Throughput Optimization and Transmitter Power Saving (TOTPS) Algorithm and Extended TOTPS (ETOTPS) Algorithm for IEEE 802.11 Links

Tianmin Mo

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Committee: **Dr. Charles Bostian (chair)**
Dr. Michael Buehrer
Dr. Thomas Martin
Dr. George Morgan
Dr. Dennis Sweeney

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Abstract

The IEEE 802.11 wireless local area network (WLAN) standard supports multiple transmission modes. However, the higher mandatory data rate mode does not necessarily yield higher throughput. This research started from the relationship between the link throughput and the channel's carrier-to-noise (C/N) ratio. Two algorithms are proposed, a throughput optimization and transmitter power saving (TOTPS) algorithm and an extended throughput optimization and transmitter power saving (ETOTPS) algorithm, based on the knowledge of the C/N ratio at the receiver. In particular, we take the approach of adjusting link parameters like transmitter power and transmission mode to achieve the maximum throughput at different C/N values. Since the TOTPS algorithm tends to reduce the transmitter power without degrading the link throughput, transmitter power can be saved. This not only prolongs battery life, which is critical in ad hoc wireless networks, but also reduces the potential interference to neighboring wireless network systems. The ETOTPS algorithm, on the other hand, aims for higher throughput by trading in more transmitter power. This is particularly desired for high-speed data transfer in an emergency situation. Both algorithms are developed to be applied to IEEE 802.11b, IEEE 802.11a and IEEE 802.11g links.

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To my parents, Menghua and Baizeng

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1. Introduction

1.1 Motivation

I became interested in the IEEE 802.11 family of standards while working as an intern at Design Telecommunications Inc. This interest led me to consider a research topic related to interference between Bluetooth and IEEE 802.11. As part of an investigation into the effects of reducing the transmitter power on an 802.11b link, I ran across a paper [1] about a theoretical analysis of throughput versus signal-to-noise ratio (SNR) of an 802.11b link.

This paper helped answer my question. However, it indicated the possibility of reducing the transmitter power without degrading the throughput of the 802.11b link. I kept on asking myself several questions: how can the transmitter know when to reduce the transmitter power, and when to stop reducing it? What should be done when the transmitter power is decreased to the value just big enough to support the best link performance that it is supposed to be able to? And, how could this help reduce the interference between the 802.11b link and the neighboring wireless link operated on the same frequency bands? The purpose of this study is to find the answers to these questions and provide a means both to verify and extend the answers.

1.2 Contributions of Research

Power control has been explored by both industrial and academic researchers. Some of these power control proposals have been applied in the cellular telephone systems, which we are using every day. But power control in 802.11 wireless links has not received as much attention. One reason for this could be that power control in cellular systems brings obvious benefits to the cell phone businesses. Another reason could be that the capacity of the 802.11 wireless links has not become a critical issue. However, if you visited the technology section in the Washington Post's website during the summer of 2004, you would have seen an icon of a scissor cutting a wire with a “Wi-Fi” highlighted column. In it, there was a story about how the spectrum got crowded and a wireless traffic jam occurred once the students returned to their apartments that surround a school campus in Boston.

Although extensive work was done on the power control methods for cellular systems, those approaches cannot be directly implemented in 802.11 networks. On the contrary, 802.11 networks need a power control algorithm designed for their specifications. The radio interface for and the information carried by the channels of cellular systems are different from those of 802.11 networks. This research addresses this issue and provides solutions to the problem.

This dissertation targets power control in the 802.11b link and extends the work to the 802.11g and 802.11a wireless links. The major work that has been done can be generalized as the follows:

1. Study the features of 802.11b, g, a links in an AWGN channel, including the bit error rate, throughput, etc.;
2. Explore the 802.11b link in Rayleigh and Ricean fading channels, including the bit error rate and the throughput of a link;
3. Develop a throughput optimization and transmitter power saving (TOTPS) algorithm and an extended throughput optimization and transmitter power saving (ETOTPS) algorithm for 802.11 wireless networks;
4. Verify the TOTPS and ETOTPS algorithms in 802.11b link in AWGN channel, Rayleigh fading channel, and Ricean fading channel via Matlab combined Opnet simulations;
5. Analyze and draw conclusions based on the performance of the TOTPS and ETOTPS algorithms over varied channels.

According to the analysis of the features associated with 802.11b and the TOTPS algorithm applied in 802.11b link, and comparing it to the features of the 802.11g link and that of the 802.11a link, the similarity among these different standardized links indicates that TOTPS and ETOTPS developed for an 802.11 link can be extended to 802.11g and 802.11a links.

Developing the TOTPS algorithm and the ETOTPS algorithm based on the features of the 802.11 links are important stages of this research. The TOTPS algorithm definitely fulfills the purpose of power saving, according to the range of the carrier-to-interference-and-noise ratio (CINR) defining the control, which is executed in a measure-determine-try-adjust loop. The ETOTPS algorithm tends to determine the balance between transmitter power and maximum throughput. As a result, the research provides two options for power saving methods that can be used in 802.11 wireless networks; with one being better depending upon the applied scenario.

1.3 TOTPS Algorithm and ETOTPS Algorithm

The characteristics of the throughput, in terms of the carrier-to-noise ratio (CNR) of 802.11b link and that of 802.11a link in an AWGN channel, have been described in [1] [2]. This study uses the features of throughput to build the power control algorithms.

The TOTPS algorithm and the ETOTPS algorithm provide a logical basis for determining power needs. This research also defines the operating procedures of how the algorithm is implemented in a wireless network link and how the necessary information will be transferred from one node to another. No study like this has been done before. The algorithms are based on a theoretical analysis, but are targeted to the practical implementation.

There are very few practical circumstances where a wireless link can be modeled as if operating in only an AWGN channel. During most of the time, multipath exists and the resulting channels are commonly described as Rayleigh or Ricean fading channels. The two algorithms developed from the study both apply to these fading channels. Currently, there are few publications that have addressed the features of the 802.11 links in fading channels. Nevertheless, since the purpose of this research is to design a practical algorithm for 802.11 links, the study of the throughput of 802.11b link in fading channels has also been addressed in this research.

The effects of the TOTPS and the ETOTPS algorithms in 802.11b links in an AWGN channel were tested and verified. The power saving purpose was achieved without degrading the throughput. There is sufficient evidence showing that the TOTPS algorithm and the ETOTPS algorithm can be applied in 802.11g and 802.11a links in the same way as they operate in an 802.11b link. Therefore, these two algorithms are general power saving approaches for most of all the 802.11 links and some of the other wireless standards whose throughput versus CNR features are similar to 802.11.

The TOTPS and ETOTPS algorithms measure the CNR at the receiving node and transfer this information to the transmitting node. Then the transmitter power is adjusted based on the knowledge of the CNR of the link. These two algorithms are different from the existing power control strategies used in cellular systems. In cellular links, a pilot channel, separated from the data transfer channels, carries signal strength information. Both closed-loop power control and open-loop power control are based on the signal strength information. But in the specifications of the IEEE 802.11 standard, no pilot channel or any other channel allocated separately from the data channel for carrying received power information is defined. The TOTPS and ETOTPS algorithms defined the procedure for delivering information about received power between the transmitting node and the receiving node in 802.11 links.

1.4 Procedure

Simulations for the 802.11b link bit error rate (BER) in an AWGN channel were developed first. To the best of my knowledge, there is no mathematical closed-form expression for the BER versus E_b/N_o (signal-to-noise ratio per bit) for the Complementary Code Keying (CCK) modulation scheme which is used for 5.5 Mbps and 11 Mbps in 802.11b links. Thus, the BER performance of the CCK modulation for both data rates is obtained by simulation in Matlab. The experience of 802.11b link simulation on BER benefited the BER simulations of 802.11a and 802.11g links.

The throughput versus CNR was analyzed theoretically. The conclusions derived from the curves of throughput versus CNR lead to the solution of power control —the TOTPS algorithm and the ETOTPS algorithm.

After the two algorithms were developed, the simulations were run in Opnet. The BER curves from Matlab were imported into Opnet. The wireless network scenarios were built in Opnet. The simulation results demonstrate that the algorithms work and illustrate how they work. In the process, I found the similarity between the BER curves of the 802.11b link and the 802.11a and 802.11g links. It is reasonable to assume that the simulation results of the 802.11b links in Opnet indicate the similar trends of the throughput curves of the 802.11g links and the 802.11a links. Therefore, the throughput simulations of the 802.11g and 802.11a links in Opnet were omitted.

1.5 Summary of Results and Conclusions

According to the specific 802.11b network scenario built in an AWGN channel, about 40% of the transmitter power is saved. The simulation results for TOTPS algorithm shows that transmitter power can be saved and the amount of the saved power can be varied, depending on the following two conditions:

1. The distance between the communications nodes and how often this distance changes;
2. The duration that the CNR stays in particular transmitter power saving ranges;

Even if a link in a fading channel has less power saved compared to the same link in an AWGN channel, the above conclusion still holds.

The ETOTPS algorithm tends to reach the maximum throughput as fast as it can subject to the transmitter power control rule being applied. It is more aggressive than the TOTPS algorithm, if we compare these two in the same simulation model and reaching a maximum throughput. Actually, the ETOTPS algorithm pushes the throughput higher by adding transmitter power. The ETOTPS algorithm can also help save transmitter power because it continuously monitors the transmitter power. But, the amount of the saved transmitter power can be less than that from the same scenario with TOTPS algorithm used instead.

The ETOTPS algorithm is designed for the circumstances that on one hand the throughput is very critical while on the other hand the power is not a concern. The TOTPS algorithm applied network can save more power, which is a more common issue in the wireless mobile communications network.

1.6 Dissertation Structure

The rest of this dissertation is organized as follows. In Chapter 2, the background of the IEEE 802.11b, 802.11g and 802.11a WLAN systems is introduced. Chapter 3 analyzes the error probability of frame transmission and the throughput for all the transmission modes in 802.11b, 802.11g and 802.11a links, via mathematical modeling and some simulations in Matlab. The CINR measurement and estimation algorithm, the TOTPS algorithm, and the ETOTPS algorithm are presented in Chapter 4. The simulation results of the TOTPS and the ETOTPS implemented links are shown and compared in Chapter 5 and Chapter 6, respectively. In Chapter 7, the performance of the TOTPS and ETOTPS implementations is summarized. Finally, the conclusion of this research is made in Chapter 8.

2. Background

2.1 IEEE 802.11, 802.11b, 802.11a and 802.11g Standards

As the Internet pervades daily life, people become more dependent on it and demand it to be more adaptive to their lifestyles. The Internet was initially designed for use at fixed locations. Today, wireless Internet is accessible almost everywhere — airport, library, coffee shop, fast food restaurant, etc.

In 1997, an IEEE working group proposed the IEEE 802.11 WLAN Standard [3], which is a specification for wireless local area networks (WLANs). During the past years, IEEE 802.11 has been expanded as a family of specifications for WLANs, which includes 802.11b, 802.11g, 802.11a, 802.11i, and so forth.

WLANs are designed to support flexible, portable and mobile computing. The original IEEE 802.11 WLAN standard supports 1 Mbps and 2 Mbps data rates. IEEE 802.11b WLAN standard [4] supports higher data rates of 5.5 Mbps and 11 Mbps while retaining compatibility with the original IEEE 802.11 standard. It supports three modulation schemes: DBPSK for 1 Mbps, DQPSK for 2 Mbps, and Complementary Code Keying (CCK) for both 5.5 Mbps and 11 Mbps, see Table 2-1.

We call each data rate and modulation scheme pair a transmission mode. The transmission mode for the 1 Mbps and the 2 Mbps data transfer will be continuously called *DBPSK* and *DQPSK* as they are in the specification. The CCK 5.5 Mbps and the CCK 11 Mbps transmission modes will be named *CCK55* and *CCK11* respectively in the rest of this dissertation.

The IEEE 802.11a standard [5] was approved in 1999. The IEEE 802.11a standard is called "a high-speed PHY in the 5 GHz band". Data transmission in an 802.11a link uses OFDM combined with BPSK, QPSK, and 16-QAM and a convolutional code with different code rates to support 6, 9, 12, 18, 24, 36, 48 and 54 Mbps data rates as listed in Table 2-1. Among these, the 6, 12 and 24 Mbps are mandatory rates, indicated by bold characters in the table.

The OFDM modulation divides a high-speed binary signal to be transmitted over a number of low data rate subcarriers. In IEEE 802.11a, there are a total of 52 subcarriers, of which 48 subcarriers take actual data traffic and 4 subcarriers are pilots that facilitate phase tracking for coherent demodulation. Each low data rate bit stream is used to modulate a separate subcarrier from one of the channels in the 5 GHz frequency band. Three levels of maximum output power regarding three 5 GHz frequency bands are defined in this standard, 2.5 mW/MHz for 5.15 to 5.25 GHz, 12.5 mW/MHz for 5.25 to 5.35 GHz, and 50 mW/MHz for 5.725 to 5.825 GHz. The frame format in 802.11a is defined differently from that in 802.11b, which will be shown later.

In 2003, IEEE 802.11g WLAN specification [6], called "Further Higher Date Rate Extension in the 2.4 GHz", was officially released by the IEEE-SA Standards Board. It uses the same OFDM technology as employed in 802.11a and is also backward compatible with 802.11b devices. This WLAN standard defines 14 data rates as shown in Table 2-1. It uses DSSS, CCK, and optional Packet Binary Convolutional Coding (PBCC) modulations for the payload data rates of 1, 2, 5.5, and 11 Mbps. Additionally, it supports ERP (extended rate PHYs)-PBCC modulation modes for 22 and 33 Mbps, and it applies DSSS, orthogonal frequency division multiplexing (OFDM) as modulation scheme for 6, 9, 12, 18, 24, 36, 48 and 54 Mbps data rates. Of these rates, it is specified that transmission and reception capability for 1, 2, 5.5, 11, 6, 12, and 24 Mbps data rates is mandatory. The frame format, which can be the mandatory long preamble PPDU format or the optional short preamble PPDU format, is very similar to the PPDU format defined in the 802.11b standard. The maximum transmit power level defined in the 802.11g standard is same as that defined in the 802.11b standard.

Table 2-1 Data Rate and Modulations in the 802.11b, 802.11a, and 802.11g Standards [4][5][6]

Standard	Data Rate (Mbps)	Modulation
802.11b	**1**	DBPSK
	2	DQPSK
	5.5	CCK
	11	CCK
802.11a	**6**	BPSK
	9	BPSK
	12	QPSK
	18	QPSK
	24	16-QAM
	36	16-QAM
	48	64-QAM
	54	64-QAM
802.11g	**1**	ERP-DSSS
	2	ERP-DSSS
	5.5	ERP-CCK, ERP-PBCC
	11	ERP-CCK, ERP-PBCC
	6	ERP-OFDM, DSSS-OFDM
	9	ERP-OFDM, DSSS-OFDM
	12	ERP-OFDM, DSSS-OFDM
	18	ERP-OFDM, DSSS-OFDM
	22	ERP-PBCC
	24	ERP-OFDM, DSSS-OFDM
	33	ERP-PBCC
	36	ERP-OFDM, DSSS-OFDM
	48	ERP-OFDM, DSSS-OFDM
	54	ERP-OFDM, DSSS-OFDM

2.2 MAC and PHY Layer Properties

The IEEE 802.11 MAC defines two access methods for the shared wireless medium. One is the fundamental access method, called Distributed Coordination Function (DCF), which is also known as carrier sense multiple access protocol with collision avoidance (CSMA/CA). DCF is required to be implemented in all stations (STAs) within both infrastructure and ad hoc wireless networks. The other access approach defined in the standard is an optional central controlled access method called Point Coordination Function (PCF), which is only used on infrastructure networks. DCF is much more widely applied than PCF in the wireless devices currently on the market. My research is focused on the DCF method. .

The carrier sense in 802.11 is performed by the physical carrier sense mechanism as well as the MAC sublayer's virtual carrier sense mechanism. The virtual carrier sense mechanism is achieved by distributing reservation information announcing the impending use of the medium, such as the exchange of request-to-send (RTS) and cleared-to-send (CTS) frames prior to the actual data frame transmission. A Duration/ID field in the RTS and CTS frames defines the period of time that the medium is to be reserved for transmitting the actual data and the ACK frames.

A DCF Interframe Space (DIFS) must be passed while the medium keeps idle during this period and before a station can get access to the medium. Moreover, the station has to defer another random backoff period for an additional deferral time prior to transmitting. The deferral period is the key point of collision avoidance in 802.11. By then, if the medium is still idle, communication between the two stations can proceed.

A so called "hand-shake" procedure between two stations, which is the exchange of RTS and CTS frames, is performed between the transmission initiator and the nominated receiver. Only after the RTS and CTS exchange finishes successfully can the actual data frame be transferred. At the end of successful reception, an ACK frame is transmitted from the receiver to the transmitter. There is always a Short Inter Frame Space (SIFS) interval in between the frames of RTS and CTS, CTS and data, and data and ACK. The frame transcieving procedure is shown in Figure 2-1.

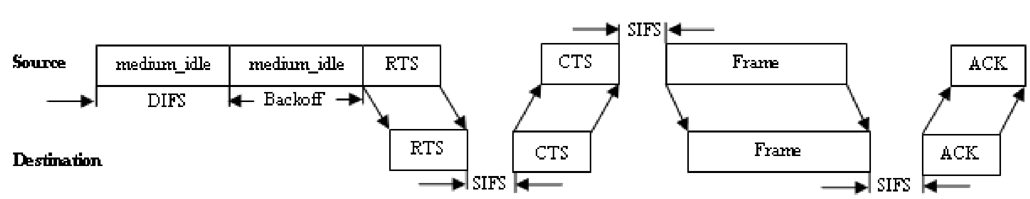

Figure 2-1 RTS, CTS, Data Frame and ACK Frame Transceiving

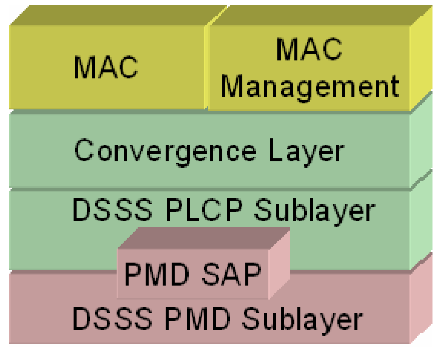

Figure 2-2 PHY and MAC Layers in IEEE 802.11 [3]

2.3 Data and Control Frame Format in MAC and PHY Layers

All the transmission modes are defined in the PHY and MAC layers. The low layer stack in IEEE 802.11 is sketched in Figure 2-2 to help us illustrating the frame transmission procedure. When transmitting, the frame carrying information is transferred from the MAC layer through the PHY layer to the wireless medium; and vice versa on receiving. When a data frame from a higher layer comes to the MAC layer, it will be encapsulated into a MAC protocol data unit (MPDU) with a 24-byte (the usual length of MAC header when address 4 is not used) MAC header and a 4-byte frame control unit sequence (FCS) attached at the tail. The data frame length is limited to 2312 bytes maximum in 802.11b, and 4095 bytes maximum in 802.11g and 802.11a.

A PHY Convergence Protocol (PLCP) sublayer is defined as an interface between the MAC layer and the Physical Medium Dependent (PMD) sublayer to minimize the dependence of the MAC layer on the PMD sublayer. The PLCP sublayer controls the frame exchange between MAC and PHY layers. In other words, before the information is carried onto the channel at the PHY layer, a PLCP header and preamble are added to the MPDU as shown in Figure 2-3 and 2-4. Such a frame on the PHY layer is called a PLCP data unit (PPDU). The exact MPDU data from MAC layer is put in the PLCP service data unit (PSDU) field in the PPDU packet. Figure 2-3 and Figure 2-4 show the PPDU long version and the short version, respectively.

Originally, IEEE 802.11 provided two wireless data transmission modes, 1 Mbps with DBPSK modulation and 2 Mbps with DQPSK modulation. Both have long PPDU versions with 192-bit PLCP preamble and header. The PLCP preamble and header in the mandatory long format are both transmitted at 1 Mbps with DBPSK modulation. Later, when the IEEE 802.11b standard was released, 5.5 Mbps and 11 Mbps were provided, both with the CCK modulation. The IEEE 802.11b standard defines an optional short PPDU version with 96-bit PLCP preamble and header. This supports 2 Mbps, 5.5 Mbps and 11 Mbps data transmission. Since the long version is the mandatory PPDU format for the data transmission in IEEE 802.11b, we use it in our analysis in the rest of this dissertation. As for 802.11g, the long format of PPDU and short format of PPDU are defined in the same way as the frames defined in 802.11b. However, it is somewhat different for the PPDU frame format defined in IEEE 802.11a specifications reflected in Figure 2-5. There is only one type of PPDU frame format defined in 802.11a.

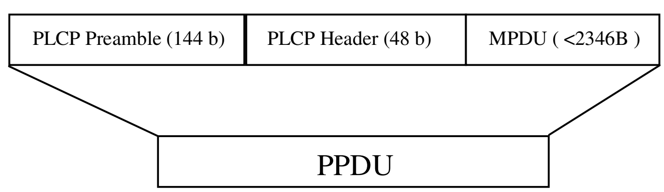

Figure 2-3 PLCP PPDU Long Format in 802.11b and 802.11g

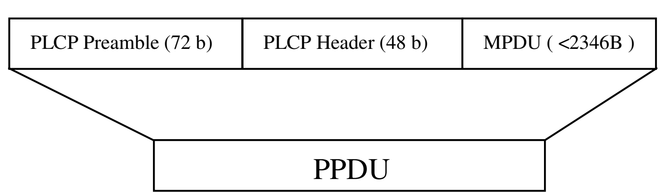

Figure 2-4 PLCP PPDU Short Format in 802.11 and 802.11g

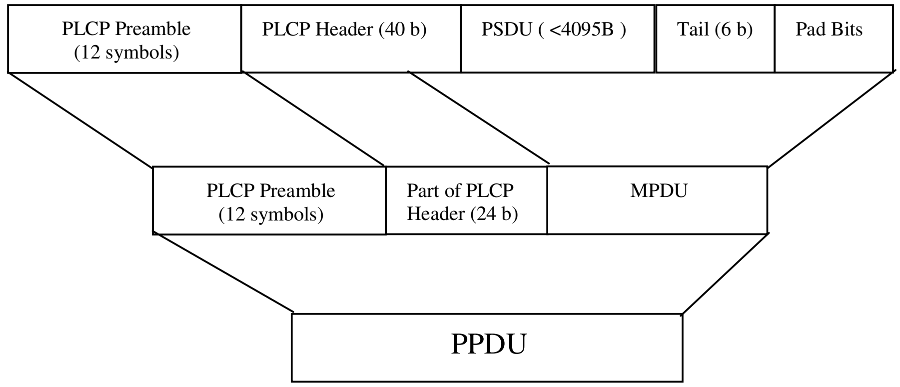

Figure 2-5 PLCP PPDU Format in 802.11a

2.4 CSMA/CA in IEEE 802.11

One of the differences between the WLAN and the MAC protocol for most wired networking applications lies in collision detection. With the receiving and transmitting antennas next to each other, a station is unable to detect any signal but its own while it is transmitting. As a result, a data packet is sent before the checksum showing that a collision can be detected. Additionally, the hidden node problem is known for causing collisions in wireless networks. Therefore, it is very important for the wireless network to limit the number of collisions to a minimum.

In the IEEE 802.11 standard, a protocol called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is defined. This protocol helps reduce the collision probability between multiple STAs accessing a medium at the point where collisions would most likely occur.

Carrier sense is performed through physical and virtual mechanisms in the MAC. One of the parameters defined in the 802.11 specifications is called "clear channel assessment", which is used in the DSSS PHY layer to indicate the status of the medium. Two other parameters, PMD_ED and PMD_CS, provide the information of energy detection status and the carrier sense status. Together, these two parameters are used in the PLCP convergence procedure to indicate activity to the MAC through the PHY interface primitive “PHY-CCA.indicate”. If there is a PHY-CCA.indicate of class BUSY, a busy channel status is reported. Otherwise, a PHY-CCA.indicate of class IDLE shows a clear channel status.

In terms of the virtual mechanisms of the “carrier sense”, a Network Allocation Vector (NAV) exists to predict the future traffic on the medium according to the medium reservation duration information distributed on the RTS/CTS frames prior to the actual data exchange.

When the wireless medium is busy, all the STAs, except the one sending the traffic, are forced to wait for a random number of timeslots called “backoff time”. They then sense the medium again, before starting a transmission. For each unsuccessful attempt to transmit a MPDU, the STA will continue to retry the counter to increment, which extends the backoff time, until the contention window (CW) reaches its maximum value.

The backoff time is determined by a pseudorandom number drawn from a uniform distribution over the interval of [0, CW]. The set of CW values, referring to Figure 2-6, are sequentially ascending integer powers of 2, minus 1, and within the range of [CW_{min}, CW_{max}]. If the medium is sensed to be busy, the random delay time will be reset based on the contention window. However, the CW value will be reset to CW_{min} after every successful attempt to transmit an MSDU or a MAC management protocol data unit (MMPDU). In the 802.11 specification, there is no predefined minimum or maximum value for the CW. However, the standard does advise minimum values of 15 or 31 and a maximum value of 1023 as the contention window.

As a result of the incremented retry backoff time and the pseudorandom number counted into the backoff time, the chance of two STAs sending data simultaneously is reduced.

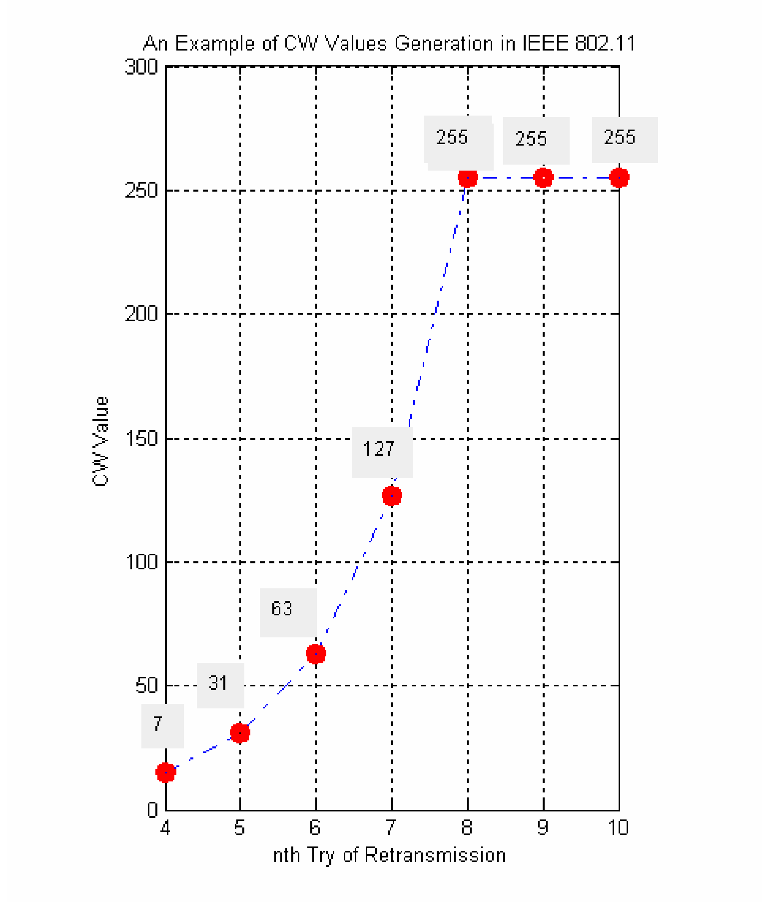

Figure 2-6 An Example of CW Value Generation in IEEE 802.11

2.5 Problem Statement and Literature Survey

The 802.11 wireless devices on the market usually support all transmission modes according to the standard specifications. They switch from one mode to another based on the sensitivity level [3] at the receiver. However, this kind of mode switching is only based on whether or not the link can support a mandatory data rate. It does not necessarily yield the highest throughput for the link at a given transmitter power.

Ideally, transmitter power should be adjustable, because 802.11b, a, or g. WLAN devices are used in varied noise and interference environments. Keeping the transmitter power fixed can waste power and potentially increase interference to collocated devices or else be insufficient to support the network in a relatively noisy environment.

The IEEE 802.11b WLAN works in the ISM 2.4 GHz frequency band. It normally uses direct sequence spread spectrum (DSSS). It is assumed that the IEEE 802.11b WLAN discussed in this paper operates on one of the four transmission modes and the DSSS technique. One of the challenges of a WLAN operation in the 2.4 GHz frequency band is the network's ability to adapt in an environment including Bluetooth short-range wireless network devices, microwave ovens, and cordless phones. Interference between WLANs and Bluetooth has drawn attention in the past few years. Researchers have worked on interference analysis [7][8][9][10] and developed different strategies [11][12] to alleviate interference from one to the other. In addition, another basic and important issue is that 802.11b devices should be able to operate with the transmission mode that leads to the maximum throughput with the given transmitter power.

Adaptive multirate mechanisms for optimal throughput have been emphasized in [13], [14], [15]. In [13], a link adaptation strategy was proposed, focusing on the information frame fragmentation scheme used in 802.11a, which can be used in 802.11b or 802.11g links. The authors of [14] suggested an approach to obtain the best throughput by selecting a transmission mode based on a measurement of the received signal strength. However, this method could not be extended to an environment with higher background noise or ambient interference. The received power would include the desired signal, the noise and all interfering signals. An adaptive multirate approach based on redefining the MAC header and modifying the reservation scheme of the network allocation vector (NAV) was presented in [15].

The literature shows that no power saving algorithm that has ever been designed for the 802.11 links, although the features of the links have been studied to some degree. Most of the adaptive mechanisms for 802.11 links take CNR or CINR as the reference parameter to select the transmission mode for the highest throughput of the link. But, the approach of measuring and monitoring the real-time CNR or CINR, particularly for the link using 802.11 standards, has not been studied or developed. This is considered an important issue and is covered in this study because the approach and the efficiency of the approach would directly determine how well the so-called adaptive mechanism could be operated in the WLAN devices.

In this research, I proposed a novel throughput optimization and transmitter power saving (TOTPS) algorithm based on readily accessible information like the CINR at the receiver. It has the following advantages

1. The real-time CINR ratio reflects the received power and the noise environment, which is relatively reliable for determining the transmission mode;
2. Adjusting the transmitter power brings the benefit of saving power, which is particularly desired in ad hoc wireless networks;
3. The interference from the network that uses this algorithm to adjacent networks is reduced;
4. The CINR information is exchanged during the existing carrier sense multiple accesses with collision avoidance (CSMA/CA) period, so no delay is added.

In addition, the ETOTPS algorithm, as an extension of the TOTPS algorithm, is developed in this study as well. It carries some of the advantages of the TOTPS algorithm mentioned above. Moreover, the ETOTPS is more aggressive on pushing the throughput of the link to a higher level. It is particularly desired in high-speed data transfer in an emergency situation, such as natural or manmade disasters.

In this dissertation, I concentrated my research on the 802.11b supported link for implementing and verifying the TOTPS algorithm and the ETOTPS algorithm. My focus was based on the similarity in the performance of the throughput versus CNR feature between the 802.11b, 802.11a and 802.11g wireless links. When the similarity became obvious, it was reasonable to consider that the result of the two algorithms in the 802.11a and 802.11g links are predictable.

3. Theoretical Analysis of Throughput

In this chapter, the features of each 802.11 link in different types of channels will be studied. The actual performance of a wireless link depends on elements such as application, interference environment, front end RF/IF implementation, radio component selection, etc. I assume that all these issues can be modeled and their effects incorporated in the carrier-to-noise (C/N) ratio. My focus is on the theoretical performance of BER versus C/N, believing that this performance is a sufficient guide for practical cases; especially for three common types of channel models used for the analysis — the AWGN channel, the Rayleigh fading channel and the Ricean fading channel. Throughout this chapter, the performance of the BER versus the C/N of all the three 802.11b, 802.11a and 802.11g links described above will be investigated.

3.1 BER

A desired result when designing a communication system is to transmit information to the receiver with as little deterioration as possible. There are several parameters indicating the quality of the wireless link, such as the bit error rate, the capacity, the throughput, etc. Meanwhile, the system is constrained by transmitter power, allowable carrier bandwidth, cost, and so on. In digital systems, one method used to measure the deterioration is the probability of the transferred information bit error, also called bit error rate (BER).

The AWGN channel is the most common channel model used for analyzing a communication link's performance. Thus, as the starting point, the 802.11 wireless links are modeled as operating on an AWGN channel.

3.1.1 BER of 802.11b Link in AWGN Channel

Referring back to Table 2-1, the 802.11b standard defines the CCK transmission at 5.5 Mbps and 11 Mbps and this standard is backwards compatible to 1 Mbps DBPSK and 2 Mbps DQPSK from the original 802.11 standard.

The relationship between BER and E_b/N_o (signal-to-noise ratio per bit) of DBPSK and DQPSK transmission modes can be found in [16]. The relationship between the C/N and the E_b/N_o is

$$\frac{E_b}{N_o} = \frac{\frac{C}{N}}{\frac{R_b}{BW}} \tag{3.1}$$

where R_b stands for the bit rate, and BW represents the noise bandwidth, which is assumed to be equivalent to the symbol rate, but not the channel bandwidth after signal spreading. The DSSS used in 802.11b does not bring any benefit in an AWGN channel. In DBPSK, each symbol is encoded by a single bit, so the bit error rate of DBPSK, P_{b_DBPSK}, in terms of C/N [16] is

$$P_{b\_DBPSK} = \frac{1}{2} e^{-\frac{C}{N}} \tag{3.2}$$

For the DQPSK transmission mode [16], each symbol is encoded by two bits, thus the bit error rate of DQPSK is

$$P_{b\_DQPSK} = Q_1(a,b) - \frac{1}{2} I_0(ab) e^{-\frac{1}{2}(a^2+b^2)} \tag{3.3}$$

in which

$$a = \sqrt{(C/N)(1-\sqrt{0.5})} \quad \text{and} \quad b = \sqrt{(C/N)(1+\sqrt{0.5})}$$

In (3.3), $Q_1(a,b)$ is the Marcum Q function and $I_0(x)$ is the modified Bessel function of order zero.

The CCK modulation is essentially derived from Binary Complementary Codes (BCC). A BCC consists of a pair of equal finite length sequences. This has the property that the number of pairs of like elements with any given separation in one series is equal to the number of pairs of unlike elements with the same separation in the other [19] series. This is obvious when observing the like and unlike pairs with 1-bit separation and with 2-bit separation within two complementary codes in Figure 3-1 and in Figure 3-2, in which the solid curve indicates a like pair and the dotted curve indicates an unlike pair.

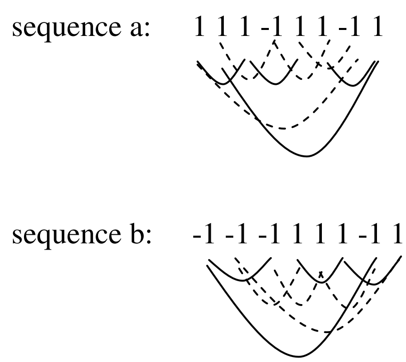

Figure 3-1 Complementary Code Paired Up by 1-bit Separation

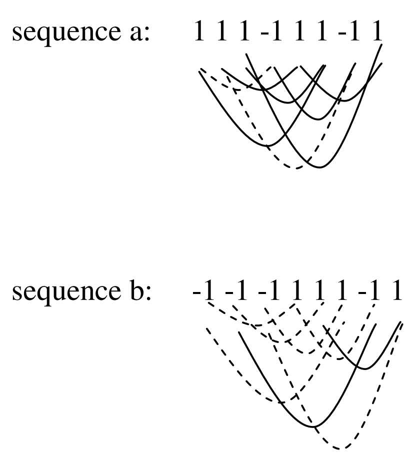

Figure 3-2 Complementary Code Paired Up by 2-bit Separation

If we look at pairs of bits in sequence a and b in Figure 3-1, each pair, connected by a solid or a dotted line, consists of 2 bits with a third bit between them. There are 4 like pairs and 4 unlike pairs in both sequences. In Figure 3-2, the pairs are grouped with 2-bit between the pairs. There are 6 like pairs and 2 unlike pairs in sequence a, while there are 2 like pairs and 6 unlike pairs in sequence b. The complementary codes are characterized by the property that their periodic auto-correlation vector sum is zero everywhere except at the zero shift. Since the orthogonality property among the code also one of the features of CCK, it makes the CCK modulation be attractive for use in digital communications.

The 802.11b CCK modulation uses a multiphase complementary code as its spreading code. The CCK code has a similar feature to the BCC except that it has the complex forms (+j, -j) of the codes involved. In both CCK 5.5 Mbps and CCK 11 Mbps modulations, the symbol rate is 1.375 Msym/sec. Each symbol is encoded into 8 chips, which will be carried onto the wireless channels at 11 Mchip/sec. In other words, each symbol is represented by 8 chips, C = {c_0 to c_7}. The signals are modulated as 4 bits/sym in CCK55 and 8 bits/sym in CCK11. Therefore, 8 chips carry 4 bits of information in 1 symbol in the former modulation, and 8 chips transfer 8 bits information in 1 symbol in the later one. All the information data (d) is encoded into phase (φ) first, and then is spread to be code words according to (3.4). Four phases φ1, φ2, φ3 and φ4 compose 4-ary sets {0, π /2, π, 3π /2}. The following formula is used to derive the CCK code words for spreading at both CCK55 and CCK11 transmission modes:

$$C = \{c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7\}$$
$$= \{e^{j(\varphi 1 + \varphi 2 + \varphi 3 + \varphi 4)}, e^{j(\varphi 1 + \varphi 3 + \varphi 4)}, e^{j(\varphi 1 + \varphi 2 + \varphi 4)}, -e^{j(\varphi 1 + \varphi 4)}, e^{j(\varphi 1 + \varphi 2 + \varphi 3)}, e^{j(\varphi 1 + \varphi 3)}, -e^{j(\varphi 1 + \varphi 2)}, e^{j(\varphi 1)}\} \quad (3.4)$$

In CCK55, 4 information bits are encoded to 4 phase angles and then to the codeword as shown in (3.4). The phase angle φ1 is obtained from (d_0, d_1), according to Table 3-1 and {φ2, φ3, φ4} are encoded from (d_2, d_3) as in (3.5), (3.6) and (3.7).

$$\varphi 2 = d_2 \times \pi + \pi /2 \quad (3.5)$$

$$\varphi 3 = 0 \quad (3.6)$$

$$\varphi 4 = d_3 \times \pi \quad (3.7)$$

Table 3-1 CCK 5.5 Mbps Phase Angle Encoding [4]

(d0, d1)	even symbols phase change	odd symbols phase change
00	0	π
01	π/2	3π/2 (-π/2)
11	π	0
10	3π/2 (-π/2)	π/2

As for CCK11, the difference from the CCK55 is that 8 information bits are encoded to 8 phases and then transferred to the codeword. The phase φ1 is encoded as it is in CCK55 based on Table 3-1. The φ2, φ3, and φ4 are encoded from $\{d_2, d_3, \ldots, d_7\}$ according to Table 3-2. There are a total of 4^4=256 codewords in the 8-chip set for 11 Mbps. However, the complex-coded codewords in the CCK modulation are not truly orthogonal among themselves. There are actually more than one hundred codewords that have nonzero cross correlation. The non-orthogonality among CCK codewords reduces the tolerance to noise and the intersymbol interference [20].

The chips, represented by codewords as described in the previous, are eventually transferred onto the wireless link. The BER versus E_b/N_o performance can vary a lot according to the channel characteristics, which will be introduced in the next section.

Table 3-2 CCK 11 Mbps Phase Angle Encoding [4]

(di, di+1)	even symbols phase change φ
00	0
01	π/2
11	π
10	3π/2 (-π/2)

CCK modulation, adopted in 802.11b, is used for achieving higher data rates in fading and interference environments. Based on the current information, there is no closed form for the BER of CCK modulation so far. According to the modulation described in [4] and [18], running the simulation for a CCK modulation in an AWGN channel model in Matlab, the behavior of the bit error probability of CCK55 and CCK11 is observable.

The performance of BER versus C/N of each modulation scheme in IEEE 802.11b is shown in Figure 3-3. The curves for DQPSK and CCK55 modulations show that the BER performance of these two modulation schemes has no significant difference. For this reason, we can foresee that theoretically, CCK55 is better for information transmission because of its higher data rate. The C/N ratio of a CCK11 link needs to reach 22 dB to achieve a link BER of 10^{-6}, while only 11 dB of the C/N ratio is required on a DBPSK link to obtain the same BER of the link.

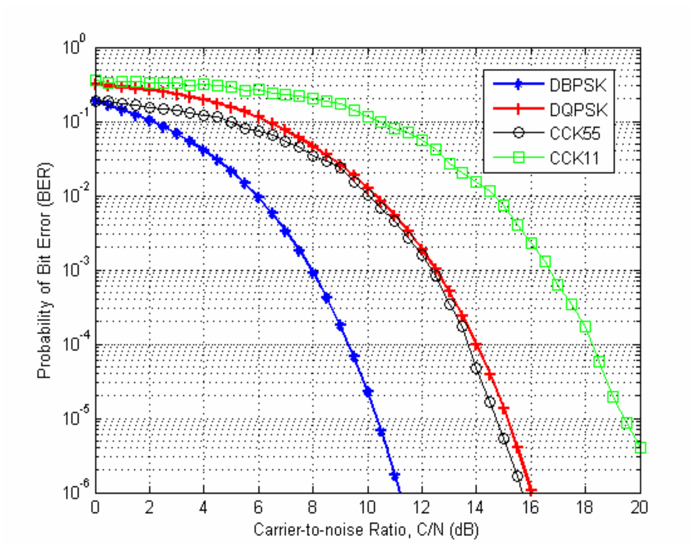

Figure 3-3 BER vs. C/N of 802.11b Links in an AWGN Channel

3.1.2 BER of 802.11a Link in AWGN Channel

Four modulation schemes are used in the IEEE 802.11a standard. They are BPSK, QPSK, 16-QAM, and 64-QAM. The standard has previously been described in Table 2-1. The selected OFDM system in the 802.11a specifications provides a WLAN with the theoretical capability of transmitting data at rates that vary from 6 to 54

Mbps. Forward error correction (FEC) is performed by bit interleaving and convolutional coding with rate 1/2. The higher code rates of 2/3 and 3/4 are obtained by puncturing the original code at 1/2 rate.

The modulation schemes used in 802.11a are very common ones used throughout digital communications. So, it is not hard to find the features of the BER versus E_b/N_o of these modulation schemes [16][21].

For BPSK, the BER in terms of E_b/N_o is

$$P_b = Q(\sqrt{2\frac{E_b}{N_o}}) \qquad (3.8)$$

The QPSK signal is equivalent to two BPSK signals — one using a cosine carrier and the other using a sine carrier. Therefore, the constellation of QPSK shows each signal having a 90^o difference from the neighboring one. The BER in terms of E_b/N_o for the QPSK link is the same as that for a BPSK system as in (3.8). However, the bandwidth of the QPSK signal is half of the bandwidth of the BPSK signal for a given bit rate.

In an M-ary PSK modulation, including BPSK and QPSK mentioned above, the amplitude of the transmitted signal remains constant, thereby yielding a circular constellation. If the modulation combines amplitude modulation with phase modulation, it is called quadrature amplitude modulation (QAM). Although QPSK uses no state changes in amplitude, it is sometimes referred to as 4-QAM. When four levels of amplitude are combined with four levels of phases, we have 16-QAM. In 16-QAM, 2 bits are encoded on phase change and 2 bits are encoded on amplitude change, which yields a total of 4 bits per symbol. The average probability of error in an AWGN channel for M-ary QAM [16] can be approximated by

$$P_b = 4(1-\frac{1}{\sqrt{M}})Q(\sqrt{\frac{3E_{s\_av}}{(M-1)N_o}}), \qquad (3.9)$$

where E_{s_av}/N_o is the average SNR per symbol. In 802.11a, M=16 for data transmission at 24Mbps and 36 Mbps and M=64 for 48 Mbps and 54 Mbps information delivery.

The BER versus E_b/N_o of the four modulation schemes used in 802.11a is shown in Figure 3-4. It seems that probability of bit error of BPSK and QPSK links is much lower than 16-QAM's. And, 16-QAM's BER is much lower than 64-QAM's. Obviously, the more information contained in a symbol, the higher the possibility of error occurring when the information is delivered by a wireless channel.

To achieve bit error rate of 10^{-6}, BPSK or QPSK signal with E_b/N_o of 10.5 dB will be enough, while for a 16-QAM signal, 14.8 dB of E_b/N_o is needed and for a 64-QAM signal, about 19 dB of E_b/N_o is necessary.

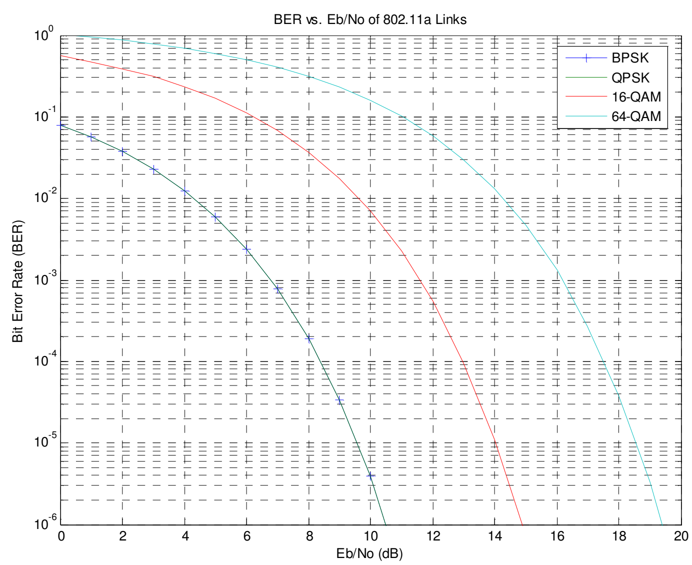

Figure 3-4 BER vs. E_b/N_o of IEEE 802.11a Links

3.1.3 BER of 802.11g Link in AWGN Channel

IEEE 802.11g is defined as an Extension Rate PHY (ERP) specification at 2.4 GHz. The ERP builds on the payload data rates of 1 and 2 Mbps as described in the original 802.11 standard using DSSS modulation. And, it also builds on the payload data rates of 1, 2, 5.5 and 11 Mbps as defined in 802.11b standard using DSSS, CCK, and optional packet binary convolutional coding (PBCC) modulation. The ERP draws from the 802.11a standard providing payload data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps but operating on 2.4 GHz. Of these rates, the mandatory transceiving capability is for 1, 2, 5.5, 11, 6, 12 and 24 Mbps data rates, which is the combination of the data rate of 802.11b and the mandatory data rate of 802.11a but on 2.4 GHz.

Another two additional optional ERP-PBCC modulations with a payload data rate of 22 and 33 Mbps are defined. An optional modulation known as DSSS-OFDM is defined in 802.11a incorporated with payload data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps.

The above can also be referred from Table 2-1. In most of the cases, the same modulation schemes are used for all the mandatory data rates defined in the 802.11b, 802.11a and 802.11g standard. Difference between these three specifications exist, but they do not affect the focus of this research. Referring to Figure 3-3 and Figure 3-4 is sufficient for understanding the BER performance of 802.11g links. Also, because of this, the throughput of 802.11b and 802.11a links can reflect the throughput of 802.11g link. Therefore, the analysis of 802.11g link is considered the same as repeating the study of 802.11b and 802.11a links, which is unnecessary. In consequence, the data rate or throughput analysis of an 802.11g link is not included in Section 3.2 and Section 3.3.

3.2 Ideal Transmission Rate in AWGN Channel

The transferred data between an access point and a mobile station or between one mobile station and another mobile station includes more than just the information data. The necessary and additional to-be-transferred data includes the preamble, the header, the tail, etc. Therefore, even if everything else, such as the wireless link and the communication environment, is perfect, the actual transmission data rate even under ideal conditions cannot be the same as the mandatory data rate. In this section, the theoretical ideal transmission rate of 802.11b and 802.11a links will be presented.

3.2.1 Data Rate in 802.11b Link

A MAC Protocol Data Unit (MPDU) has a 24-byte (usual length of MAC header, when address 4 is not used) header, variable-length information frame body and a 4-byte frame control unit sequence (FCS) attached at the tail as in Figure3-5. Thus, the MAC overhead with MAC header and FCS combined is 28 bytes. The frame format of ACK frame is shown in Figure 3-6.

Bytes: 2	2	6	6	6	2	0~2312	4
Frame control	Duration / ID	Address1	Address2	Address3	Sequence control	Frame body	FCS

MAC Header

Figure 3-5 802.11 MPDU Data Frame Format

Bytes: 2	2	6	4
Frame control	Duration	Receiver address	FCS

MAC Header

Figure 3-6 802.11 ACK Frame Format

At the PHY layer as shown in Figure 2-3, a PLCP header of 48 bits and a preamble of 144 bits added to the MPDU forms the PLCP data unit (PPDU). A PPDU has two possible formats— the PPDU long format, as described, and the PPDU short format. Since the long format is the mandatory PPDU format in IEEE 802.11b, it is used in my analysis for this research.

The PLCP preamble and header in the long format are both transmitted at 1 Mbps with DBPSK modulation. The MPDU is sent at the mandatory data rate just as the information data transfer is done. The RTS and the CTS frames are short frames and are not used for every data frame transmission; thus I omitted the RTS/CTS exchange, and the propagation delay was ignored. Then, the total data transmission time of a successful data transfer with payload length of $L_{payload}$ is composed of a successful information data transfer and a successful ACK frame transfer as

$$T = T_{DIFS} + T_{Backoff} + (T_{PLCP\_Preamble\&Header} + T_{payload}) + T_{SIFS} + (T_{PLCP\_Preamble\&Header} + T_{ACK}), \text{ where} \quad (3.10)$$

$$T_{SIFS} = 10\ \mu s, \quad (3.11)$$

$$T_{slot} = 20\ \mu s, \quad (3.12)$$

$$T_{DIFS} = T_{SIFS} + 2\times T_{slot} = 10 + 2\times 20 = 50\ \mu s, \quad (3.13)$$

$$T_{Backoff} = T_{slot} \times \text{Random(CW)} = 20 \times 15 = 300\ \mu s, \quad (3.14)$$

$$T_{PLCP\_Preamble\&Header} = (144 + 48) / 1\ \text{Mbps} = 192\ \mu s, \quad (3.15)$$

$$T_{payload} = (L_{payload}+28) \times 8 / R_b,\ R_b \text{ is the data rate in Mbps}, \quad (3.16)$$

$$T_{ACK} = 14 \times 8 / R_b. \quad (3.17)$$

The shortest contention window length is assumed to be 31, since the minimum value of the CW is suggested as 15 or 31 in the standard. And, I took the average value from the random values of 0 to 31 to obtain 15 as the estimate of the backoff period. In addition, it is assumed that $L_{payload}$ equals to 1500 bytes. Consequently, the ideal achievable data rate of each transmission mode can be found by

$$R\_{ideal} = L_{payload} / T = 1500 \times 8 / T \quad (3.18)$$

Applying (3.18) to four transmission modes in 802.11b, it turns out that

- R_{DBPSK}=0.9 Mbps for DBPSK 1 Mbps,
- R_{DQPSK}=1.8 Mbps for DQPSK 2 Mbps,
- R_{CCK55}=4.3 Mbps for CCK 5.5 Mbps, and
- R_{CCK11}=7.2 Mbps for CCK 11 Mbps.

In practical terms, even if the link is perfect, the obtainable data transmission speed is always below the mandatory data rate because of the transmission time required for the header, the preamble, and the tail. Also, a retransmission for both the data frame and the control frame is another issue that should be counted into the delay of the data transfer.

3.2.2 Data Rate in 802.11a Link

The way that the data is transferred from MAC to PHY and then carried into the wireless channel is the same in the 802.11b link and in the 802.11a link. The links in the two standards differ in their frequency bands, some defined frame transmission times, etc.

During the transmission, a PLCP preamble and a PLCP header are added to an MPDU to create a PLCP protocol data unit (PPDU). The PPDU format for the IEEE 802.11a PHY is shown in Figure 2-5. The PLCP preamble field is composed of 10 repetitions of a short training sequence with 0.8 μs for each sequence, and 2 repetitions of a long training sequence with 4 μs for each. Thus, the total transmission time of a PLCP preamble field, known as $T_{PLCP\_Preamble}$ is 16 μs. The PLCP header, except the SERVICE field, constitutes a single OFDM symbol, which is transmitted with BPSK modulation and rate 1/2 convolutional code. The header takes 4 μs to be transferred, because each OFDM symbol interval is 4 μs. The SERVICE field is a 16-bit field, which equals to 2 bytes in length. Some of the parameters of the time slot defined in 802.11a differ from those defined in 802.11b. The ideal transmission data rate can be analyzed in the same way as was done for 802.11b. With all the parameters listed from (3.19) to (3.26), the total transmission time is found as in (3.27).

$$T_{Slot} = 9\ \mu s, \quad (3.19)$$

$$T_{SIFS} = 16\ \mu s, \quad (3.20)$$

$$T_{DIFS} = T_{SIFS} + 2\times T_{slot} = 16 + 2\times 9 = 34\ \mu s, \quad (3.21)$$

$$T_{Backoff} = T_{slot} \times Random(CW) = 9 \times 15 = 135\ \mu s, \quad (3.22)$$

$$T_{PLCP\_Preamble\&Header} = 16 + 4 = 20\ \mu s, \quad (3.23)$$

$$T_{symbol} = 4\ \mu s, \quad (3.24)$$

$$T_{payload} = [(16 + 6)/8 + (28 + L_{payload})] / BytesPerSymbol \times T_{symbol}, \quad (3.25)$$

$$T_{ACK} = [(16 + 6)/ 8 + 14] / BytesPerSymbol \times T_{symbol}, \quad (3.26)$$

$$T = T_{DIFS} + T_{Backoff} + (T_{PLCP\_Preamble\&Header} + T_{payload}) + T_{SIFS} + (T_{PLCP\_Preamble\&Header} + T_{ACK})$$

$$= 34 + 135 + (20 + T_{payload}) + 16 + (20 + T_{ACK}) \quad \mu s \qquad (3.27)$$

$$R' = L_{payload} / T \qquad (3.28)$$

Assuming the $L_{payload}$ is 1500 bytes long, all the 8 modulation modes described in 802.11a have the ideal transmission rates listed in Table 3-3. They are lower than the nominal data rate for the same reason illustrated when we explained the same thing about an 802.11b link at the end of Section 3.2.1.

Table 3-3 Data Rates of 802.11a Link

Mode	Modulation	Code Rate	Norminal Data Rate (Mbps)	bytes per symbol	Actual Transmission Data Rate (Mbps)
1	BPSK	1/2	6	3	5.2
2	BPSK	3/4	9	4.5	7.5
3	QPSK	1/2	12	6	9.6
4	QPSK	3/4	18	9	13.2
5	16-QAM	1/2	24	12	16.2
6	16-QAM	3/4	36	18	21.1
7	64-QAM	2/3	48	24	24.9
8	64-QAM	3/4	54	27	26.4

3.3 Derivation of Throughput in AWGN Channel

In the previous section, the actual transmission rates were found based upon an assumption that a single data transmission is a successful transmission. In other words, retransmission was not considered in deriving the ideal transmission rate, although retransmission is highly probable on a real wireless link. In the following, the throughput will be discussed with retransmission taken into account, which reflects more practical scenarios.

3.3.1 Throughput of 802.11b Link

The network throughput is affected by whether a frame can be transmitted successfully at its first transmission time or has to be retransmitted. If a transmission fails, the sender has to wait for an SIFS time, followed by an ACK transmission time, a slot time and a backoff period, and then begin to retransmit. In [14], the total transmission time for a packet with (i-1) retransmissions and the throughput analysis are given. As a summary,

1) *Probability of a successful data transmission:*

$$P_{success} = (1 - P_{e\_data})(1 - P_{e\_ACK}), \tag{3.29}$$

where
$$P_{e\_data} = 1 - (1 - P_{e\_PLCP\_P\&H})(1 - P_{e\_payload}) \tag{3.30}$$

and
$$P_{e\_ACK} = 1 - (1 - P_{e\_PLCP\_P\&H})(1 - P_{e\_ACK}). \tag{3.31}$$

P_e is the error rate of a data frame with a specific subscript showing the type of data it stands for. It depends on the bit error rate and the frame length expressed in terms of the number of bits.

2) *Probability of successful data transmission after (i-1) retransmissions:*

$$P_i = (1 - P_{success})^{i-1} P_{success}. \tag{3.32}$$

3) *Total transmission time for a successful data transmission* is in (3.33). The transmission time in that equation has been discussed in 3.2.1.

$$T = \sum_{i=1}^{\infty} \{ P_i [\sum_{j=0}^{i-1} (T_{SIFS} + T_{ACK} + T_{slot} + T_{Backoff(j)} + T_{payload}) + T_{payload} + T_{SIFS} + T_{ACK}]\} \tag{3.33}$$

4) *Throughput* = $L_{payload}$ / T. (3.34)

According to (3.29) to (3.34), the throughput performance versus C/N with four transmission modes is plotted in Figure 3-7. As we expected, the maximum throughput of each mode approaches the ideal data rate as in Section 3.2.1. Both the first-time transmission and the retransmissions have been considered. As a result of this, the maximum throughput can be reached when the C/N and is big enough to guarantee the desired performance.

In Figure 3-7, five C/N thresholds were defined as CNRTH1, CNRTH2, … , CNRTH5 to divide the C/N into six ranges — cnr_rg1, cnr_rg2, …, cnr_rg6. As for DBPSK 1 Mbps, as long as C/N is larger than 11.5 dB, the throughput reaches 0.9 Mbps. One interesting observation is that once the C/N becomes large enough, such as in cnr_rg3 and cnr_rg4, CCK55 always generates higher throughput than DQPSK 2 Mbps for the same C/N value. The CCK11 transmission mode provides the maximum throughput when C/N is over 18.5 dB. It is also shown that the throughput can be optimized by selecting different transmission modes within certain C/N ranges. When C/N is below 13.7 dB, DBPSK supports the highest throughput. The CCK 5.5 Mbps should be used while C/N is between 13.7 and 18.5 dB. Once C/N is over 18.5 dB, CCK11 supports the maximum throughput. If we are concerned solely with throughput, DQPSK for 2 Mbps does not bring any benefits.

Furthermore, the maximum throughput remains constant when C/N is in cnr_rg2, cnr_rg4 and cnr_rg6. The increase of the C/N value does not bring higher throughput at all. This indicates that transmitter power can be saved in these three C/N ranges without degrading the throughput performance.

The above observations introduce the TOTPS algorithm, which will be discussed in Chapter 4.

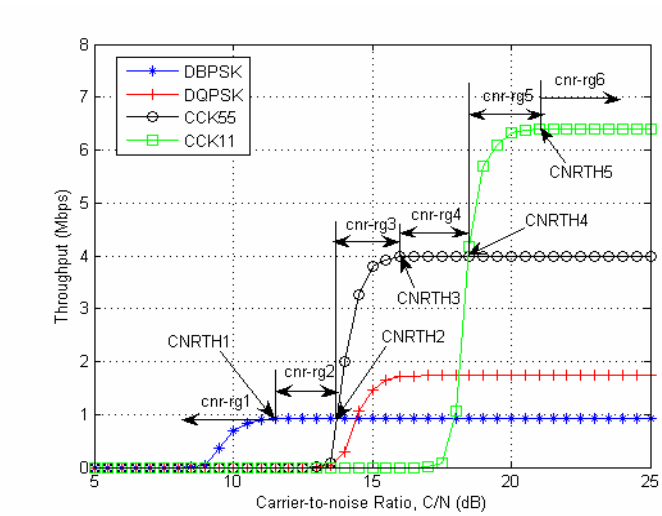

Figure 3-7 **Throughput vs. C/N of 802.11b Link in an AWGN Channel**

3.3.2 Throughput of 802.11a Link

The performance of BER versus E_b/N_o as found in Section 3.1.2 shows the BER of an 802.11a link. Since convolutional coding is used in 802.11a links, the probability of error for decoding will affect the overall packet error rate at the receiver. Assuming hard-decision decoding of convolutional code is used, and based on [16], the packet error rate of the header and preamble and the information data frame is determined by

- BER (P_b) of BPSK, QPSK, 16-QAM and 64-QAM modulations;
- Distance (d) between the decoding selected path and the all-zero path with the all-zero path assumed to be transmitted;
- Number of paths (a_d) corresponding to the distance, also called total number of error events of weight d. It relates to the code rate of the convolutional coding and it is referred from [23].

If d is odd, the probability of selecting incorrect path is

$$P_{p\_mode\_E_b/N_o} = \sum_{k=(d+1)/2}^{d} \binom{d}{k} P_{e\_mode\_E_b/N_o}{}^{k} (1 - P_{e\_mode\_E_b/N_o})^{d-k} \qquad (3.35)$$

Otherwise, if d is even, the probability of selecting an incorrect path is

$$P_{p\_mode\_E_b/N_o} = \sum_{k=d/2+1}^{d} \binom{d}{k} P_{e\_mode\_E_b/N_o}{}^{k} (1 - P_{e\_mode\_E_b/N_o})^{d-k} + \frac{1}{2}\binom{d}{\frac{1}{2}d} P_{e\_mode\_E_b/N_o}{}^{d/2} (1 - P_{e\_mode\_E_b/N_o})^{d/2} \qquad (3.36)$$

And, the union bound of the error rate of each bit is

$$P_{e\_mode\_E_b/N_o} < \sum_{d=d_{free}}^{\infty} a_d P_{p\_mode\_E_b/N_o} \qquad (3.37)$$

Correspondingly, if an n-byte packet is transferred, the packet error rate will be

$$P_{np\_mode\_E_b/N_o} \leq 1 - (1 - P_{e\_mode\_E_b/N_o})^{8n} \qquad (3.38)$$

The probability of a successful data transmission can be expressed the same as in (3.29), depending on a successful header, preamble transmission and a successful MPDU frame transmission as well. The packet error rate of transmission for these two types of frame can be estimated by (3.38). Therefore, as long as the length of the information data frame in the MPDU is determined, everything can be solved. The probability of a successful data transmission after (i-1) retransmissions will be counted out from (3.32). Assuming the data payload length is $L_{payload}$ and the data payload is defragmented into N_{frag} data frames for transfer, the length of each fragmented data is $L_{frag} = L_{payload} / N_{frag}$ length of the transmission time for information data is

$$T_{frag} = [(16 + 6)/8 + (28 + L_{frag})] / BytesPerSymbol \times T_{symbol}, \qquad (3.39)$$

The equations in (3.26) show the transmission time for ACK frames in an 802.11a link as well. The throughput of an 802.11a link with length of $L_{payload}$ data transferred is

$$Throughput = \frac{8 \times L_{payload}}{T_{IMPDU} + N_{frag} \times T_{frag} - T_{SIFS}}, \qquad (3.40)$$

where T_{IMPDU} is the time interval between the transmission of two MPDU frames, and it can be described as

$$T_{IMPDU} = T_{DIFS} + CW_{min}/2. \qquad (3.41)$$

In (3.41), it is assumed that low possibility of two MPDU transmission taking place at the same time.

The throughput of the 8 transmission modes described in 802.11a standard is shown in Figure 3-8. The $L_{payload}$ is assumed 1500 bytes long as in Section 3.2.1 and 3.2.2. It is interesting that the throughput of 802.11a link turns out to be very similar to 802.11b link in the way of the trend of each curve, which rises before then leveling off.

Moreover, from the plot, it became obvious that in an AWGN channel, two transmission modes — BPSK 9 Mbps with 3/4 convolutional coding and 48 Mbps using 64-QAM with 2/3 convolutional coding, do not have much advantage over others. When E_b/N_o is larger than 3 dB, a proper selection of a transmission mode can help the data transfer remain at the maximum throughput that a specified value of E_b/N_o is able to support. For instance, when E_b/N_o is 10 dB, if the data are transmitted via the link using defined QPSK 18 Mbps with 3/4 convolutional code, a 14.2 Mbps actual transmission speed can be reached.

Another fact observed from the Figure 3-8 is that the throughput cannot be improved further, once the E_b/N_o value is within a certain range and the "right" transmission mode for that range is being used over the link. An example could be the case when E_b/N_o is between 16 dB and 20 dB. When E_b/N_o is 16 dB, as long as the 16-QAM with 3/4 convolutional coding is used for the wireless link, 24 Mbps data delivery is obtained. Before the E_b/N_o value reaches 20 dB, the fastest speed on the link is still 24 Mbps but no more.

Since the results of the throughput of an 802.11a link are very similar to those of an 802.11b link, some algorithms applied to the 802.11b link can also be used on an 802.11a link. The TOTPS and the ETOTPS algorithms discussed later are designed based on the 802.11b link. They can also be implemented on the 802.11a link with limited changes — basically just adjusting the algorithms to the 802.11a link, and no major difference.

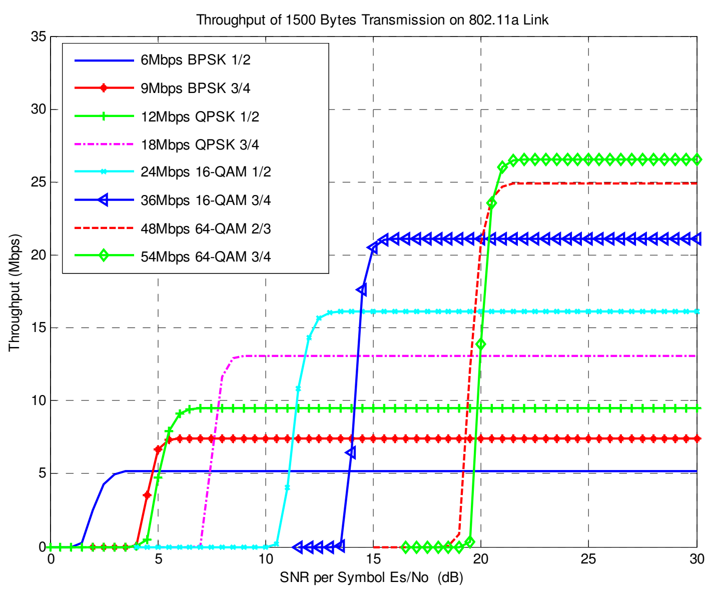

Figure 3-8 Throughput vs. E_s/N_o of 802.11a Link

3.4 802.11b Link in Rayleigh Fading Channel

The physical characteristics of the wireless communications media can change constantly, which causes the channel to have time varying impulse responses. Those changes can be generated by multipath propagation from the reflecting objects and scatterers in the channel, relative motion between the base station and the mobile terminals, the speed of surrounding objects and the transmission bandwidth of the signal. The transmitted signals pass through the media following multiple paths and they arrive the receiver at slightly different times. The interference between two or more versions of the transmitted signals at the receiver is called multipath fading.

The fading channels are described by their statistical features. There are two types of fading channel models in common use: the Rayleigh fading channel and the Ricean fading channel.

In the material which follows, the Rayleigh fading channel and the Ricean fading channel are introduced. Furthermore, the 802.11b link's performance in both fading channels is investigated.

3.4.1 Rayleigh Fading Channel

If the impulse response of a signal can be modeled as a zero-mean complex-valued Gaussian process, the envelope of the impulse response at any instant is Rayleigh distributed. When the signals carried on a channel having such feature, the channel is called a Rayleigh fading channel. Rayleigh fading usually occurs in the presence of clutter between the transmitting and receiving nodes. It is known that the envelope of the sum of two quadrature Gaussian noise signals obeys a Rayleigh distribution [16].

Assume that a signal received from the i^{th} path in a multipath fading channel is defined as

$$r(t) = \alpha_i x_i(t) + n(t). \qquad (3.42)$$

where α is the amplitude of the i^{th} path signal on the channel and is modeled by a Rayleigh distribution with a probability density function (PDF) given as

$$p(\alpha) = \frac{\alpha}{\sigma^2}\exp(-\frac{\alpha^2}{2\sigma^2}) \quad (0 \le \alpha \le \infty) \quad (3.43)$$

where σ is the root mean square (rms) value of the received voltage signal before envelope detection. And, and σ^2 is the time average power of the received signal.

The instantaneous and average SNR of the i^{th} path are defined as γ and $\overline{\gamma}$, and the PDF of γ is described by

$$p(\gamma) = \frac{1}{\overline{\gamma}}\exp(-\frac{\gamma}{\overline{\gamma}}) \qquad (3.44)$$

The cumulative distribution function (CDF) is

$$F(\gamma) = 1 - \exp(-\frac{\gamma}{\overline{\gamma}}) \quad . \qquad (3.45)$$

3.4.2 BER of 802.11b Link in Rayleigh Fading Channel

The performance of the BER of an 802.11b link is discussed in this section. All four modulation modes of 802.11b in Rayleigh fading channel will be analyzed.

If there are multiple antennas installed at the receiver, several replicas of the same information arrive as signals transmitted over independently fading channels. A method for obtaining diversity is based on the use of a signal having a bandwidth much greater than the coherence bandwidth of the channel. The model for the diversity receiving system is described in Figure 3-9.

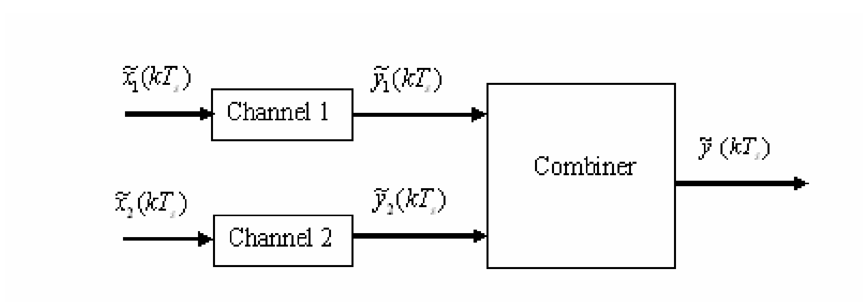

Figure 3-9 Model of Diversity Receiving System

Assume that $\overline{\gamma_c}$ is the average SNR per channel, $\overline{\gamma_b}$ is the average SNR per bit and the fading on the L channels is mutually statistically independent. Then the average BER over the fading channel of DBPSK is given in [16] as

$$P_b = \frac{1}{2^{2L-1}(L-1)!(1+\overline{\gamma_c})^L} \sum_{k=0}^{L-1} b_k (L-1+k)! (\frac{\overline{\gamma_c}}{1+\overline{\gamma_c}})^k \qquad (3.46)$$

in which

$$b_k = \frac{1}{k!} \sum_{n=0}^{L-1-k} \binom{2L-1}{n} \qquad (3.47)$$

and

$$\overline{\gamma_b} = \frac{L \cdot \overline{\gamma_c}}{k} \qquad (3.48)$$

The BER of DQPSK over Rayleigh fading channel is mathematically represented as

$$P_b = \frac{1}{2}[1 - \frac{\mu}{\sqrt{2-\mu^2}} \sum_{k=0}^{L-1} \binom{2k}{k} \left(\frac{2-\mu^2}{4-2\mu^2} \right)^k] \qquad (3.49)$$

where

$$\mu = \frac{\overline{\gamma_c}}{1+\overline{\gamma_c}} \quad . \qquad (3.50)$$

The BER curves of DBPSK and DQPSK in Rayleigh channels with diversity (L=2) and without a diversity (L=1) scheme applied is illustrated in Figure 3-10. The transmission mode followed by “L1” or “L2”, like “DBPSKL2”, means that the data on the link is sent in DBPSK mode with a diversity receiver at the receiving side. If it is “DBPSKL1”, then this means that no diversity is applied upon receipt with the link uses DBPSK transmission mode.

An interesting observation from Figure 3-10 is that the BER versus E_b/N_o curve of the DBPSK signals carried over a Rayleigh fading channel by using diversity receiving overlays the one of the DQPSK on the same fading channel also with diversity scheme used at the receiver. Coincidently, the BER curves of the DBPSK and the DQPSK signals over a Rayleigh fading channel show almost the same link features regardless of whether receive diversity is used or not. The links with diversity used at the receiver support the link with lower probability of error per bit. To obtain the same BER, the link without diversity at the receiver requires 3 to 4 dB more E_b/N_o compared to the link with diversity receiving.

The BER versus average C/N plot is presented in Figure 3-11, which simply applies (3.1) for changing a BER versus E_b/N_o plot to a BER versus C/N plot. It is presented primarily for generating the plots of throughput versus C/N later.

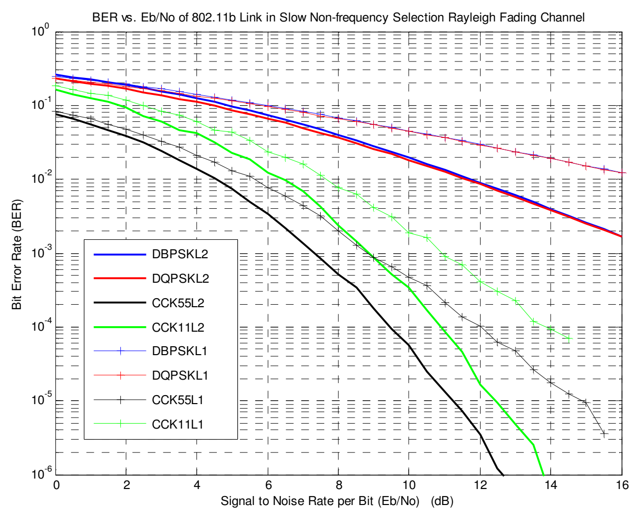

Figure 3-10 BER vs. Average E_b/N_o of 802.11b Link in a Rayleigh Fading Channel

Since there is no closed-form solution for the CCK55 and CCK11 transmission modes, the BER of these links over a Rayleigh fading channel is determined by simulating the transceiving links in Matlab. A conceptual link for a single ray of the Rayleigh fading channel is shown in Figure 3-12.

As described in 3.1.1, the codeword is encoded from the original data information through a phase angle encoder. Then it is carried as symbols on the Rayleigh fading channel. At the front end of the receiver, Gaussian noise is added to the received signal as an input to the filter. This is not shown in the plot.

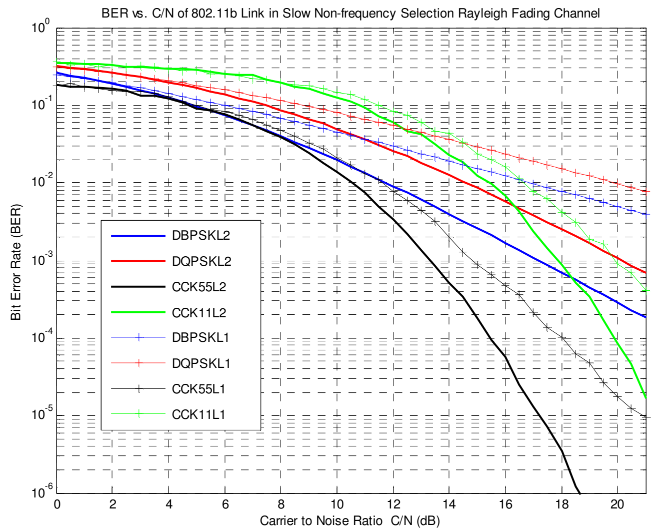

Figure 3-11 BER vs. Average C/N of 802.11b Link in a Rayleigh Fading Channel

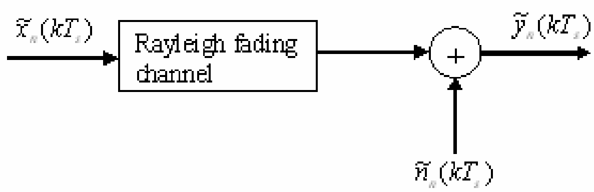

Figure 3-12 Transceiving Link of Rayleigh Fading Channel

Assuming equal weight combining is applied in the diversity receiving system for the CCK modulation modes, the BER performance is simulated in Matlab and presented in Figure 3-10 and in Figure 3-11.

Meanwhile, observations from Figure 3-10 are that the bit error probability of the receiver diversity system is lower than that of the same transmission mode without diversity combination method used for receiving. Furthermore, for a larger value of the average CNR, the CCK11 transmission mode of a link with receive diversity method supports a lower BER than the BER of CCK55 transmission mode of a link without receive diversity, although the BER of the CCK11 is still higher than the BER of CCK55 for a diversity link.

From the BER versus average CNR of 802.11b links indicated in Figure 3-11, it is obvious that, at the same average CNR value, the BER of CCK55 mode is the lowest among the four transmission modes. The BER of CCK11 mode is the second lowest one when the CNR exceeds 20 dB. Under the same conditions for comparison, the DBPSK transmission mode has the highest BER among the four transmission modes. In other words, the relatively more sophisticated transmission mode defined in the 802.11b standard supports better performance in terms of BER versus average E_b/N_o. This result is completely different from the BER performance of 802.11b links in an AWGN channel plotted in Figure 3-4.

The model of the link with a diversity receiver over the Rayleigh fading channel is selected as the reference for the performance of 802.11b link in Rayleigh fading channel. The throughput performance of a link over a Rayleigh fading channel by using diversity combination at the receiver is studied in the next section.

3.4.3 Throughput of 802.11b Link in Rayleigh Fading Channel

The BER of the 802.11b links over a Rayleigh fading channel with an L=2 diversity receiver is shown in Figure 3-10. An assumption made for investigating the throughput of 802.11b link is that the information transferred on the link totals 1500 bytes, which is the same data length used in the study of the throughput of 802.11b link in the AWGN channel. The BER values read from the simulation results in Figure 3-11 are applied in the simulation for obtaining the throughput performance of the links, which is shown in Figure 3-13.

In Figure 3-13, CCK55 or CCK11 mode shows a promising advantage over DBPSK or DQPSK, in terms of throughput on a Rayleigh fading channel at any average C/N value. When the average CNR is less than 20.8 dB, CCK55 carries the highest throughput. Once the average CNR is larger than 20.8 dB, CCK11 supports the fastest data transfer with 6.4 Mbps as maximum throughput. If the average C/N is over 25 dB, the throughput remains at the maximum value, no matter how much C/N increases. About 7 dB more required for the average C/N values of CCK55 and CCK11 to achieve the highest throughput that each of them can reach in a Rayleigh fading channel comparing to the same transmission modes in an AWGN channel by comparing the curves in Figure 3-13 to the ones in Figure 3-7.

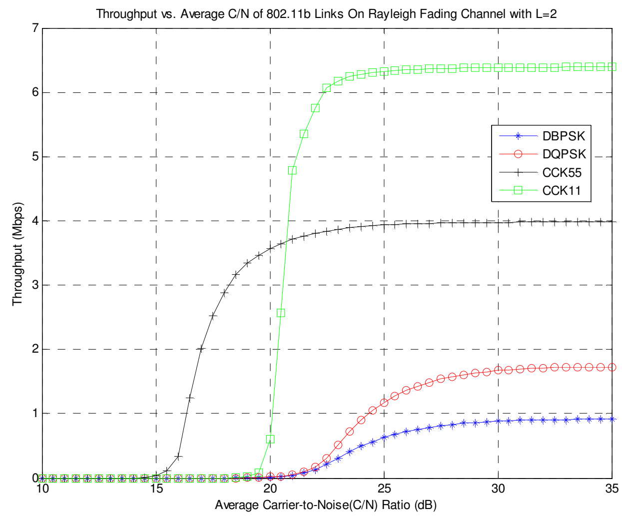

Figure 3-13 Throughput vs. C/N of an 802.11b Link in Rayleigh Fading Channel

3.5 802.11b Link in Ricean Fading Channel

In this section, the BER and throughput of 802.11b links over Ricean fading channel will be studied. This will provide an overview of 802.11b link's performance in fading channels by combining the results from Section 3.4.

3.5.1 Ricean Fading Channel

In a fading channel, when a dominant non-fading signal component is present, i.e. a line-of-sight (LOS) propagation path, the fading envelope distribution has a Ricean distribution. The channel carrying the signals is called Ricean fading channel.

The probability density function of a Ricean distributed random variable X can be described by

$$p_X(x) = \frac{x}{\sigma^2} e^{-\frac{x^2+A^2}{2\sigma^2}} I_0\left(\frac{Ax}{\sigma^2}\right), x \geq 0 \qquad (3.51)$$

where A stands for the peak amplitude of the LOS component, σ denotes to the standard deviation of the constituent real and imaginary Gaussian variables of the Rayleigh component, and I_0 is the zeroth order modified Bessel function of the first kind. In some circumstances, a Ricean channel is described by using a Ricean fading factor, the K-factor, represented as $K = \frac{A^2}{2\sigma^2}$. When K=0 dB, the Ricean distribution becomes the Rayleigh distribution. And, when K = ∞ dB, the link can be modeled as if it is an AWGN channel.

The PDF of the SNR per symbol γ can be expressed as

$$p_\gamma(\gamma) = \frac{(1+K)e^{-K}}{\bar{\gamma}} e^{-\frac{(1+K)\gamma}{\bar{\gamma}}} I_0\left(2\sqrt{\frac{K(1+K)\gamma}{\bar{\gamma}}}\right) \qquad (3.52)$$

where $\bar{\gamma}$ stands for the average SNR per symbol.

The CDF of γ is denoted as

$$F(\gamma) = 1 - Q\left(\sqrt{2K}, \sqrt{\frac{2(K+1)\gamma}{\bar{\gamma}}}\right) \qquad (3.53)$$

in which Q(a,b) is the first order Marcum Q function defined as

$$Q(a,b) = \int xe^{-\frac{x^2+a^2}{2}} I_0(ax)dx. \qquad (3.54)$$

3.5.2 BER of 802.11b Link in Ricean Fading Channel

The BER of 802.11b link in Ricean fading channel is studied by simulating the link performance in Matlab under the assumption that a diversity receiver is used and L=2. A 2.4 GHz band measurement report [24] from Ulffe, Platino and Barreto points out that the mean value of the Ricean K factor for indoor environments is approximately independent of distance and it varies from 16 dB to 30 dB for different antenna configurations. Thus, the K factor was set at 22 dB as an applicable value for the BER simulation in this research.

The BER versus the average E_b/N_o per channel of DBPSK and DQPSK links over Ricean fading channels can be found from [24]. The fading is identically distributed with the same fading parameters and the same average SNR per bit $\overline{\gamma}$ for all L channels, and the average BER is denoted as

$$\overline{P}_b(L,\overline{\gamma},i;a,b,\eta) = \frac{\eta^L}{2\pi(1+\eta)^{2L-1}} \int_{-\pi}^{\pi} \frac{f(L;\beta,\eta;\phi)}{1+2\beta\sin\phi+\beta^2} \cdot [J_i(\overline{\gamma},i;a,b;\phi)]^L \, d\phi \quad (3.55)$$

in which

$$f(L;\beta,\eta;\phi) = f_0(L;\beta,\eta;\phi) + f_1(L;\beta,\eta;\phi) \quad (3.56)$$

$$f_0(L;\beta,\eta;\phi) = \left[-\frac{(1+\eta)^{2L-1}}{\eta^L} + \sum_{l=1}^{L} \binom{2L-1}{L-l} (\eta^{-l} + \eta^{l-1}) \right] \cdot \beta(\beta+\sin\phi) \quad (3.57)$$

and

$$f_1(L;\beta,\eta;\phi) = \sum_{l=1}^{L} \binom{2L-1}{L-l} \{ (\eta^{-l}\beta^{-l+1} - \eta^{l-1}\beta^{l+1}) \cdot \cos[(l-1)(\phi+\frac{\pi}{2})]$$
$$- (\eta^{-l}\beta^{-l+2} - \eta^{l-1}\beta^{l}) \cdot \cos[l(\phi+\frac{\pi}{2})] \} \quad (3.58)$$

In (3.55), *i* is the fading factor, represented in K in (3.59) as a Ricean fading factor.

$$J(\overline{\gamma},K;a,b;\phi) = \frac{2(1+K)}{2(1+K)+b^2\overline{\gamma}(1+2\beta\sin\phi+\beta^2)}$$
$$\times \exp\left[-\frac{Kb^2\overline{\gamma}(1+2\beta\sin\phi+\beta^2)}{2(1+K)+b^2\overline{\gamma}(1+2\beta\sin\phi+\beta^2)} \right] \quad (3.59)$$

The parameter values in the above equations from (3.55) to (3.59) will be a = 0, b = $\sqrt{2}$, $\beta = \frac{a}{b} = 0$, and $\eta = 1$ for DBPSK and a = $\sqrt{2-\sqrt{2}}$, b = $\sqrt{2+\sqrt{2}}$, $\beta = \frac{a}{b} = 0.4$, and $\eta = 1$ for DQPSK.

The performance of the BER versus C/N is as plotted in Figure3-14 for the link with Ricean factor K = 22dB and L=2. The BER of the links in four transmission modes are more like the BER performance of the same link in an AWGN channel, but with higher BER value for corresponding C/N values.

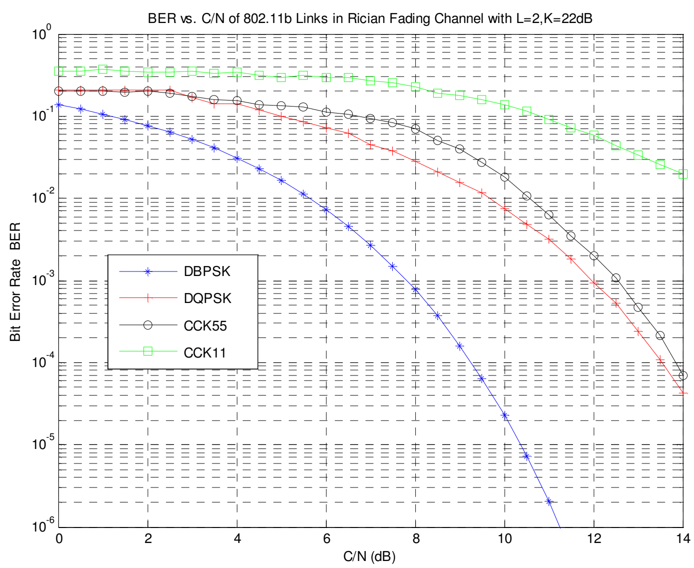

Figure 3-14 BER vs. C/N of an 802.11b Link over Ricean Fading Channel with K=22dB, and L=2 Diversity Receiver

3.5.3 Throughput of 802.11b Link in Ricean Fading Channel

Based on the experience of the throughput of 802.11b link in an AWGN channel and in Rayleigh fading channel and the BER versus C/N of 802.11b link over Ricean fading channel, it is not difficult to generate the throughput curves of 802.11b link in a Ricean fading channel as in Figure 3-15. The shape of throughput curves in Figure 3-15 shows the similarity of the throughput curves in Figure 3-7 and the ones in

Figure 3-15, but illustrates the difference of the C/N values when the peak throughput of each mode is reached.

In DBPSK link, when C/N is over 12 dB, the data can be transferred at 0.9 Mbps, which is the highest throughput that the DBPSK transmission mode can support. The minimum required value of C/N is 14 dB, if the maximum transmission speed of DQPSK, 1.7 Mbps is expected. However, when C/N is larger than 15.7 dB but smaller than 19.2 dB, using CCK55 as a transmission mode is preferred, since it can support the higher throughput than any other transmission mode. Once the C/N value is larger than 19.2 dB, CCK11 will be the only choice of all four modes for a data link, because the highest throughput is generated on the link with this mode. Particularly, when the C/N value is larger than 22.5 dB, a 6.4 Mbps data transfer rate can be supported on the wireless link.

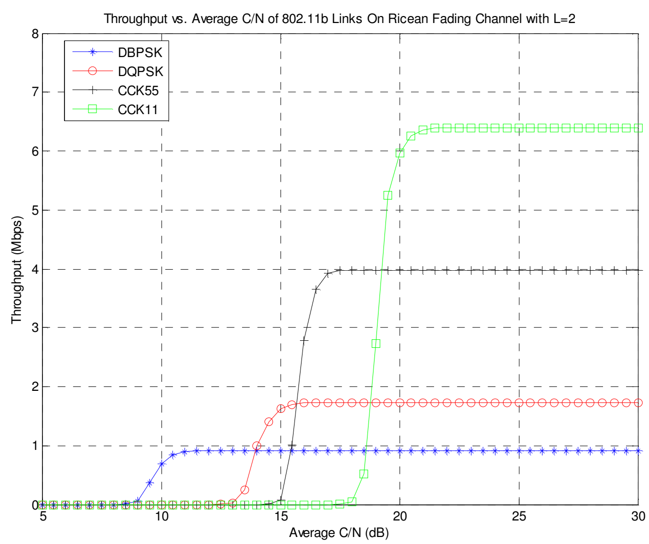

Figure 3-15 Throughput vs. C/N of 802.11b Link over Ricean Fading Channel with K=22dB

4. TOTPS Algorithm and ETOTPS Algorithm

Based on the previous analysis of the throughput in terms of C/N ratios, a throughput optimization algorithm is developed in this chapter. The following two facts

1. the terrace-shaped throughput versus C/N curves of 802.11b link among the AWGN channel, the Rayleigh fading channel and the Ricean fading channel, and
2. the similarity of the throughput curves of the 802.11b link in AWGN channel and those of the 802.11a link in AWGN channel

tell us that the throughput optimization algorithm generated on an 802.11b link using an AWGN channel model can be adopted in the same standardized link in a Rayleigh fading channel as well as in a Ricean fading channel. Moreover, the algorithm is extendable to 802.11a and 802.11g links in the three studied channel models.

The throughput optimization and transmitter power saving algorithm, also called the *TOTPS algorithm*, is designed based on the behavior of 802.11b links in AWGN channel. Methods of obtaining the necessary link parameters and implementing the algorithm will be described in this chapter.

4.1 TOTPS Algorithm and ETOTPS Algorithm Initiation

The terrace-shaped throughput versus C/N plots in Figure 3-7, Figure 3-8, Figure 3-13 and Figure 3-15 indicate that there is always one out of the four transmission modes supporting the highest throughput within a certain C/N range. This identified transmission mode is the desired one for the best data transfer performance.

It also has been shown that the throughput can be optimized by choosing different transmission modes in certain C/N ranges. In Figure 3-7, as for DBPSK transmission mode, as long as C/N is larger than 11.5 dB which is marked as “CNRTH1” (CNR threshold 1), the throughput reaches 0.9 Mbps. When the C/N ratio is smaller than

11.5 dB, DBPSK supports higher throughput than any one of the other three transmission modes. The same thing happens to the CCK11 mode when C/N is larger than 21 dB. When the C/N falls in cnr_rg3 (CNR range 3) and/or cnr_rg4, the CCK55 mode delivers higher throughput than DQPSK mode for the same C/N value.

The maximum throughput remains constant when the C/N is between 11.5 dB and 13.7 dB corresponding to cnr_rg2, between 16 dB and 18.5 dB corresponding to cnr_rg4 and when C/N is larger than 21 dB which is in cnr_rg6. This indicates that the transmitter power can be reduced to a certain level without degrading the throughput performance when C/N ratio falls in these three C/N ranges.

The observation and the analysis made above tell us that the throughput can be controlled by an algorithm if the C/N ratio of the wireless link is known. Therefore, the TOTPS algorithm monitors the C/N ratio periodically, and adjusts the transmitter power at the relatively lowest level to support the maximum throughput.

In addition, for situations where the C/N ratio is increasing, such as when it is in cnr_rg1 or cnr_rg3 or cnr_rg5, raising the transmitter power within some limit imposed by a maximum value can push the link to reach the maximum throughput in a shorter time period. Since the power remains under control, the overall performance of the link will be upgraded while the average transmitter power is being monitored. This algorithm is named the *extended TOTPS algorithm,* also called the *ETOTPS algorithm.*

4.2 Estimation and Transfer of CNR in TOTPS Algorithm

The TOTPS algorithm depends on the real-time C/N ratio of the wireless link. Therefore, it is critical to obtain the instantaneous C/N value. On an 802.11 link, the receiver measures and estimates the C/N ratio and then passes it to the sender to determine a transmission mode to achieve optimal throughput. The estimation and transfer of C/N value in TOTPS algorithm is as described in Figure 4-1. A wireless link between AP (access point) and STA1 (station 1) and a wireless link between STA1 and STA2 are defined. Assume that data information is transferred from the AP to the STA1 and then it is sent from the STA1 to the STA2. The TOTPS algorithm is used on the link between the STA1 and the STA2.

The C/N ratio at the receiver, STA2 in Figure 4-1, changes with the variable radio link environment as the adjacent devices are turned on and off. It is possible that the C/N level at one moment changes a lot from the value at the next moment. On the other hand, when electronic equipment nearby starts to operate, the C/N becomes C/(N+I), where *I* represents interference. Because of this, making multiple measurements of received power at different time but close enough to the upcoming data transfer will be a good solution to the problem of making an accurate estimate of C/N.

Referring to Figure 4-1, during the DIFS and the backoff periods, the N measurements of the received power P_n (n=1, 2, …, N) are basically the noise, or the noise plus the interference, if the interference exists.

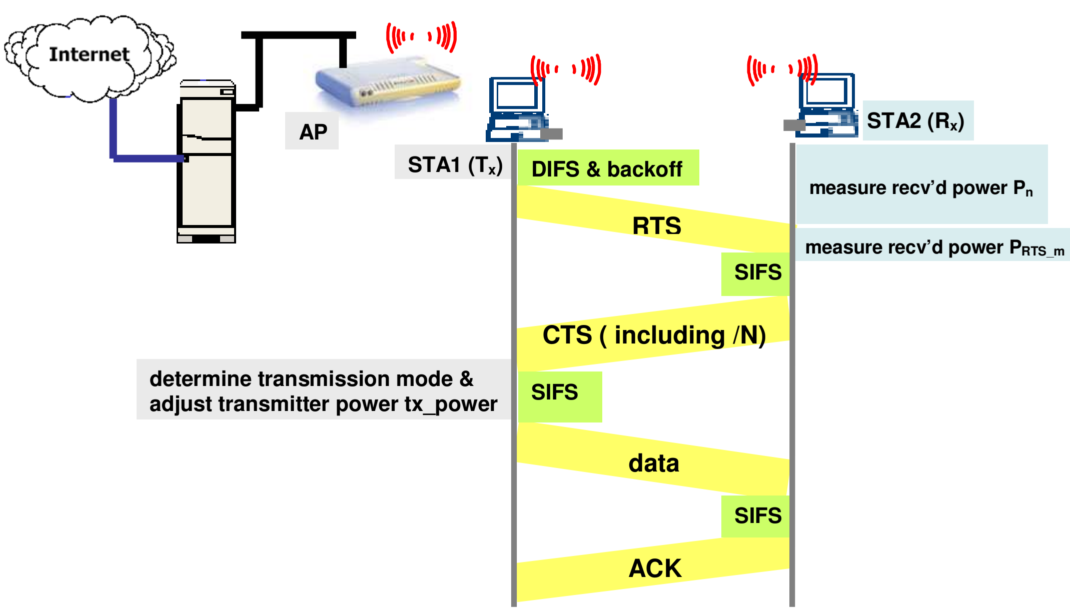

Figure 4-1 Operation Procedure of TOTPS and ETOTPS Algorithm

Generally, multiple measurements of the received power have higher chances to capture the exact power level to help the estimation of an expected power level rather than a single measurement does. In a wireless environment, it is highly possible that the measurement of the received power made in one moment is completely different from the measuring result generated in the next moment, for the mobility of the devices. We also believe that the closer to the determination of the received power based on the measurement, the more reliable of this measuring result in the sense of its affects on the accuracy of the estimated received power. Hence, a weighting factor α_n is introduced.

Under the assumption that the time of starting to send data is T, and the time of each measurement is T_n, the time difference between these two instances is

$$\Delta T_n = T - T_n. \qquad (4.1)$$

Then, α_n will be

$$\alpha_1 : \alpha_2 : \ldots : \alpha_N = \Delta T_N : \Delta T_{N-1} : \ldots : \Delta T_1, \qquad (4.2)$$

and the α_n also satisfy

$$\alpha_1 + \alpha_2 + \ldots + \alpha_N = 1. \qquad (4.3)$$

The estimation of the received power, P', will be

$$P' = \sum_{n=1}^{N} \alpha_n P_n \qquad (4.4)$$

Assuming that a wireless station starts to count time when it begins to detect the noise and the interference at its receiver. In 2 seconds, it records the received power is P_1. It continues detecting and memorizing the received power as P_2 in 5 seconds, and P_3 when the timer counts to 7 seconds. After it counts for 10 seconds, the wireless station sends out data message. According to (4.1), we have the values of the power detection time T_1, T_2, T_3, and the ΔT_1, ΔT_2, and ΔT_3 obtained by (4.1) as in Table 4-1. With (4.2) and (4.3), the values of α_1, α_2, and α_3 can be figured out. To apply (4.4), we have $P' = (3 P_1 + 5 P_2 + 8 P_3)/16$. Thus, with the detected power P_1, P_2 and P_3, P'is easily calculated.

It appears obvious that the closer to the data transfer time that the received power is detected, the more weight should be put on its value when it is counted in the estimation of the received power. This is relatively more reliable than taking the unweighted value of the received power as the value of (N+I). Take a look at the above example again, because it is more likely that the wireless environment remains the same or similar 3 seconds before the station starts to sending data rather than the environment situation at 8 seconds before, P_3 is weighed more than P_1 is when we calculate P'.

Table 4-1 An Example of Parameter Calculation for the Value of Received Power

$T_1 = 2$ s	P_1	$\Delta T1 = 8$ s	$\alpha_1 = 3/16$
$T_2 = 5$ s	P_2	$\Delta T2 = 5$ s	$\alpha_2 = 5/16$
$T_3 = 7$ s	P_3	$\Delta T3 = 3$ s	$\alpha_3 = 1/2$

The M measurements of the received power P_{RTS_m} during the RTS period include the desired signal power, the noise and the interference power. Using the same scheme as for P' and assuming a weighting factor β_m, the estimation value P_{RTS}' is

$$P_{RTS}' = \sum_{m=1}^{M} \beta_m P_{RTS\_m} \qquad (4.5)$$

Consequently, the estimated value of C/(N+I) can be obtained from

$$\frac{C}{N+I} = \frac{P_{RTS}' - P_n'}{P_n'} = \frac{P_{RTS}'}{P_n'} - 1 = \frac{\sum_{m=1}^{M} \beta_m P_{RTS\_m}}{\sum_{n=1}^{N} \alpha_n P_n} - 1 \cong \frac{\sum_{m=1}^{M} \beta_m P_{RTS\_m}}{\sum_{n=1}^{N} \alpha_n P_n} \qquad (4.6)$$

under the condition C>>(N+I).

In the following discussion, C/N will be used instead of C/(N+I), because in the theoretical analysis and later simulation, the channel model used for the wireless link is an AWGN channel. This simplifies the analysis. This is particularly true for the simulations in the following chapters, because the total background noise in the simulation is kept the same during all the simulation time. So, only one C/N value checked at the receiver will be enough.

Once the C/N value is measured at the receiving terminal, what is the best way to pass it to the sender? To minimize the change to the standards, some reserved fields in CTS or ACK frames should be chosen.

For long frame transmission, a “hand-shake” is usually executed. CTS can carry the C/N information to the sender as shown in Figure 4-1. Although an RTS/CTS exchange does not happen in retransmission, an ACK frame can take the C/N values towards the sender. However, if a short frame transmission happens, no “hand-shake” is processed, and ACK means the end of the data transfer. In this case, the link performance should not be seriously degraded, even if the node uses a transmission mode which does not optimize the throughput.

As discussed for Figure 3-7, when C/N is within cnr_rg2, cnr_rg4 and cnr_rg6, the transmitter power can be decreased to some level without degrading the throughput performance. This feature helps in developing a power saving scheme. If the C/N value tends to be larger, transmitter power can be reduced to a specified level. The initial transmitter power value is stored and is resumed whenever transmitter power reduction happens or decreasing C/N degrades the throughput performance. In cnr_rg1, cnr_rg3 and cnr_rg5, using DBPSK, CCK55 and CCK11 respectively, the larger the C/N value is, the higher throughput that can be achieved. However, considering the possibility of raising the interference to neighboring wireless networks, the power level should not be increased without control, and the TOTPS algorithm operates this way. In other words, in the TOTPS algorithm, the transmitter power remains unchanged in cnr_rg1, cnr_rg3 and cnr_rg5.

The TOTPS algorithm is described in Figure 4-2, where tx_power_max equals to the original transmitter power, all the “cnr” relevant values are in decibels, and the “power” relevant values are in dBm. In cnr_rg2, cnr_rg4 and cnr_rg6, when the C/N value at the receiver becomes bigger, the sender determines to reduce the transmitter power to be

$$tx\_power = tx\_power\_prev - (cnr\_prev - CNRTH1) \quad (4.7)$$

for C/N in cnr_rg2, and to use *CNRTH3* and *CNRTH5* to replace the *CNRTH1* in (4.7) for C/N in cnr_rg4 and cnr_rg6, respectively. By doing so, the TOTPS algorithm guarantees that the throughput stays at the optimal value while the transmitter power is adjusted to be lower. Concurrently, the C/N is continually being checked to see whether using the original transmitter power can bring the link to a higher throughput. If so, the original transmitter power will be resumed in the next transmission.

On the other hand, if the C/N comparison result shows that the C/N becomes smaller, which indicates that the throughput will drop, the original transmitter power will be resumed. Since the transmitter power is never increased to be larger than the initial transmitter power in TOTPS, neither the instantaneous transmitter power nor the average power level is a concern in the TOTPS algorithm, as long as the original transmitter power is within a safe range.

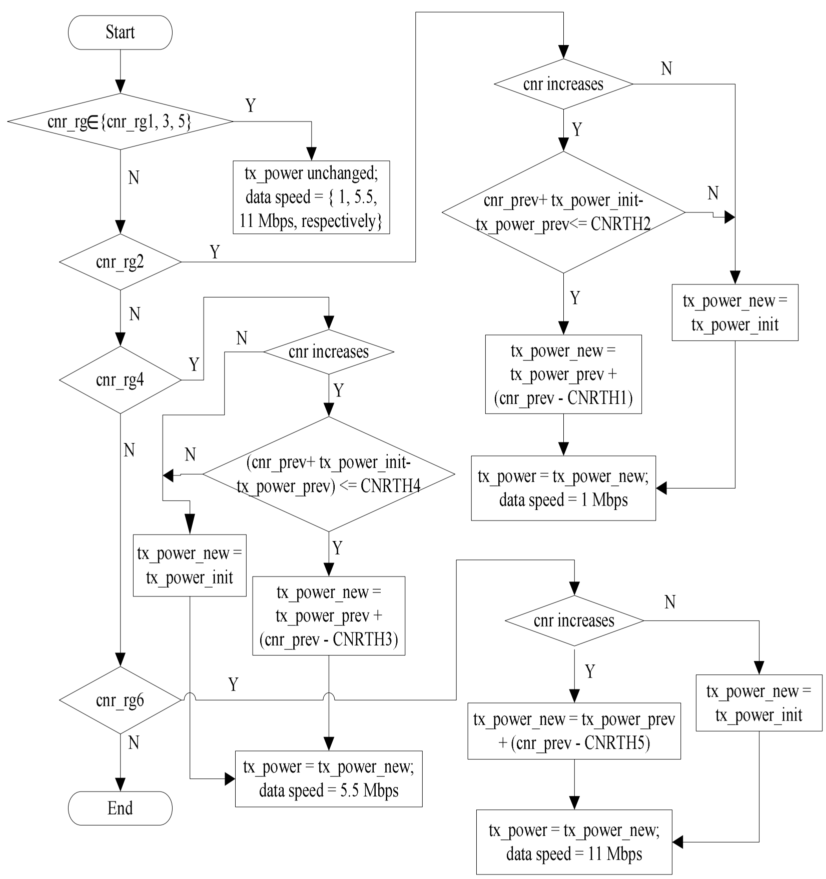

Figure 4-2 Throughput Optimization and Transmitter Power Saving (TOTPS) Algorithm for IEEE 802.11b Links

4.3 Introduction of ETOTPS Algorithm

ETOTPS is an extension of TOTPS in the sense that a more aggressive throughput optimization algorithm is added to the original TOTPS algorithm. Looking back to Figure 3-7 again, the TOTPS algorithm does not do anything when the C/N value falls in the ranges — cnr_rg1 or cnr_rg3 or cnr_rg5. The ETOTPS algorithm, in contrast, raises the transmitter power within an allowed limit. This will raise the throughput of the link and enable it to reach a higher level faster. The so called *allowed level* is normally a pre-set maximum transmitter power or a maximum average transmitter power in a specified time interval. Meanwhile, when the C/N value is within cnr_rg2 or cnr_rg4 or cnr_rg6, the strategies applied by the ETOTPS algorithm are inherited from the TOTPS algorithm.

Since unlike the TOTPS algorithm, the ETOTPS algorithm sometimes increases the transmitter power, it is necessary to check whether the instantaneous transmitter power or the average power level stays in a safe range. This provides us an alternative way to limit the interference caused to neighboring networks. The safe range of the power is defined by a pre-set maximum transmitter power in ETOTPS algorithm in the simulation presented later in this chapter.

In an ETOTPS algorithm installed network, the more power is added at the transmitter, the sooner the throughput of the link will be supported at a higher level, regardless of the interference from nearby wireless networks. On the other hand, as long as there is another wireless network in the neighborhood, the interference from the ETOTPS applied link to its neighbor will be increased, which causes trouble to the quality of the neighboring wireless link. Meanwhile, the neighboring wireless link might also have its transmitter power increased because of the higher level of interference. Thus, to increase the transmitter power while monitoring the C/(N+I) level is an approach to take the advantage of the ETOTPS algorithm and to avoid causing problem to nearby wireless links.

In Figure 4-2, the flow chart of TOTPS algorithm, the first condition for action is whether the CNR value is within cnr_rg1 or cnr_rg3 or cnr_rg5 or not. If this condition is satisfied, the transmitter power remains unchanged. In ETOTPS, this condition is changed. We can see from Figure 4-3 that the transmitter power is increased by X dB after each CNR detection, when the CNR value becomes larger on the link. The power increment value of X is varied based upon a particular condition of the link. We tend to tune it with a fine value. The reason is that we do not want to add too much power at one time to make the whole wireless environment suffer from one link being over-powered. On the other hand, when the CNR value gets smaller, the transmitter power is tuned to resume the previous value if it helps to preserve a relatively larger CNR value.

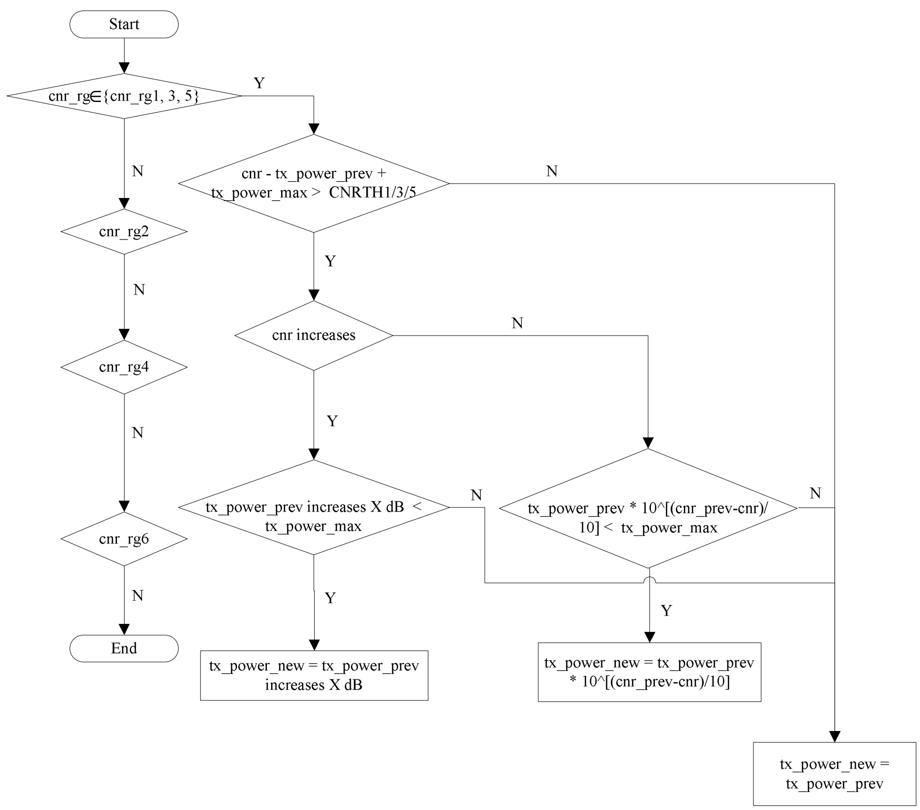

Figure 4-3 **Flow Chart of ETOTPS Algorithm Applied to an 802.11b Link**

The basic power control rule for the link in cnr_rg 1, cnr_rg3, and cnr_rg5 is similar, except that different CNR threshold values should be applied to different cnr_rg's. Again, the percentage by which the power is increased depends on the deployment plan and the network environment. No matter which cnr_rg the CNR falls in, the main purpose of ETOTPS is to power up the transmitter to pursue higher throughput. The power control for cnr_rg 2, 4, 6 is unchanged from TOTPS algorithm, thus it is not shown in Figure 4-3. See Figure 4-2 for details.

4.4 Operation Procedure of ETOTPS Algorithm

Most parts of the operation procedure of ETOTPS algorithm are the same as those of TOTPS algorithm, except for some rules for determining the transmitter power at the sender. The transmitter power remains unchanged, as with the TOTPS algorithm, when the C/N value is in cnr_rg1 or cnr_rg3 or cnr_rg5 indicated in Figure 3-7. Contrarily, the ETOTPS algorithm will push the throughput of the link to be higher or to be able to reach a higher level faster by raising transmitter power under an allowed level, when the C/N value is within those three CNR ranges. The so called *allowed level* is usually described as an instantaneous maximum transmitter power in this study. Meanwhile, when the C/N value is within cnr_rg2 or cnr_rg4 or cnr_rg6, the strategies applied in ETOTPS algorithm is inherited from TOTPS algorithm.

From the above descriptions of the TOTPS and ETOTPS algorithms, it becomes clear that there are always tradeoffs between using one rather than the other on a wireless link. The TOTPS algorithm promises less power consumption, because it usually does not raise the transmitter power. On the other hand, it is not as aggressive as the ETOTPS algorithm in terms of pursuing a higher throughput. The ETOTPS algorithm aims for higher throughput all the time, although it may be unable to save as much power as the TOTPS algorithm can. However, overall, the ETOTPS algorithm still saves the transmitter power of the data transmitting terminal, comparing to the link which does not ever have power saving scheme used.

Unlike the TOTPS algorithm, since the ETOTPS algorithm sometimes increases the transmitter power, it is necessary to check whether the instant transmitter power or the average power level stays in a safe range, which is usually defined by a maximum transmitter power in the ETOTPS algorithm as described above.

How do we increase the transmitter power level when a link has the ETOTPS algorithm applied to it? The more power is increased at the transmitter, the sooner that the throughput of the link will be supported to a higher level. However, as long as there is another wireless network is in the neighborhood, the interference to the neighboring network jumps up, which degrades the quality of the other wireless links. Meanwhile, a neighboring wireless link might also have its transmitter power increased because of the higher level interference. Thus, to add a specific power at the transmitter and keep the power level monitored is an approach to take advantage of the ETOTPS algorithm and avoid causing problem to other nearby wireless links.

5. Performance of TOTPS Algorithm Applied to 802.11b Links

In this chapter, the proposed TOTPS algorithm is simulated in different scenarios in Opnet. The performance of the simulations is displayed and conclusions are made based upon the performance.

The simulation results indicate that the TOTPS algorithm will benefit the 802.11b standard wireless link. The analysis of the performance illustrates how the optimal throughput on the link is achieved and how much transmitter power is saved by implementing the algorithm in each particular scenario. The results of the wireless network simulation show the expectable similarity of the network performance if the algorithms are applied to other discussed wireless links, like 802.11a and 802.11g.

5.1 Simulation Scenarios and Results

This section analyzes five scenarios of the TOTPS algorithm implemented in 802.11b wireless links.

- TOTPS algorithm applied to an 802.11b link in an AWGN channel
- TOTPS algorithm applied to an 802.11b link in a Rayleigh fading channel
- TOTPS algorithm applied to an 802.11b link in a Ricean fading channel
- TOTPS algorithm applied to a multi-user 802.11b network with the same distance between AP and each STA in an AWGN channel
- TOTPS algorithm applied to a multi-user 802.11b network with different distances between AP and each STA in an AWGN channel, and

The simulation tools used in this part of the research are Matlab for BER results combined with Opnet for simulating the wireless network.

5.1.1 TOTPS Algorithm Applied 802.11b Link in an AWGN Channel

A single 802.11b AP and STA link with the DCF MAC scheme in an AWGN channel is built in Opnet, as shown in Figure 5-1. The data frame generated from the AP's higher layer goes through its MAC layer and then is transferred to STA through a wireless link on 2.4 GHz frequency band. The frame length is 1500 bytes. The AP (node_0) remains at a fixed position while the STA (mobile_node_0) moves forward and backward,. This causes the received power at the STA to change because of the change of the distance between these two wireless terminals.

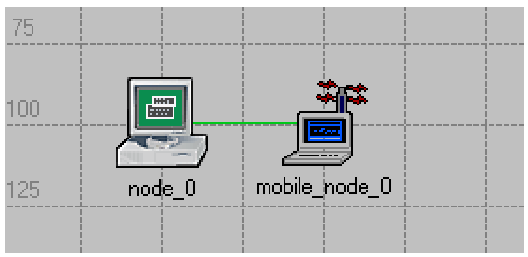

Figure 5-1 Simulation Scenario of 802.11b Link in Opnet

In the simulation, the C/N ratio is calculated at the mobile node and then is transferred to the AP. The procedure for passing the C/N ratio is simplified, since there is no co-existing wireless network and an AWGN channel is assumed for carrying the data information. When C/N is calculated at the receiver, it is then stored in a packet and passed to the sender before the next data frame transmission.

The TOTPS algorithm controls the transmitter power at the AP. The noise at the STA includes the receiver thermal noise and the ambient noise. The important parameters are listed in Table 5-1 and are basically identical to the values used in the theoretical analysis in Chapter 3.

Table 5-1 Parameters Used In 802.11b Wireless Link Simulation

Parameter	Value	Parameter	Value
PLCP Preamble&Header	192 bits	DIFS	50 us
MAC Header	192 bits	CW_min	31
MAC FCS	32 bits	CW_max	1023
SIFS	10 us	CNRTH1	11.5 dB
Slot_time	20 us	CNRTH2	13.7 dB
background noise temperature	290 K	CNRTH3	16 dB
noise figure	7 dB	CNRTH4	18.5 dB
ambient noise	10^{-26} J/s	CNRTH5	21 dB
Long_Retry_Limit	10		

The first simulation operates the wireless link without the TOTPS algorithm. In the theoretical analysis the number of retransmissions is close to unlimited, but it is limited to 10 in the Opnet simulation. The feature of the link model, such as the distance between the AP and the STA and the type of channel that the link operates on, basically determines the BER of a wireless link, based on one condition that the interference from the co-located wireless links is not taken into account. The results of BER versus C/N of the four modulation modes from Matlab are imported into Opnet to characterize the wireless link.

Figure 5-2 shows that the result of the throughput versus C/N of an 802.11b standardized link in Opnet generally agrees with the theoretical results in Figure 3-7. The maximum throughputs in DBSPK, in DQPSK and in CCK55 modes are very close to the analytical values. However, the throughput of CCK11 is 6 Mbps at maximum, which is about 0.4 Mbps lower than the theoretical results. This can be ascribed to the RTS/CTS exchange and the error correction used in Opnet simulation.

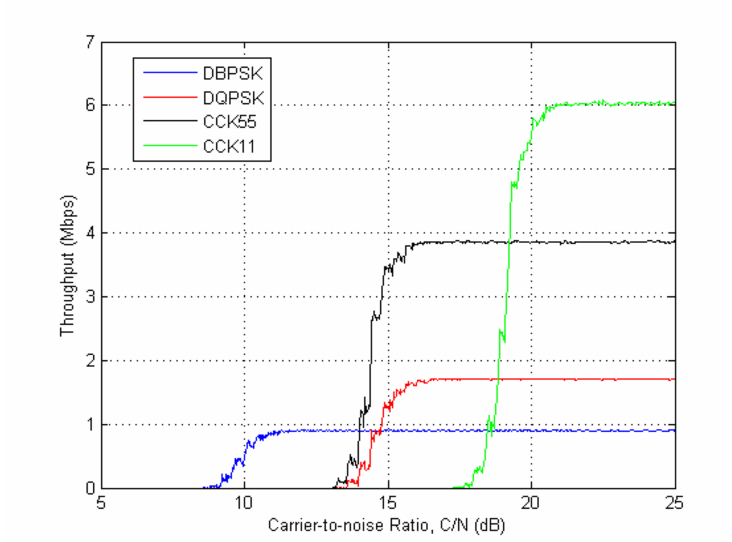

Figure 5-2 Throughput vs. C/N of an 802.11b Link over an AWGN Channel Simulated in Opnet

The throughput performance of an 802.11b link with TOTPS algorithm implemented is shown in Figure 5-3. The light blue star-connected curve stands for the throughput of the link using TOTPS algorithm. The purple solid curves represent the "right" transmission mode selected for the best throughput performance at each CNR range, which is basically the contour of the curves in Figure 5-2. But there is no power control scheme applied on the link. The purple curved link has only throughput optimization scheme applied but nothing to do with power control, it is called *throughput optimization only* (TOO) scheme. The TOO mechanism selects the modulation type that supports the highest throughput for the particular C/N plateau.

Comparing the two curves in Figure 5-3, the throughput at data rate 1 Mbps, 5.5 Mbps and 11 Mbps has transmitter power controlled to keep the C/N value just big enough to support the same throughput as with the original transmitter power. In other words, transmitter power is saved by applying the TOTPS algorithm when the C/N ratio is in the range of cnr_rg2, cnr_rg4 and cnr_rg6.

Another view of the result displayed as C/N varying with time is illustrated in Figure 5-4. When the STA moves forward and backward, the total noise does not change as a consequence of the AWGN channel; therefore, the difference in the received power in decibels (dB) equals the change in the value of C/N in decibels (dB). The change of the received power at an instance has the same effect as a corresponding change of the transmitter power from the sender at that moment. Since the STA moves on the same trajectory with the same speed in both scenarios with the TOTPS algorithm applied and with TOO applied. It makes sense to compare the transmitter powers for these two cases according to the received power. The ranges indicated as "power control" are the instances when the transmitter power on the TOTPS link is less than that on the link without power saving algorithm applied. According to the data extracted from Figure 5-4, it is found that 45% less transmitter power is consumed for the link with TOTPS algorithm applied in the particular scenario as in Figure 5-1.

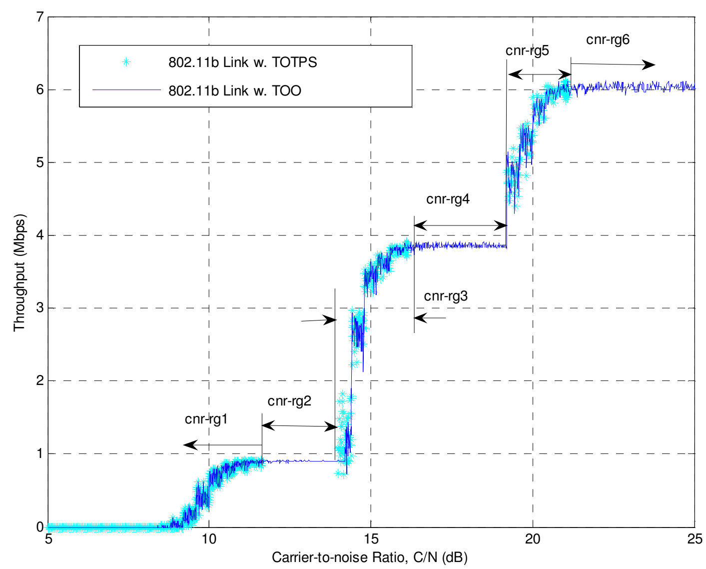

Figure 5-3 **Throughput vs. C/N of an 802.11b Link with TOTPS Applied in an AWGN Channel**

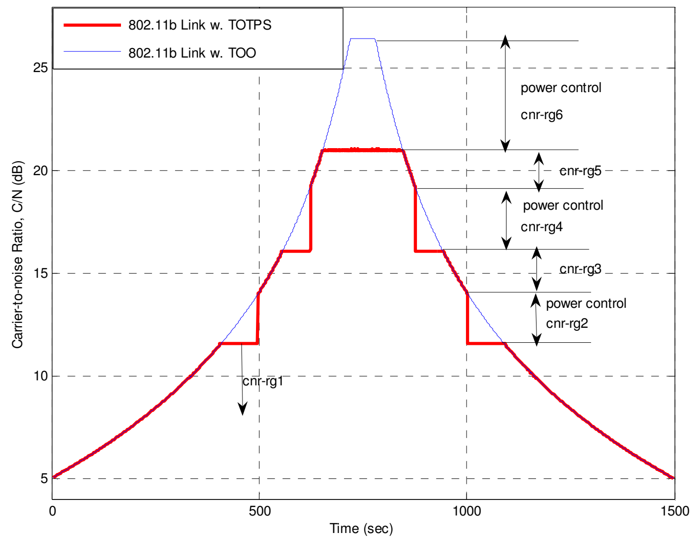

Figure 5-4 **C/N vs. Time of an 802.11b Link with TOTPS Applied in an AWGN Channel**

In fact, the amount of the saved transmitter power depends on how long the C/N ratio stays within the power controlled range — cnr_rg2, cnr_rg4 and cnr_rg6. The longer that the instantaneous C/N value with TOO applied remains in these three ranges, the more transmitter power can be saved by using the TOTPS algorithm.

5.1.2 TOTPS Algorithm Applied 802.11b Link in Rayleigh Fading Channel

In 3.4.2 and 3.4.3, the features of the bit error rate and the throughput of the Rayleigh fading channel have been studied. In this section, the performance of TOTPS algorithm used on a link in a Rayleigh fading channel will be discussed. Particularly, since multi-receiver radio becomes more commonly used in the WLAN, the performance of TOTPS algorithm for diversity reception in a Rayleigh fading channel is investigated.

The result of BER versus average C/N with diversity reception in Figure 3-11 is imported to Opnet, so that the modulation curves of the four types of modulation can be generated in Opnet. The bit error rate indirectly determines the throughput of the link as it does for the corresponding link in an AWGN channel.

According to the simulation experience of the TOO applied link in an AWGN channel, it is assumed that the throughput versus C/N of a TOO deployed link in a Rayleigh fading channel in Opnet simulation would turn out to be close to the same as the contour of the curves generated from Matlab simulation shown in Figure 3-13. Thus, the simulation for the TOO used link in a Rayleigh fading channel is not repeated in Opnet. And, the analysis below referring to Figure 3-13 prepares for further simulation of the TOTPS applied link in a Rayleigh channel.

From Figure 3-13, it is obvious that a link using CCK55 modulation in a Rayleigh channel obtains larger throughput than any of the other three modulation schemes, when the average C/N is below 21 dB. Once the average C/N is over 21 dB, the CCK 11 Mbps modulation brings the best link performance in terms of throughput. To an 802.11b deployed diversity receiving link in a Rayleigh fading channel, neither the DBPSK nor the DQPSK can create the highest throughput, no matter what the C/N value is.

Because of the observation described above, to pursue the highest throughput, the threshold of the average C/N value for tuning the modulation from CCK55 mode to CCK11 mode is about 21 dB, as found in Figure 3-13. The simulation parameters of the simulation of the TOTPS algorithm of an 802.11b link in a Rayleigh fading channel are listed in Table 5-2.

Before simulating the TOTPS deployed link, the simulation of the link with TOO (throughput optimization only) algorithm is executed first. The throughput versus time and the average C/N versus time are plotted in Figure 5-5. It is not hard to see that the Rayleigh fading channel requires the C/N value to be at least 25 dB on a link with CCK 11 Mbps to be able to support the best throughput, while same modulation mode in an AWGN channel with C/N of 21 dB is enough to support the highest throughput.

Table 5-2 Parameters Used in Simulation of an 802.11b Wireless Link with TOTPS Applied in a Rayleigh Fading Channel

Parameter	Value	Parameter	Value
PLCP Preamble&Header	192 bits	ambient noise	10^{-26} J/s
MAC Header	192 bits	Long_Retry_Limit	10
MAC FCS	32 bits	DIFS	50 us
SIFS	10 us	CW_min	31
Slot_time	20 us	CW_max	1023
bkground noise temperature	290 K	CNRTH	21 dB
noise figure	7 dB		

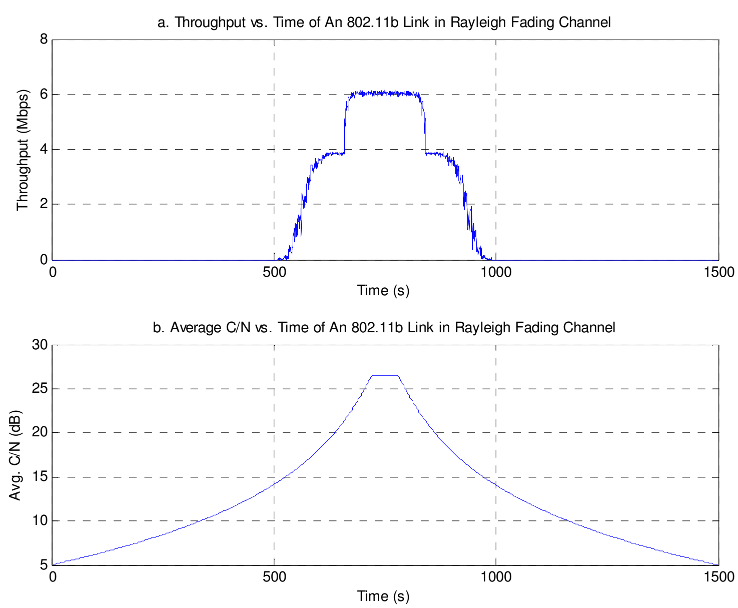

Figure 5-5 a. Throughput vs. Time of an 802.11b Link in a Rayleigh Fading Channel with TOO Algorithm Applied
b. Average C/N vs. Time of an 802.11b Link in a Rayleigh Fading Channel with TOO Algorithm Applied

In addition, it is clear as shown in Figure 5-6 that when the average C/N is below 21 dB, CCK55 transmission mode is used on the link to support the highest throughput. Once the value of the average C/N is larger than 21 dB, CCK11 mode should be applied to the link to achieve the best throughput. According to the experience from the TOTPS applied link in an AWGN channel, once we are facing the situation that the throughput does not improve when the value of C/N increases, the strategy of power saving should be used on the link.

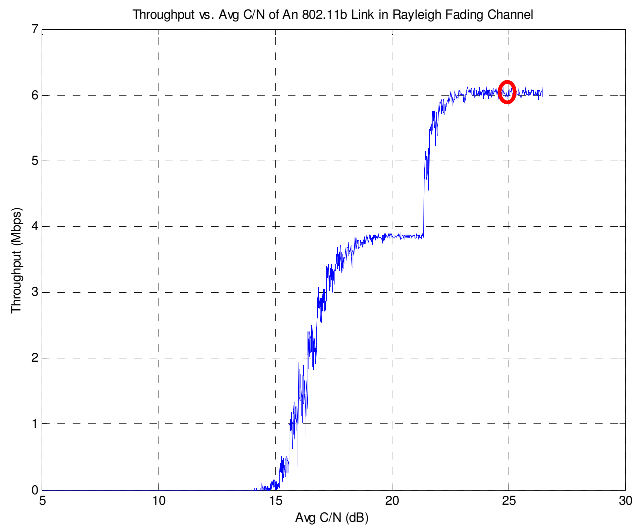

Figure 5-6 **Throughput vs. Average C/N of a TOO Applied 802.11b Link in a Rayleigh Fading Channel**

At this point, TOTPS is ready to be used in an 802.11b link over a Rayleigh fading channel beyond the point marked in red circle in Figure 5-6, where the average C/N goes above 25 dB. In the specific scenario as described by the parameters in Table 5-2, i.e., only controlling the power when the average C/N is over 25 dB, the simulation results shows that 10.2% power can be saved. The throughput of the link when using TOTPS is displayed in time domain in Figure 5-7. In Figure 5-8, the throughput versus C/N of an 802.11b link with TOO and with TOTPS deployed are plotted in dark blue curve and light blue curve, respectively.

In Figure 5-8, it is obvious that the transmitter power is under the control of the power saving algorithm when the C/N value is over 25 dB. In other words, the power saving algorithm applied to the link in a Rayleigh fading channel adjusts the power to keep the C/N value to be just as much as being needed to support the largest throughput. This guarantees that we will save transmitter power. The amount of the saved power still depends on a specific scenario, as mentioned before.

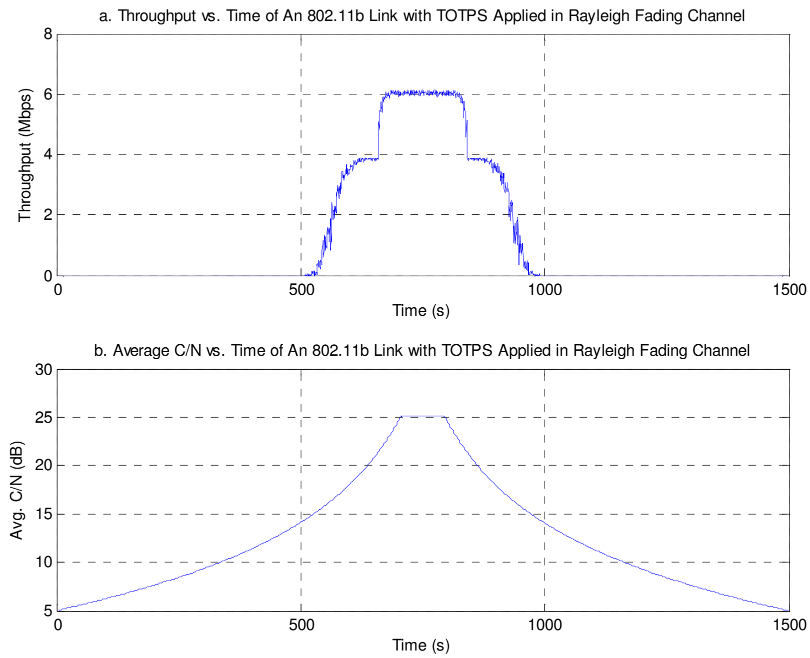

Figure 5-7 a. Throughput vs. Time of an 802.11b Link with TOTPS Applied in a Rayleigh Fading Channel
b. Average C/N vs. Time of an 802.11b Link with TOTPS Applied in a Rayleigh Fading Channel

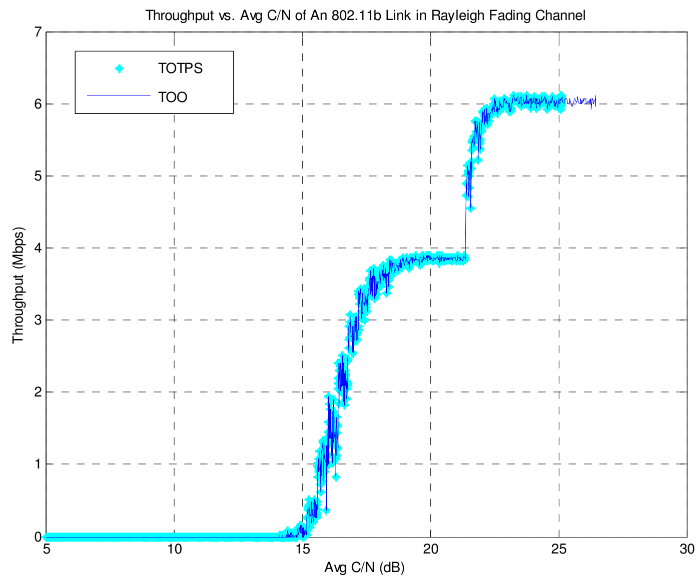

Figure 5-8 Throughput vs. Average C/N of an 802.11b Link with TOO and with TOTPS Applied in a Rayleigh Fading Channel

5.1.3 TOTPS Algorithm Applied 802.11b Link in Ricean Fading Channel

The features of the bit error rate and the throughput of the Ricean fading channel have been described in 3.5.2 and in 3.5.3. The TOTPS algorithm can be applied to the Ricean fading channel in a similar way as it is used on the AWGN and the Rayleigh fading channel. In this section, as further study of the 802.11b link in a Ricean fading channel discussed in 3.5, the performance of the TOTPS algorithm used in a link with diversity receiving on a Ricean fading channel, characterized with Ricean fading factor of K=22 dB, will be studied.

It is illustrated in Figure 3-15 that a link over a Ricean fading channel with K=22 dB has each of the four modes of 802.11b supporting the largest throughput at different C/N values of the link. Once we divide the C/N into six ranges with five thresholds, as shown in Figure 5-9, it appears easier to determine which modulation mode to use for the largest throughput at a particular C/N value. In Rayleigh fading channel, either CCK55 or CCK11 is selected to be used on the link. However, in a

Ricean fading channel, each one of the four modulation modes helps to generate the largest throughput at different C/N ranges.

The defined thresholds of the C/N value are shown in Table 5-3. Meanwhile, Figure 5-9 indicates that DBPSK supports the largest throughput while the value of C/N is below 14.6 dB, which is equivalent to cnr_rg1 and cnr_rg2. In cnr_rg2, the increasing C/N value does not bring higher but rather the same throughput. DQPSK is the best choice as a modulation scheme applied to the link when C/N is in cnr_rg3, and CCK55 transmission mode is the best one for the C/N within cnr_rg3 and cnr_rg4. Once the C/N value is beyond 19.6 dB, CCK11 mode is the one bring up the largest throughput.

Table 5-3 Parameters Used in an 802.11b Link Simulation in a Ricean Fading Channel

Parameter	Value	Parameter	Value
PLCP Preamble&Header	192 bits	DIFS	50 us
MAC Header	192 bits	CW_min	31
MAC FCS	32 bits	CW_max	1023
SIFS	10 us	CNRTH1	12 dB
Slot_time	20 us	CNRTH2	14.6 dB
background noise temperature	290 K	CNRTH3	15.7 dB
noise figure	7 dB	CNRTH4	18 dB
ambient noise	10^{-26} J/s	CNRTH5	19.6 dB
Long_Retry_Limit	10	CNRTH6	22.5 dB

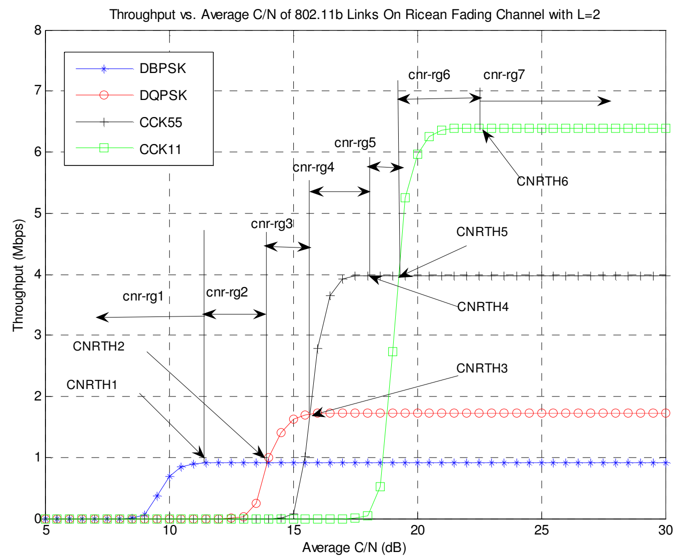

Figure5-9 Throughput vs. C/N of 802.11b Link over a Ricean Fading Channel with K=22dB

Figure 5-9 is helpful for picking the best modulation mode for a specific C/N value to use in the throughput optimization algorithm. By running an Opnet simulation of the similar scenario as shown in Figure 5-1, the performance of the throughput versus time of a TOO link is displayed in Figure 5-10. The left half of the plot in Figure 5-10 indicates the similarity as the theoretical analysis of the throughput contour in Figure 5-9.

The performance of the throughput versus C/N is illustrated in Figure 5-11, which is more obviously showing the one-to-one relationship of the throughput value and the C/N value when the modulation mode is defined, corresponding to each C/N range in the Ricean fading channel.

As before, the modulation curve of bit error rate in the Ricean fading channel results from a Matlab simulation. All the CNR thresholds are found in this way. These results are imported to the simulation model in Opnet, which is a straightforward simulation environment for WLAN.

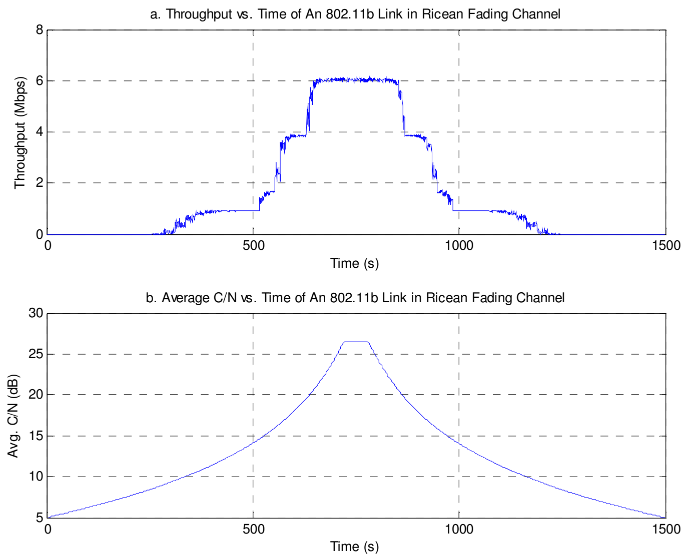

Figure 5-10 **a. Throughput vs. Time of an 802.11b Link in Ricean Fading Channel with TOO Algorithm Applied**
b. Average C/N vs. Time of an 802.11b Link in Ricean Fading Channel with TOO Algorithm Applied

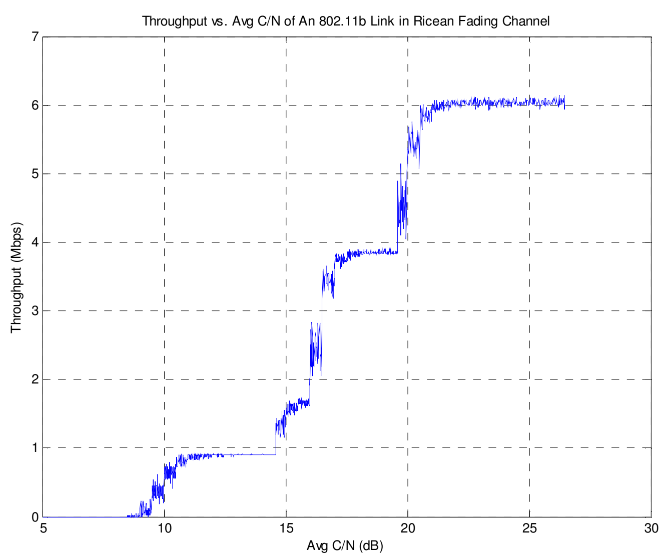

Figure 5-11 **Throughput vs. Average C/N of an 802.11b Link in Ricean Fading Channel with TOO Algorithm Applied**

The TOTPS is implemented to a link in a Ricean channel, while CNR falls in the cnr_rg2, cnr_rg5 and cnr_rg7. Therefore, TOTPS reduces the transmitter power to a value such that the corresponding C/N value is just big enough to support the throughput at the highest level that a link without power control can reach. The simulation result of the TOTPS algorithm used in an 802.11b link on a Ricean fading channel can be referred from Figure 5-12 and Figure 5-13. The power saving algorithm can be recognized by comparing the two curves in Figure 5-13. It shows that the CNR value is remained at a desired value when it is in cnr_rg2, cnr_rg5 and cnr_rg7. In this scenario, 38.6% of the transmitter power is saved.

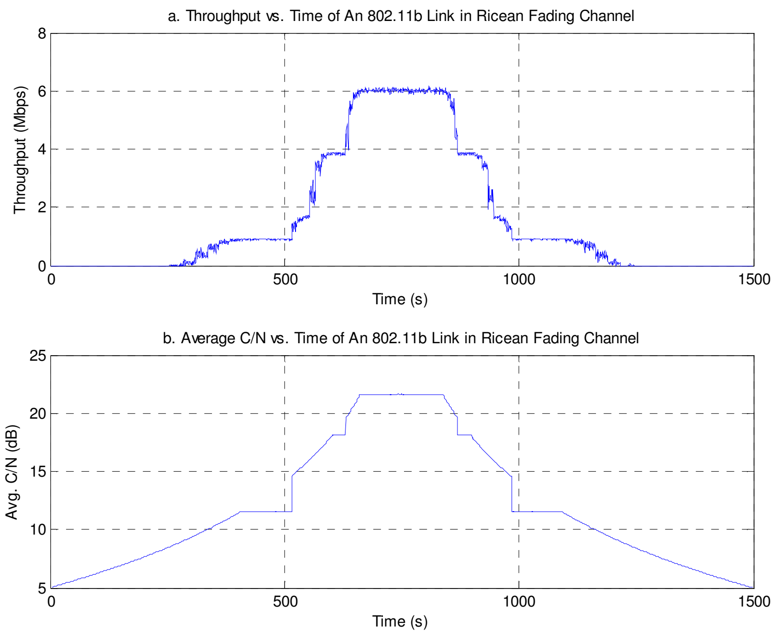

Figure 5-12 a. Throughput vs. Time of an 802.11b Link with TOTPS Applied in a Ricean Fading Channel
b. Average C/N vs. Time of an 802.11b Link with TOTPS Applied in a Ricean Fading Channel

The simulation results of the 802.11b link in Ricean fading channel proves that both the TOO algorithm and the TOTPS algorithm work for the 802.11b link in a Ricean channel as they can be operated in an AWGN channel as well as in a Rayleigh fading channel. The key points of applying these algorithms are observing the theoretical throughput versus C/N curve from the simulation, defining the C/N thresholds and C/N ranges for power control, and implementing the algorithm in the defined C/N ranges.

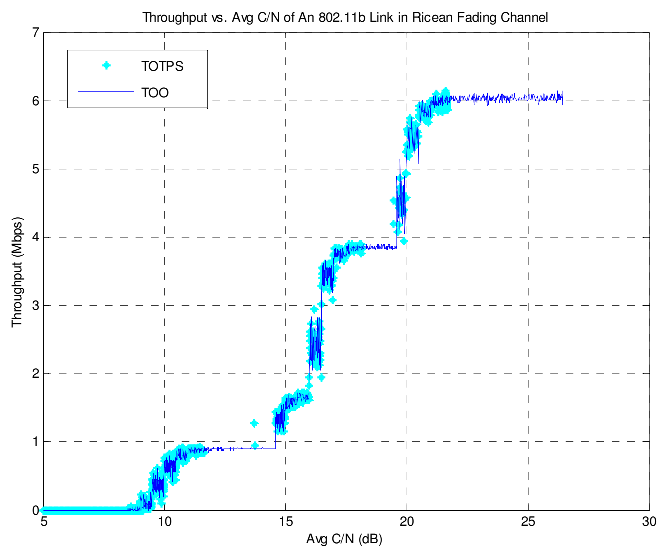

Figure 5-13 Throughput vs. Average C/N of an 802.11b link with TOO and TOTPS Applied in a Ricean Fading Channel

5.1.4 TOTPS Algorithm Applied Multi-user 802.11b Network with Same Distance between AP and Each STA in an AWGN Channel

Previously, we studied the performance of point-to-point link with TOTPS algorithm applied. In real cases, multi-user wireless network is much more appealing rather than single user wireless connection. Thus, the scenario of a wireless network with one static AP and two mobile STAs is built as in Figure 5-14.

In Figure 5-14, the distance between each mobile node and the AP is the same as 40 meters (m) and the mobile nodes move forward and backward from the AP in the same speed at 0.1 m/s. Once the mobiles nodes move to the point at 3 meters away from the AP, they stop moving but remain static for 1 minute before moving away from the AP. The data transmission is under the control as from AP to mobile_node_0 at one moment and from AP to mobile_node_1 at the next moment.

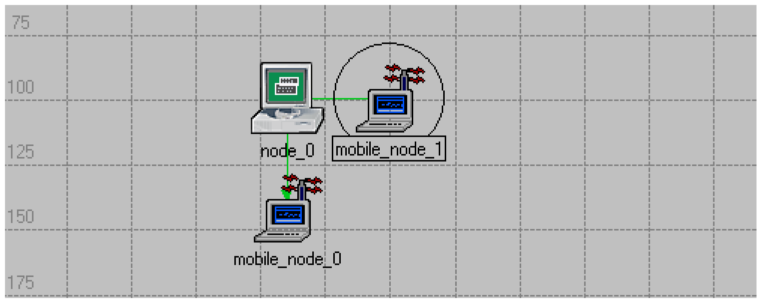

Figure 5-14 Simulation Scenario of Multiple 802.11b Links with Same Distance between AP and Each STA in Opnet

So long as we are dealing with an AWGN channel and there is no other wireless link around, the C/N value is sufficient information for the transmission power determination in the TOTPS algorithm. The C/N value is measured at each mobile node and then transferred to the AP once that mobile node gets its turn to transfer data. The parameter setting for this specific simulation is basically the same as in Table 5-1.

Firstly, the simulation is based on a wireless network operating without the TOTPS algorithm. This provides a baseline for comparing the performance of the link that uses the TOTPS algorithm. The result is displayed in two ways in Figure 5-15 and in Figure 5-16. The resulting throughput versus time and the C/N versus time on each link are shown in Figure 5-15. From another view of the results joined via time, the throughput versus C/N is illustrated in Figure 5-16. In both Figure 5-15 and Figure 5-16, the plots in blue represent the simulation results of the link between AP and mobile_node_0, and the plots in red are generated from the link of AP and mobile_node_1.

From the data results and the figures, the two links show very similar performance in either throughput or C/N in terms of time. The difference depends on the value of the C/N or the value of the throughput at a specific time. When the STA moves to the closest spot from the AP and remains there for 1 minute, which is indicated as the flat top of the curves in the C/N versus time plot, the C/N reaches the highest value. However, for the throughput of the links, it remains the same value till the C/N value of the link increases or decreases to the point being able to support another relevant throughput value. So, the maximum throughput reaches 6 Mbps for both links once the C/N value is over 21 dB, which is identical to the largest throughput of the single link.

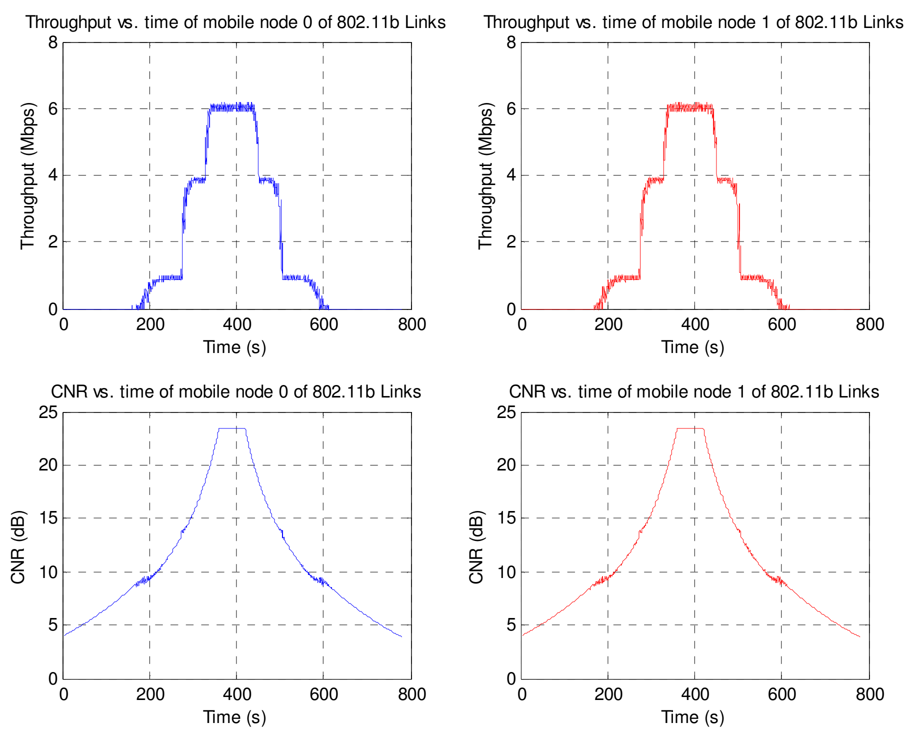

Figure 5-15 Throughput vs. Time and C/N vs. Time in Multiple 802.11b links with Same Distance between AP and STAs in an AWGN channel

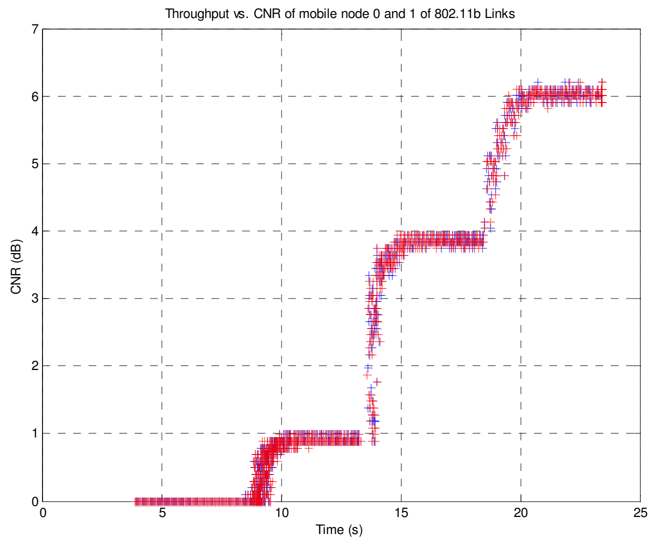

Figure 5-16 Throughput vs. C/N of Multiple 802.11b Links with Same Distance between AP and STAs in an AWGN Channel

The next step is to observe the performance of the same point-to-multipoint network as above with TOTPS algorithm implemented. All the wireless devices in the network operate with TOTPS algorithm activated, and the power saving is expected to be achieved on the terminal having data transferred. The same simulation network was built as in Figure 5-14.

In Figure 5-17, the performance of the C/N versus time and the throughput versus time are displayed in blue and in red for the link between the AP and the mobile_node_0 and for the link between the AP and the mobile_node_1, respectively. For the same scenario, Figure 5-18 shows the performance of the throughput versus C/N on each link, from which we can tell that the transmitter power is saved by comparing Figure 5-18 to Figure 5-16. Moreover, the transmitter power for the TOTPS applied multi-user network is about 22% less on each point-to-point link than the power consumed in the similar network without TOTPS used on the link. Thus, the total transmitter power saving of the network is around 44%.

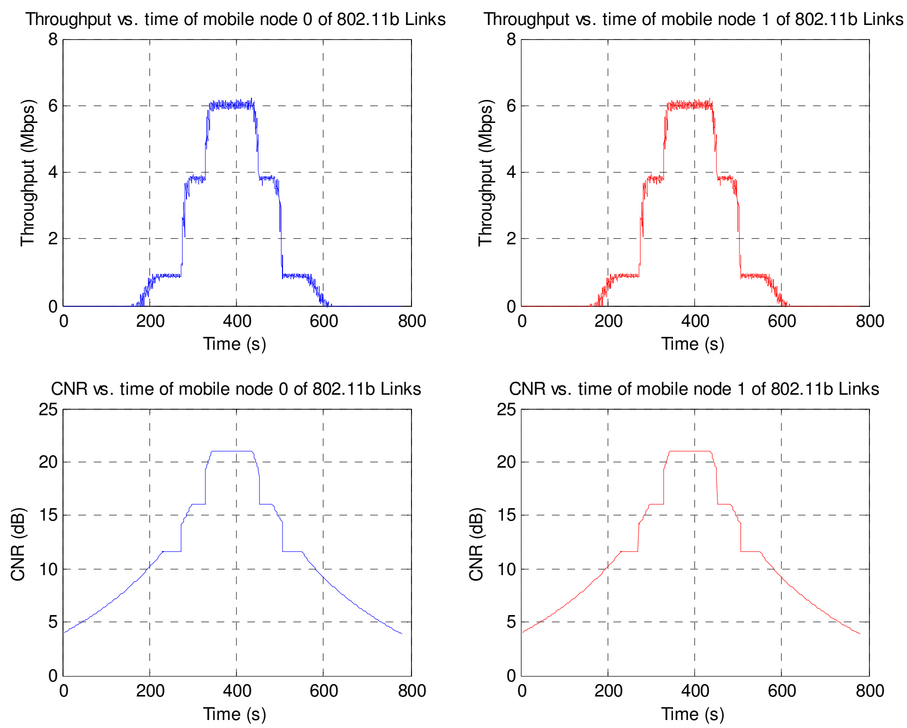

Figure 5-17 Throughput vs. Time and C/N vs. Time in Multiple TOTPS Implemented 802.11b links with Same Distance between AP and STAs in an AWGN channel

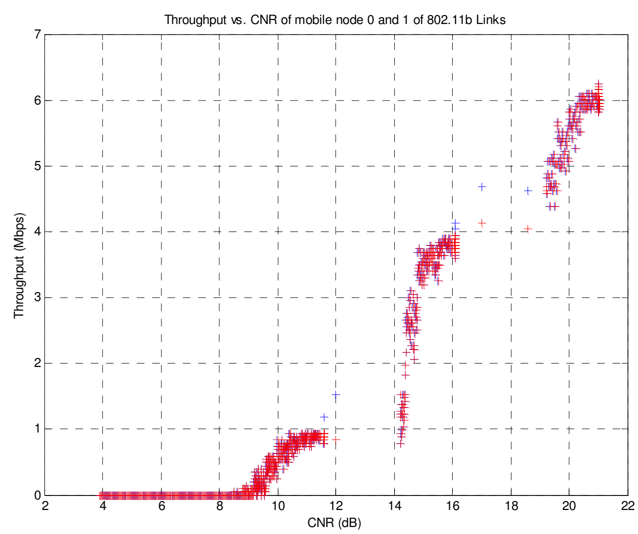

Figure 5-18 Throughput vs. C/N in Multiple TOTPS Implemented 802.11b links with Same Distance between AP and STAs in an AWGN channel

5.1.5 TOTPS Algorithm Applied Multi-user 802.11b Network with Different Distance between AP and Each STA in AWGN Channel

Another scenario displayed in Figure 5-19 is created with the distance between the AP and the mobile_node_0 being 40 meters as previous scenario, but with the different distance between the AP and the mobile_node_1, which is 60 meters in this case. The mobile_node_0 moves to the AP and stops when it is 3 meters away from the AP and waiting there for 1 minute. Then, the mobile_node_0 moves away from the AP and returns to its original position. On the other hand, the mobile_node_1 moves to the AP and stops at 10 meters away from the AP, and remains staying there for 1 minute. Then it moves back to its starting point. It takes the same time for both mobile nodes to finish moving along the defined trajectory.

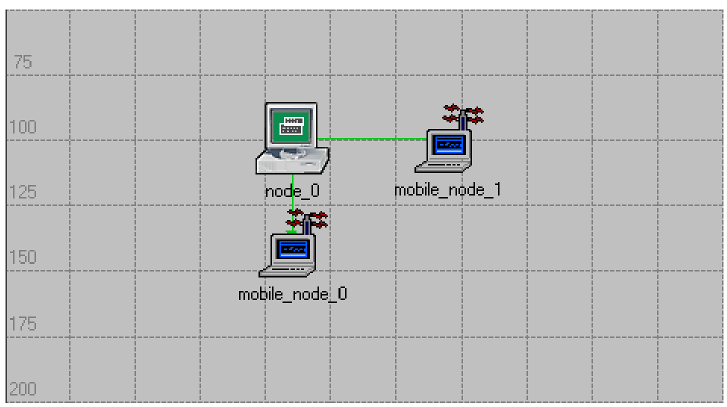

Figure 5-19 Simulation Scenario of Multiple 802.11b Links with Different Distance between AP and Each STA in Opnet

When the wireless network has no TOTPS applied, the throughput versus time and the throughput versus CNR for both STAs in this scenario are shown in Figure 5-20 and in Figure 5-21, respectively.

In Figure 5-20, the throughput versus time and the CNR versus time of mobile_node_0 remains the same as in Figure 5-15, because there is no change made for this node. However, mobile_node_1 starts from a spot farther away from AP comparing to it in Figure 5-14, and it stops moving at a distance from AP longer than that in Figure 5-14. Thus, Figure 5-20 indicates that the CNR values of mobile_node_1 are smaller than those of the scenario in Figure 5-14 regarding to the same instances. When mobile_node_1 stops moving, the CNR value is maximized at 15.6 dB, without any change to the transmitter power. As a result, the throughput of the link between the AP and the mobile_node_1 cannot be more than 3.85 Mbps. Obviously, the distance between the AP and the two mobile terminals determines the throughput via the CNR in this scenario, which can be also referred from Figure 5-21.

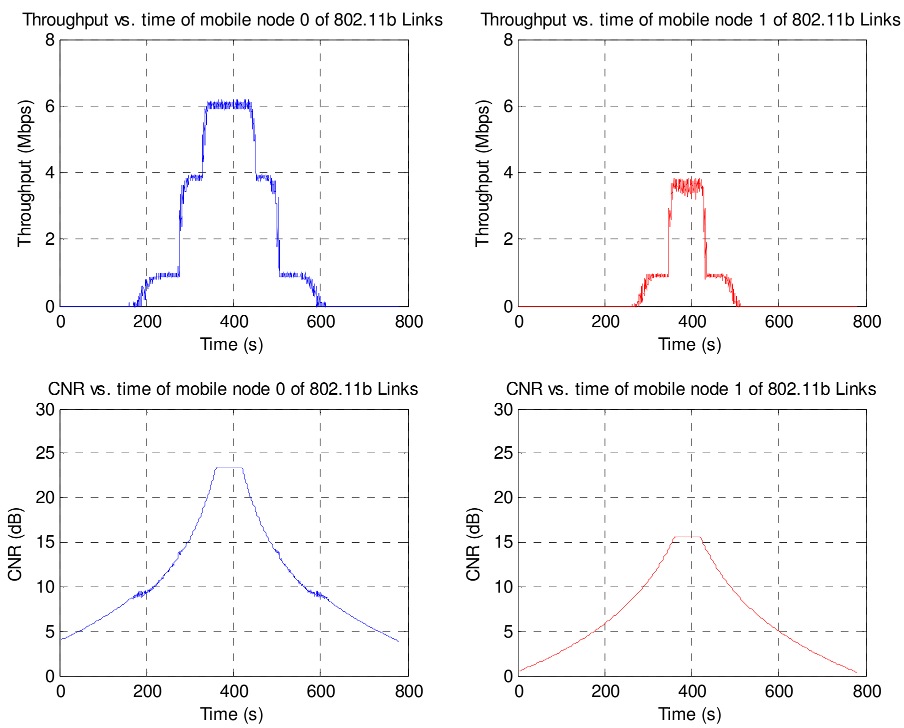

Figure 5-20 Throughput vs. Time and C/N vs. Time in Multiple TOO 802.11b Links with Different Distance between AP and STAs in an AWGN channel

What will happen if this network implements TOTPS algorithm on the links? It is not hard to observe from Figure 5-22 that the transmitter power is under the control while the CNR value of the link between the AP and the mobile_node_0 falls in cnr_rg2, or cnr_rg4 or cnr_rg6 as indicated in Figure 3-7. And, to the mobile_node_1, the transmitter power is saved when the CNR value falls in cnr_rg2. By the time that the mobile_node_1 reaches the point closest to the AP on its trajectory, the CNR value is not even 16 dB. In other words, the highest throughput of this link is only close to 4 Mbps. Thus, the power control is necessary only in the CNR range of cnr_rg2 for mobile_node_1.

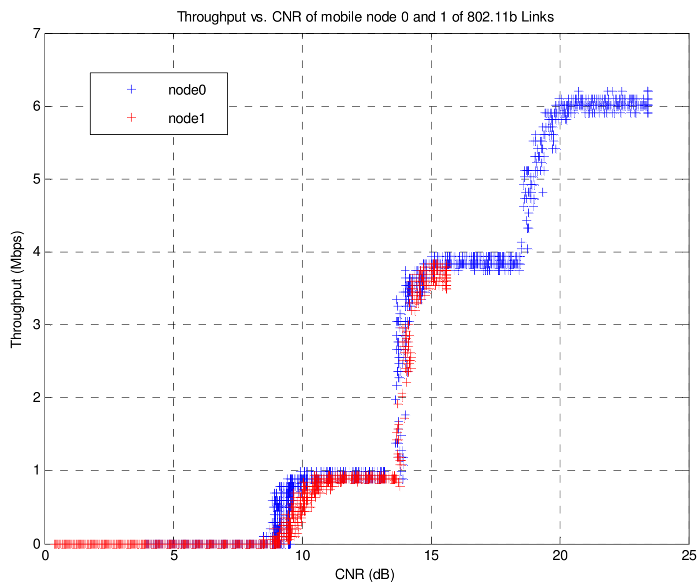

Figure 5-21 Throughput vs. C/N in Multiple TOO 802.11b Links with Different Distance between AP and STAs in an AWGN channel

In Figure 5-23, the throughput versus C/N plot shows the curve in blue regarding to the link between AP and mobile_node_0 and the curve in red for the link between AP and mobile_node_1. The overlay part of the two curves demonstrates that the TOTPS algorithm can be used for an 802.11b link regardless of how many mobile nodes are in the network.

In this case, the total saved transmitter power in the network is 26.7%. As stated before, the amount of the power saved by using TOTPS algorithm depends on the particular scenario. One thing guaranteed by using this algorithm is that the transmitter power will always less than or equal its initial value.

The successful implementation of TOTPS algorithm in a point-to-multipoint 802.11b network in an AWGN channel indicated that the TOTPS should be able to work for the same network in either Rayleigh or Ricean fading channel. Moreover, the algorithm should also work for the 802.11a or 802.11g multi-user network in various channel models.

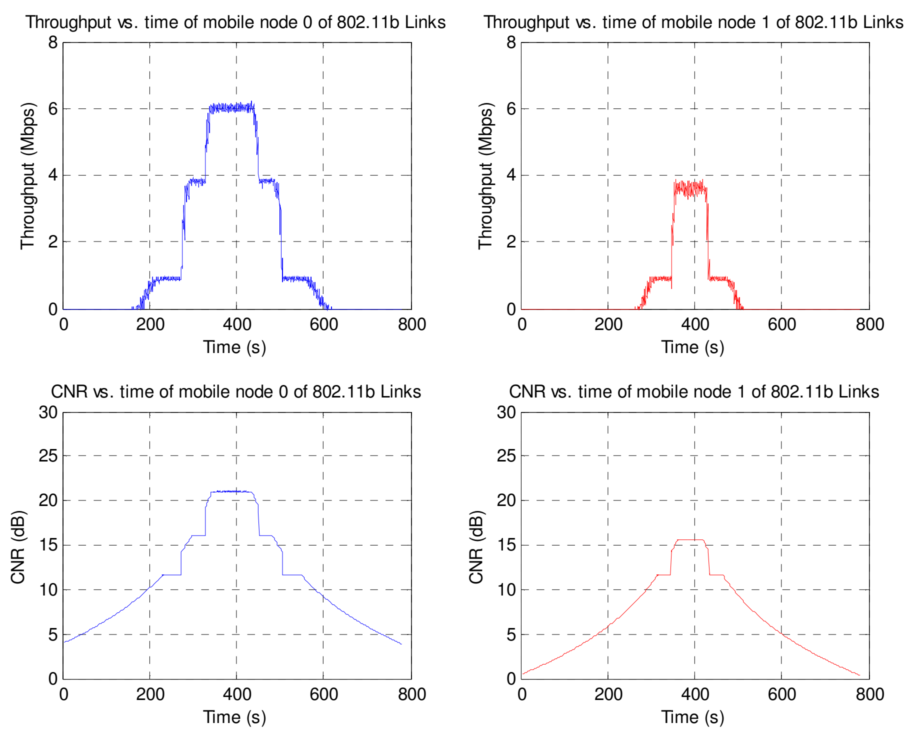

Figure 5-22 Throughput vs. Time and C/N vs. Time in Multiple 802.11b Links Having TOTPS Implemented with Different Distance between AP and STAs in an AWGN channel

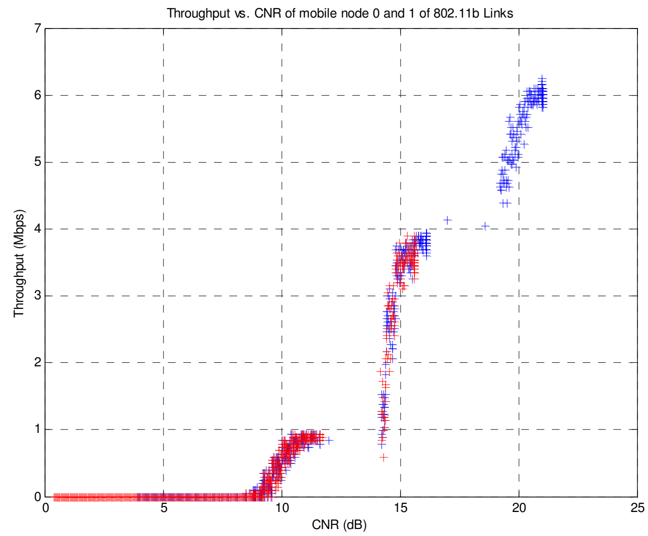

Figure 5-23 **Throughput vs. C/N in Multiple 802.11b links Having TOTPS Implemented with Different Distance between AP and STAs in an AWGN channel**

5.2 Performance Analysis of TOTPS Algorithm Applied 802.11b Links

Previously, the simulations of the TOTPS algorithm for the 802.11b wireless link in AWGN, Rayleigh fading and Ricean fading channels and the TOTPS implemented multi-user 802.11b network scenario have been built and their performance has been discussed.

To implement the TOTPS algorithm, the CNR thresholds for achieving the highest throughput with one of the four transmission modes in different channel models are different. However, the terrace shaped outputs of the throughput versus C/N in either the AWGN or the fading channels show the same trend.

It is common to all the links that the TOTPS needs to be used once the C/N value is large enough to bring the link about 6.4 Mbps as its throughput, no matter which type of channels it is operated in. As for the lower C/N values, the TOTPS determines to select the DBPSK and CCK55 modes to support the best throughput in an AWGN channel, only the CCK55 useful in a Rayleigh fading channel, and all the other three transmission modes used according to a particular C/N value. Additionally, it has been shown that the TOTPS works in multi-user 802.11 network scenario as well as it does in the single link scenario.

The amount of the saved power by using the TOTPS algorithm in 802.11b links varies from case to case. In some cases, the power consumed on data transfer is 40% less than the TOO applied link like the AWGN channel scenario introduced in Section 5.1.1 and the Ricean fading channel scenario shown in Section 5.1.3. In some other cases, around 10% of power is saved on data transfer like the Rayleigh fading channel scenario discussed in Section 5.1.2.

There is no way to guarantee a minimum amount of power that can be saved on a TOTPS deployed link. However, the simulation results tell us that the TOTPS algorithm guarantees power saving on the links. In terms of the specific amount of saved power, it depends on a particular scenario as the ones presented in the early sections in this chapter. And, those are all normal cases. In general, the longer that a link remains in the status as throughput unchanged with continuously increasing C/N on the link, the more power can be saved by using the TOTPS algorithm.

6. Performance of ETOTPS Algorithm Applied 802.11 Links

Previously, the TOTPS algorithm for the 802.11 b wireless link was developed and testified via the simulations. In this chapter, the performance of ETOTPS implemented wireless link in an AWGN channel and in Rayleigh fading channel will be displayed and discussed.

The ETOTPS algorithm will be applied to the 802.11b wireless link in an AWGN channel and the 802.11b wireless link in a Rayleigh fading channel. The first represents an ideal wireless link, which has no interference or multi-path signals at the receiver. The latter one, on the other hand, stands for a practical scenario with multi-path non-LOS (line of sight) signals on the channel. Both of the link models have been used in theoretical analysis of the 802.11b links previously, when discussing the TOO and the TOTPS algorithm applied networks.

After the simulation of each scenario, the performance of the ETOTPS algorithm applied link will be discussed and compared with links using just the TOTPS algorithm.

6.1 ETOTPS Algorithm Applied 802.11b Link in AWGN Channel

The ETOTPS algorithm is built in a point-to-point link in an AWGN channel as shown in Figure 6-1. The mobile STA is 50 meters away from the AP initially. It moves towards the AP with the average speed of 241 meters per hour and stops moving when it is 3 meters from the AP. The STA remains at 3 meters away from the AP for 1 minute and then moves away from the AP with the same speed on the same trajectory, as it comes till it returns to the original start point.

The same parameters listed in Table 5-1, including the CNR thresholds defined for tuning the link from using one modulation scheme to another, are used for the simulation of the ETOTPS applied 802.11b link in an AWGN channel. The results of the throughput and the CNR values of links are displayed in a way that shows the difference between three cases — the links with the TOO, the TOTPS and the ETOTPS algorithms.

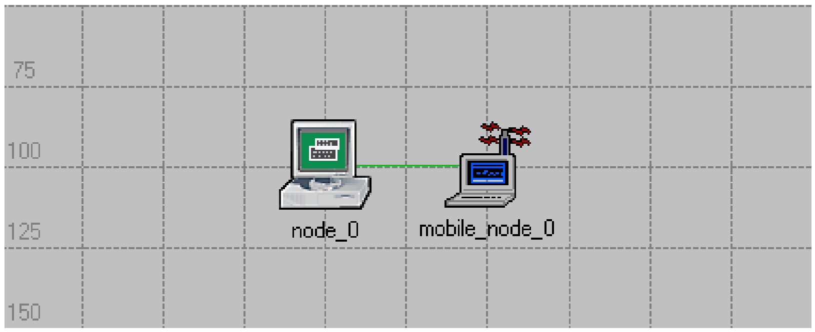

Figure 6-1 Simulation Scenario of 802.11b Link with ETOTPS Algorithm Applied in an AWGN Channel

In Figure 6-2, the red line stands for the ETOTPS link and the green one represents the TOO applied link. The TOO algorithm applied link is the one that does not use the power saving algorithm. When the link has CNR value in cnr_rg1, the throughput of the ETOTPS link reaches 0.9 Mbps faster than the TOO applied link reaches the same throughput. The reason is that the transmitter power is increased under the control in the ETOTPS link while CNR is in this range. The same thing happens to the links when their CNR values fall in cnr_rg3 and cnr_rg5.

When the value of the CNR falls in cnr_rg2, or cnr_rg4 or cnr_rg6, there is no throughput improvement. The corresponding CNR values of the ETOTPS applied link stay lower than the CNR values of the TOO applied link. In other words, the former link uses less transmitter power than the latter link does. This makes up the higher power consumption when CNR is within cnr_rg_1, cnr_rg3, and cnr_rg5. Thus, the total power consumption of the ETOTPS link may be lower than a TOO applied link. In the specific scenario depicted by Figure 6-2, the transmitter power is saved by 41.6% on an ETOTPS link comparing to a TOO link.

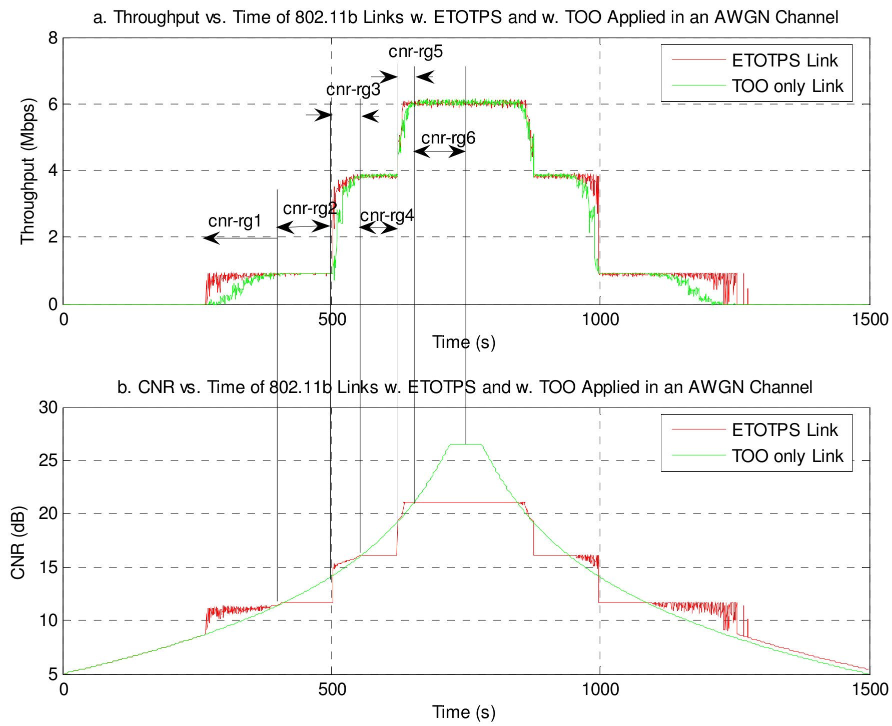

Figure 6-2 **a. Throughput vs. Time of 802.11b links having ETOTPS and TOO Implemented in an AWGN channel**
b. CNR vs. Time of 802.11b links having ETOTPS and TOO Implemented in an AWGN channel

Figure 6-3 displays the performance of the throughput and the CNR of the link with ETOTPS and the link with TOTPS algorithms applied. When the CNR value is in cnr_rg1, cnr_rg3 and in cnr_rg5, the throughput in the ETOTPS link reaches the largest value sooner rather than does the throughput in the TOTPS link. And, the performance of throughput as well as CNR is the same for these two types of links when the CNR of the link is within cnr_rg2, cnr_rg_4 or cnr_rg6. The TOTPS link saves 44% of the transmitter power compared to the link without power saving algorithm applied. Based on the conclusion of 41.6% transmitter power saved on the ETOTPS link from Figure 6-2, the ETOTPS link trades 3% more transmitter power than the TOTPS link for reaching the larger throughput sooner.

Since the power increment can be varied from case to case, the amount of saved power is not fixed, and it cannot be fixed. It depends on the particular scenario of the wireless link. Particularly, it is relevant to how long the CNR value of the link is within each defined CNR range — cnr_rg. No matter how aggressive is the algorithm applied to the link, so long as there is a pre-set power ceiling and the transmitter power is monitored, the overall power consumption can be less in an ETOTPS link than in a TOO applied link. If not, the ETOTPS link exchanges higher transmitter power for higher throughput.

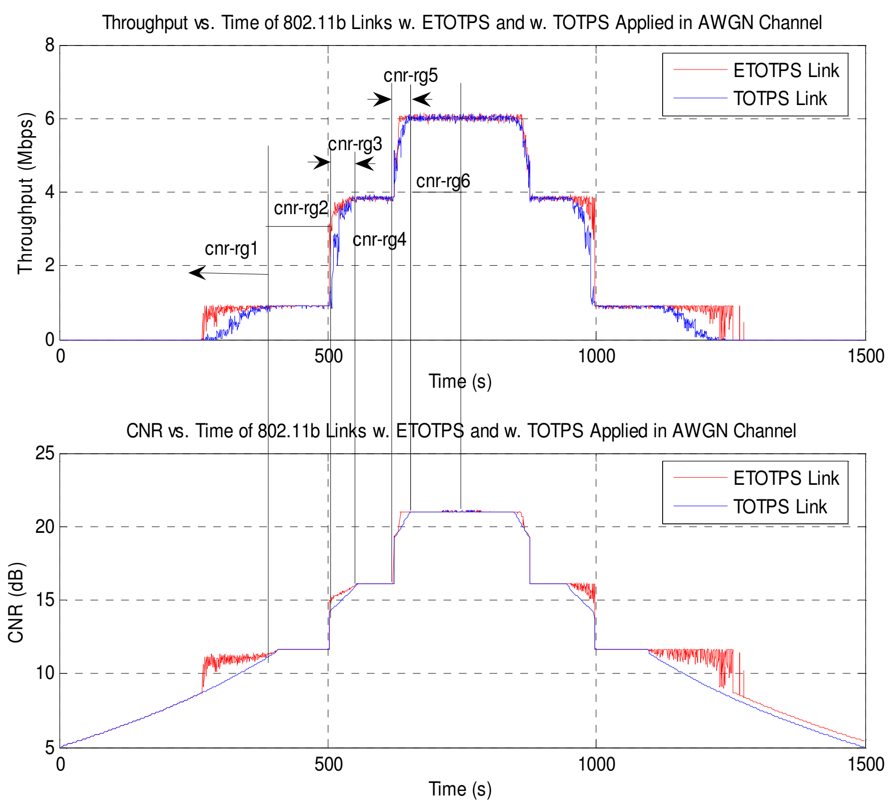

Figure 6-3 Throughput vs. Time and C/N vs. Time in an 802.11b link having ETOTPS and TOTPS Implemented in an AWGN channel

6.2 ETOTPS Algorithm Applied 802.11b Link in Rayleigh Fading Channel

The ETOTPS algorithm is also tested on an 802.11b link in a Rayleigh fading channel. The simulation is based on the throughput analysis of the 802.11b link in a Rayleigh fading channel in Section 3.4. The wireless link model consisted of an AP and a mobile STA and operated in the same way as depicted in Figure 6-1. The only difference between the simulation scenario and the one in Section 6.2.1 is that the channel model in this simulation has been changed from an AWGN channel to a Rayleigh fading channel and the CNR threshold is 21 dB taken from Table 5-2.

Previously it has been mentioned more than once that the power-up speed can be varied in different scenarios. This will be demonstrated in the following simulations. In terms of ETOTPS algorithm applied link in this simulation, three different cases were created for better understanding of the advantage and disadvantage of the ETOTPS algorithm. We have

- ETOTPS link 1: the ETOTPS link has the transmitter power increases with 0.033 dB each time when the CNR value is detected being below 25 dB; and, its maximum power level is pre-set as 20 times of the initial transmitter power
- ETOTPS link 2: the ETOTPS link has the transmitter power increases with 0.017 dB each time when the CNR value is measured below 25 dB; and, its maximum power level is pre-set as 10 times of the initial transmitter power; and,
- ETOTPS link 3: the ETOTPS link increases with 0.0033 dB per hour of its transmitter power each time when the CNR value is found being under 25 dB; and, its maximum power level is set as 5 times of the initial transmitter power

The performance of the three ETOTPS links is displayed in Figure 6-4 in the manner of comparison with the performance of the TOTPS and the throughput optimization only used links. The throughput versus time of all the wireless link models is shown in Figure 6-4 a, and their corresponding performance of CNR versus time is illustrated in Figure 6-4 b.

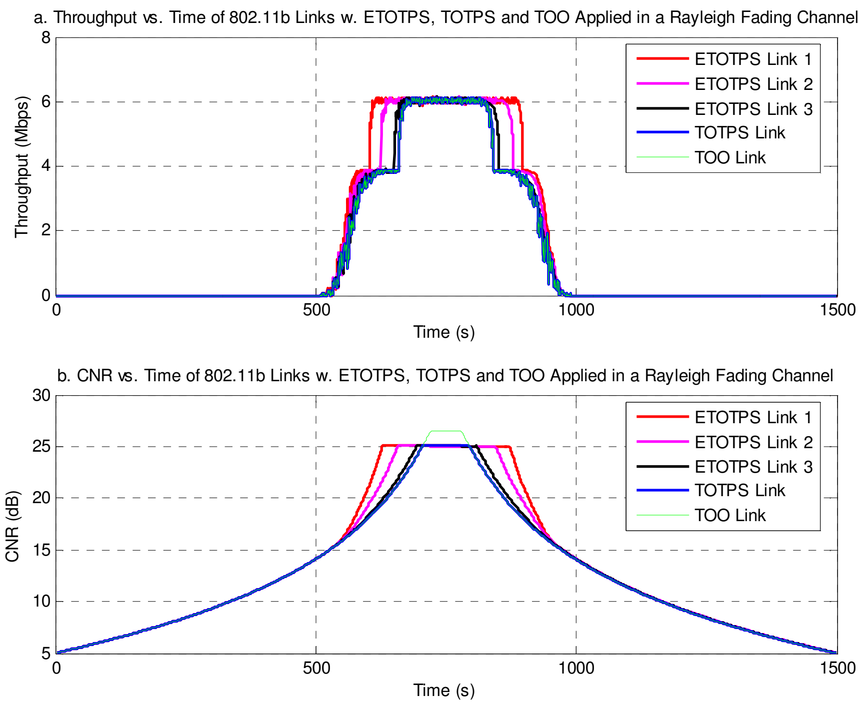

Figure 6-4 a. Throughput vs. Time of an 802.11b link having ETOTPS, TOTPS and TOO Implemented in a Rayleigh Fading channel
b. CNR vs. Time of an 802.11b link having ETOTPS, TOTPS and TOO Implemented in a Rayleigh Fading channel

In the plot of the CNR versus time, the throughput optimization only used link is the only one has the CNR value over 25 dB, since there is no power saving algorithm used in that link. For the ETOTPS link, the red, the magenta, and the black curves all show that the transmitter power starts to be controlled once the CNR reaches 25 dB, since this CNR value as of 25 dB is big enough to support the biggest throughput.

As for the three ETOTPS links, their CNR value is bigger than the CNR value of the TOO link or the TOTPS link when the CNR value of the link is between 15 dB and 25 dB, regarding to the link at the same time instances. The reason for this is that ETOTPS increases transmitter power within an allowed range, which is limited under the maximum power level. In addition, we can see that the ETOTPS link 1 has the largest CNR value, next to it is the ETOTPS link2, and the ETOTPS link 3 has the smallest CNR value among the three ETOTPS links, when the CNR value is over 15 dB but below 25 dB. It is because that the ETOTPS link 1 has more transmitter power increased than the other two ETOTPS links. And, the ETOTPS link 3 is the one with the lowest power increasing percentage. Therefore, the faster the transmitter power is raised, the sooner the wireless link reaches the CNR value which supports the highest throughput.

As a result of the CNR, and refer to the throughput analysis of the link in a Rayleigh fading channel as shown in Figure 3-13, the link applies CCK55 to approach throughput of 4 Mbps before the CNR reaches 21 dB. Once the CNR is over 21 dB, CCK11 transmission mode is applied to the link and the throughput increases with the raising CNR till it reaches 6 Mbps or so. At this stage, the CNR value is about 25 dB. In Figure 6-4 a, the ETOTPS link 1 always reaches higher throughput than the other two ETOTPS links for its aggressive power increasing on the link. The throughput on all the ETOTPS links is generally higher or at least equal to the throughput on the TOTPS link or the throughput optimization only applied link.

The main purpose of raising the transmitter power in the ETOTPS link is for obtaining higher throughput. However, the total power used on the link can still be a concern.

Based on the result shown in Figure 6-4, the power consumption of the varied algorithms applied on the 802.11b link can be analyzed by comparing the transmitter power spent on each of the ETOTPS and the TOTPS link models to the power used on the throughput optimization only applied link. We find that the TOTPS link saves 10% of the transmitter power. On the other hand, the ETOTPS link 1 expends 27.5% more power for reaching higher throughput in the C/N ranges when it is between 21 dB and 25 dB. It takes the ETOTPS link 2 about 13.8% more power than the TOO link. However, the ETOTPS link 3 saves 4% power comparing to the TOO link. In other words, it takes 6% more power to trade for higher throughput than the link with TOTPS algorithm applied.

Therefore, if saving power is the major concern of a wireless link, TOTPS algorithm is the best one to use with no doubt. However, if throughput is the most important issue while power consumption is less important, to use an aggressive ETOTPS algorithm can help to achieve the goal. If we want the throughput can be reached as high as the link can and saving power is the same important to be considered at the same time, a relatively conservative ETOTPS algorithm, like the ETOTPS link 3 mentioned above, will be a good candidate to be applied to the link.

From the above discussions of the TOTPS and the ETOTPS algorithms, it becomes clear that there is always tradeoff between using one or the other algorithms on a wireless link. The TOTPS algorithm promises less power consumption, because it never raises the transmitter power above its initial value. One of the key points to have the TOTPS algorithm implemented successfully is to set the power ceiling, which is beyond the scope of this research.

Meanwhile, it has been illustrated that the TOTPS algorithm is not as aggressive as the ETOTPS algorithm can be in terms of pursuing a higher throughput. The ETOTPS algorithm aims for higher throughput all the time, although it may be unable to save as much power as the TOTPS algorithm can or even use more power. Nevertheless, overall, the ETOTPS algorithm may still save the transmitter power of the data transmitting terminal, depending on the power increasing and the defined maximum power level.

In this section, the ETOTPS algorithm is introduced and investigated. The simulations of the ETOTPS algorithm implemented on an 802.11b link in an AWGN channel and in a Rayleigh fading channel have been presented. Moreover, the ETOTPS applied wireless links with varied power control schemes like different power increasing stages and maximum transmitter power levels have been studied.

The simulation results tell us that ETOTPS algorithm pursues higher throughput more aggressive than TOTPS algorithm, while it involves more power consumption, correspondingly. A wireless link with ETOTPS algorithm deployed can also save transmitter power comparing to a link without any power control.

7. Summary of TOTPS and ETOTPS Implementation

Two algorithms were developed in this research — the TOTPS algorithm and the ETOTPS algorithm. Both have been described and their advantages and disadvantages for 802.11b links were analyzed through simulations.

In this chapter, the simulation results of an 802.11b link with different algorithms applied in different channels will be put together for comparison and drawing conclusions. There are three cases created for gaining an insight of the 802.11b link's performance in various scenarios. These are

- Throughput versus CNR of 802.11b links in AWGN, Rayleigh and Ricean fading channel models
- Throughput versus CNR of 802.11b links with TOTPS algorithm applied in AWGN, Rayleigh and Ricean fading channel models
- Throughput versus CNR of 802.11b links using TOO, TOTPS and ETOTPS in AWGN and Rayleigh fading channel models

7.1 An 802.11b Link in AWGN Channel, Rayleigh Fading and Ricean Fading Channels

In Chapter 3, the BER performance of an 802.11b link in an AWGN channel and in Rayleigh and Ricean fading channels have been shown in separate sections focusing on each channel model. Once all the simulation results are put together as in Figure 7-1, it becomes obvious that wireless links in the three different channel models need to be tuned to different modulation schemes at different CNR values.

Figure 7-1 plots the contour of the maximum throughput of an 802.11b link for each channel model. This is exactly the performance of the TOO algorithm applied link under an assumption that the modulation scheme which supports the highest throughput is used at a specific CNR value. According to Figure 7-1, Table 7-1 lists the modulation schemes used in the three types of channel model for pursuing the highest throughput. For a TOTPS applied 802.11b link in an AWGN channel, DBPSK, CCK55 and CCK11 transmission modes are selected to be used on a link, However, in a Rayleigh fading channel, only the two CCK transmission modes are supposed to be used for the best throughput. As for the wireless link in a Ricean fading channel, each of the four modulation schemes is selected to be used on the link at a particular CNR range for the largest throughput.

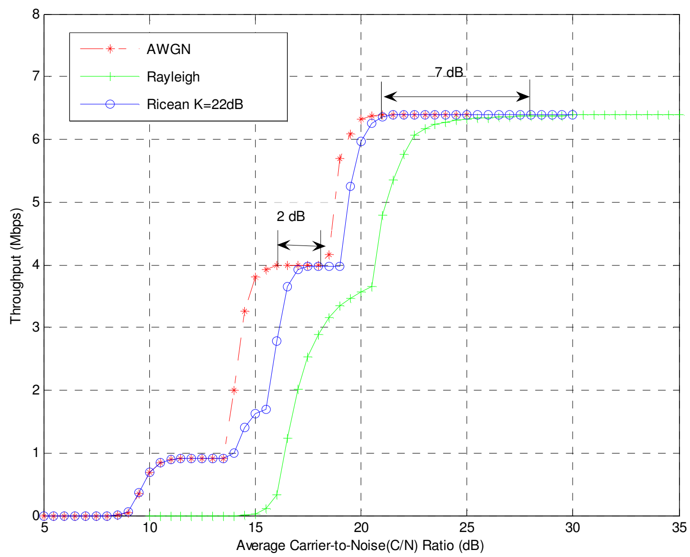

Figure 7-1 Throughput vs. C/N of 802.11b Link in AWGN Channel, Rayleigh Fading Channel and Ricean Fading Channel

Table 7-1 Minimum CNR Values Required for Certain Throughput Levels in an 802.11b Link

	DBPSK	DQPSK	CCK55	CCK11	CNRTH(dB) for TP=0.9Mbps	CNRTH(dB) for TP=1.8Mbps	CNRTH(dB) for TP=4Mbps	CNRTH(dB) for TP=6.4Mbps
AWGN	•		•	•	11.5	13.8	16.0	21.0
Rayleigh			•	•	16.4	16.8	20.7	28.0
Ricean	•	•	•	•	12.0	15.7	18.0	22.5

The transmission modes necessarily to be used on an 802.11 link over each discussed channel model are respectively listed in Table 7-1. The relation between the throughput and the CNR of an 802.11b link in different channels is also reflected in Table 7-1. The throughput is broken into four stages — such as 0.9, 1.8, 4 and 6.4

Mbps. These are actually the maximum throughputs that each one of the four transmission modes supports. If a throughput of around 1 Mbps is expected on an 802.11b link, the CNR has to be 11.5 dB on an AWGN channel, 12 dB on a Ricean fading channel, and 16.4 dB on a Rayleigh fading channel. To obtain a throughput of 6.4 Mbps on an 802.11b link, the CNR of the link must be at least 21 dB for an AWGN channel, 22.5 dB for a Ricean fading channel, and 28 dB for a Rayleigh fading channel.

From Figure 7-1 and Table 7-1, we can conclude that 2 dB more CNR value is required on a Ricean fading channel, particularly with Ricean factor of 22, for the link to reach as high throughput as an 802.11b link in an AWGN channel can. For an 802.11b link over a Rayleigh fading channel, the link needs up to 7 dB more CNR value to obtain as high throughput as the same link in an AWGN channel can.

It is always important to select the modulation scheme which can bring the maximum throughput at a particular CNR in any channel model. Otherwise, with the same CNR value on the 802.11b link, a link using CCK55 mode for transmission in a fading channel can have higher throughput than the same link using DBSPK in an AWGN channel.

7.2 A TOTPS Applied 802.11b Link in AWGN Channel, Rayleigh Fading and Ricean Fading Channels

In Section 7.1, the TOO algorithm applied 802.11b links in the three channel models have been compared. In this section, the performance of the link with TOTPS algorithm in the three channel models will be put together for analysis. Furthermore, the performance of the links with TOO algorithm, as discussed in Section 7.1, will be brought up again for comparison between TOTPS and the link without power control.

If Figure 5-3, Figure 5-8 and Figure 5-13 are put together, the result will be like the thick magenta, blue, and yellow dotted curves in Figure 7-2. The purple, red and black curves in line represent the TOO implemented links in the AWGN, Rayleigh fading and Ricean fading channels. Two sorts of comparisons can be categorized from Figure 7-2. The comparisons made from Figure 7-2 are sorted into two categories. The first is the TOO applied 802.11b link to be compared to the TOTPS applied link when they are operated in the same channel model. Table 7-2 lists which CNR ranges have TOO and/or TOTPS algorithms applied for each transmission mode.

From Table 7-2, it can be seen that for each type of channel model, TOO applies to broader CNR range than that for which TOTPS can be used. For example, in a Rayleigh fading channel, TOO is used for selecting CCK55 when C/N is less than 21 dB and selecting CCK11 when C/N is over 21 dB, while TOTPS is only applied when C/N is more than 25 dB. This is because the TOO algorithm solely picks the transmission mode for the highest throughput at a certain CNR range but does not deal with transmitter power. On the other hand, the TOTPS algorithm goes one step farther. It not only picks the "right" transmission mode, which supports the best throughput, but also controls the transmitter power while the highest throughput is supported at the CNR range for which TOTPS is applied.

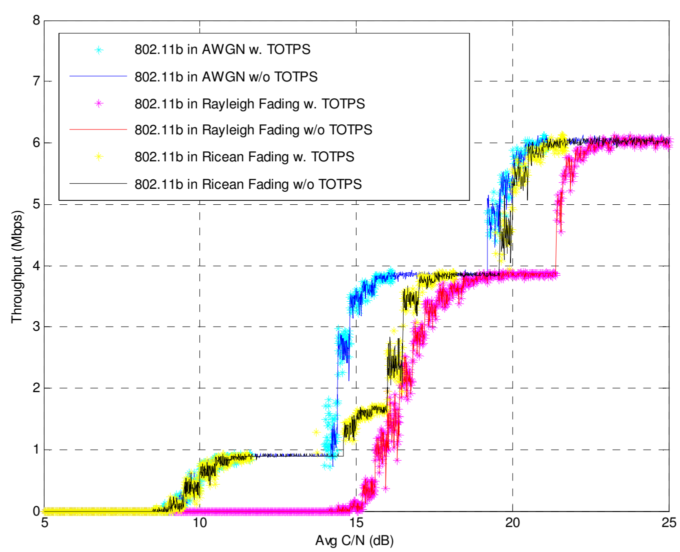

Figure 7-2 Throughput vs. C/N of 802.11b Link with TOTPS and TOO in AWGN Channel, Rayleigh Fading Channel and Ricean Fading Channel

No matter which channel conditions an 802.11b link is operated in, the TOTPS guarantees that the transmitter power being under the control so that CNR value will not keep increasing if this does not improve the throughput. For each channel model studied in this research, the CNR ranges that require using the TOTPS algorithm are listed in Table 7-2.

The second comparison that we can make from Figure 7-2 is the TOTPS link in one channel model to be compared to the same link on another channel model. We can see that TOTPS is useful for all the channel models when the link uses CCK11 to support the highest throughput. Normally, a mobile station in a WLAN has signal bars showing that it has a strong signal. In such a scenario, a wireless link TOTPS algorithm can save transmitter power. Table 7-2 tells us that TOTPS is more often to be used in AWGN and Ricean fading channel when the value of CNR only supports lower throughput such as 4 Mbps and 1 Mbps. As we have found in Section 5.1.1, Section 5.1.2 and Section 5.1.3, an 802.11 link set up as in Figure 5-1 can have transmitter power saved as 45%, 10%, and 39% or so in AWGN channel, Rayleigh fading channel, and Ricean fading channel respectively, by applying TOTPS algorithm on the link.

Table 7-2 can be considered as an example of a look-up table for a real application case. It can be deployed once the radio is capable of recognizing which channel model it is working on and the receiver is able to detect the CNR value or the CINR value.

Table 7-2 CNR Ranges with TOTPS Applied in 802.11 Links

	cnr_rg (dB) for using TOO and TOTPS in each transmission mode				power saving
	DBPSK	DQPSK	CCK55	CCK11	
AWGN - TOO	< 13.7	—	13.7 ~ 18.5	> 18.5	
AWGN - TOTPS	11.5 ~ 13.7	—	16.0 ~ 18.5	> 21.0	45%
Rayleigh - TOO	—	—	<21.0	> 21.0	
Rayleigh - TOTPS	—	—	—	> 25.0	10.2%
Ricean - K22 - TOO	< 14.6	14.6 ~ 15.7	15.7 ~ 18.0	> 18.0	
Ricean - K22 - TOTPS	12 ~ 14.6	—	—	> 22.5	39%

7.3 An 802.11b Link with TOO, TOTPS, and ETOTPS Algorithms Applied in an AWGN Channel

TOTPS focuses on reducing the transmitter power to the level that will allow a desired throughput to be reached. If the initial transmitter power is set at a reasonable value, the total power used on a link with TOTPS applied in a specific time period will be less or equal to that the link would use in the absence of this algorithm. The ETOTPS algorithm targets higher throughput by being willing to trade in more transmitter power. It causes more power consumption than would be observed in a wireless link without the algorithm. But, it enables the link to achieve higher throughput.

The ETOTPS algorithm has been introduced in Chapter 6. The performance of the throughput of TOO, TOTPS and ETOTPS applied links in AWGN and Rayleigh fading channels are displayed in Figure 7-3.

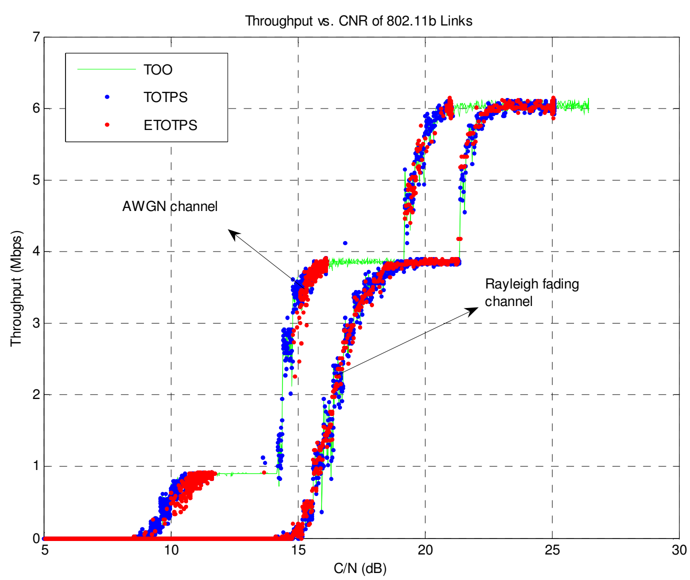

Figure 7-3 Throughput vs. C/N of 802.11b Links with TOO, TOTPS and ETOTPS Applied in AWGN Channel and in Rayleigh Fading Channel

In Figure 7-3, the green curves stands for the TOO link, the blue ones represents the TOTPS link and the red ones are for the ETOTPS links. Observing the plot in Figure 7-3 carefully, we can find that the distribution of the throughput from an ETOTPS 802.11b link is more concentrated when the C/N value gets closer to the point that the link launches the power saving algorithm, regardless of which channel the link operates in. For example, the results from an ETOTPS applied link in an AWGN channel is distributed more in the range of C/N values between 15 dB and 16 dB rather than the range from 14 dB to 15 dB.

The reason for this behavior is that ETOTPS adds more power at the transmitter before the throughput of the link reaches the highest that the transmission mode can support. Therefore, relatively, the ETOTPS link has more results allocated in higher CNR value ranges than the TOTPS link. Once the highest throughput is obtained, the ETOTPS acts just like the TOTPS, reducing the transmitter power and maintaining the throughput performance.

The CNR ranges with the three algorithms applied in an AWGN channel are shown in Table 7-3. The ETOTPS algorithm takes care of the link in all the CNR ranges as the TOO algorithm does. One thing common in TOO, TOTPS and ETOTPS algorithms is that they all monitor the CNR value and select the "right" transmission mode, which is the only thing that TOO cares for. Besides this, the ETOTPS algorithm determines and acts on increasing, remaining or reducing transmitter power when it detects the CNR value of the link, while the TOTPS algorithm waits till the link approaches the point to reduce transmitter power. Undoubtedly, this will be the similar situation to the Rayleigh fading channel and the Ricean fading channel, based on our knowledge of the throughput feature of the 802.11 links in the three types of channel models obtained previously.

Table 7-3 802.11b Links' CNR Ranges for Applying TOO, TOTPS and ETOTPS in an AWGN Channel

	cnr_rg (dB) for using TOO and TOTPS in each transmission mode			
	DBPSK	DQPSK	CCK55	CCK11
AWGN - TOO	< 13.7	—	13.7 ~ 18.5	> 18.5
AWGN - TOTPS	11.5 ~ 13.7	—	16 ~ 18.5	> 21
AWGN - ETOTPS	< 13.7	—	13.7 ~ 18.5	> 18.5

8. Conclusion

This research addressed a practical approach for power saving in 802.11 wireless systems. Two algorithms — the TOTPS algorithm and the ETOTPS algorithm were developed and testified. The process of deploying these algorithms was defined and simulated in Opnet by applying both algorithms to the 802.11b links in three typical channel models — an AWGN channel, a Rayleigh fading channel and a Ricean fading channel. The simulation results are illustrated in this dissertation. It has been proved that the TOTPS algorithm guarantees saving transmitter power independent of the channel conditions. The total amount of power saved depends on how long a link is in a status that allows a continuously increasing CNR value without any throughput improvement. The longer a link is in such status, the more power can be saved. Nevertheless, the ETOTPS algorithm pursues higher throughput by trading in more transmitter power.

The advantage of the TOTPS algorithm is that it not only can prolong battery life, which is critical in ad hoc wireless networks, but also can reduce the potential interference to neighboring wireless systems. The ETOTPS algorithm, on the other hand is particularly desired in wireless high-speed data transfer in an emergency situation, such as natural or manmade disaster fields.

The behavior of throughput versus CNR of the wireless link in AWGN channel, a Rayleigh fading channel and a Ricean fading channel is extremely important to this study. In Chapter 3, the discussion starts from the bit error rate to the data rate of a wireless link, then to the throughput of 802.11b, a and g links. The similarity from the results of the throughput in terms of CNR indicates that the algorithms can be applied to 802.11a and g links. This is done in Chapter 5.

The TOTPS algorithm and the ETOTPS algorithm propose to use some reserved bits in the existing RTS or ACK frames defined in the 802.11 standard for carrying the CNR information from the receiver to the sender to help the sender determine its transmitter power. Both algorithms can be operated without any major change to the standard. The value of the CNR indicates the exact transmission mode to be used on the link for the best throughput performance. The algorithms also include how to find the CNR or CINR value of the link.

The performance of the two proposed algorithms is illustrated in Chapter 5 and Chapter 6. The results from simulations show that both of the algorithms can be operated on the 802.11b links with outputs in terms of the relationship between the transmitter power and the throughput. Table 7-2 provides a look-up table for the TOTPS installed 802.11b link to select the transmission mode to obtain the highest throughput at a specific CNR value when the link is in a particular channel model. In the case of an ETOTPS used link, Table 7-3 is an example of a look-up table for that type of link to check for the modulation scheme to be used. It has been also shown that the ETOTP algorithm applies to the same CNR ranges as the TOO does, and the TOTPS algorithm controls a narrower CNR range than the former two algorithms.

These two algorithms are both implemented under an assumption that the receiving node can identify the type of the channel that the link is operated in. In a real case, by comparing the features of the channel that a node detected to the existing features of the channel models already installed in that node, an 802.11 wireless link can treat the closest channel model as if the one that it is operated on. Then, based on that, the transmission node selects the transmission mode to obtain the best throughput by applying one of the algorithms. The algorithms developed in this research are not only limited to the links over the three types of channels investigated in the research. Instead, they can be applied to 802.11 wireless networks operating in other kinds of channels.

At present, cognitive radio is a hot topic in the wireless communications research area. One of the goals is to make the radio capable of figuring out what kind of channel it is operating in. Once the radio is able to know which type of channel the data is carried on, the TOTPS and ETOTPS algorithms can be used to reduce power consumption on the link with minor change such as parameters.

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