes, " Universal Wireless LANs", pp 94-108, May 1994.

[Mul97] Barry E. Mullins, " CATER: An Opportunistic Medium Access Control Protocol for Wireless Local Area Networks", Dissertation, June 1997.

[New95] David Newman, "Wireless LANs: How Far? How Fast", *Data Communications*, pp 77-86, March 96.

[PaP95] Kaveh Pahlavan, Thomas H. Probert, Mitchell E. Chase, "Trends in Local Wireless Networks", *IEEE Communication Magazine*, pp 88-95, March 1995.

[Pra97] Ramjee Prasad, "Overview of Wireless Personal Communications: Microwave Perspectives", *IEEE Communications Magazine*, pp 104-108, April 1997.

[Sta97] William Stallings, "Data and Computer Communications", 4th edition, Prentice Hall, New Jersey ,1997.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
December 1998

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
The simulation, modeling and analysis of wireless local area networks supporting the IEEE 802.11 standard.

5. FUNDING NUMBERS

6. AUTHOR(S)
Jaikwan Joo R.O.K.A.F

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GCS/ENG/98D-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Major Barry E. Mullins
AFRL / IFSD
Wright Patterson AFB, OH

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Research to improve the performance of the IEEE 802.11 has been ongoing since 1990. The focus of this research has investigated the use of the MAC and Physical layers for improving throughput. An adaptive MAC protocol, CATER (Code Adapts To Enhance Reliability) is based on the proposed MAC standard for wireless local area networks (WLAN)-802.11. IEEE 802.11 uses a fixed Pseudo-Noise (PN) code for spreading the information signal, implying a fixed process gain at the receiver. When the channel degrades, IEEE 802.11 offers only retransmissions at the MAC layer to contend with the corrupted medium. However, CATER allows communicating stations to reconfigure their transceivers to use a longer PN code after a prescribed number of failed retransmissions. The longer PN code increases the process gain of the receiver and reduces the error rate.

This thesis analyzes the performance of CATER as changing the factor: Start (the number of transmission before the channel is reconfigured) and Max (additional frame transmissions during reconfigure), PN code length, the number of station, and implementing Forward Error Correction (FEC). CATER provides better throughput for smaller Start and larger Max at a high bit error rate (10-3). When CATER uses a PN code length of 63, the throughput is increased by 101 percent at high bit error rate (BER). However, 802.11 is better than CATER at low BER (< 10-3). As the number of stations is increased, the throughput is decreased, resulting from more stations contending for the channel to transmit the frames. When FEC is implemented with CATER, the throughput is improved by 156 percent at high BER (> 10-3).

14. SUBJECT TERMS
Wireless LAN standard 802.11

15. NUMBER OF PAGES
85

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94