Performance Evaluation for IEEE 802.11e Wireless Local Area Network System

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Abstract

As cost decreases and data rate advances, IEEE 802.11 wireless local area networks (WLANs) become prevalent in recent years. The existing standards, such as IEEE 802.11a and IEEE 802.11b, even if they respectively support up to 54 and 11 Mbps data rates, do not support quality of services. Therefore, to enhance the current standards with the quality of service capability becomes the next focus of the IEEE 802.11 standard body. This results in the upcoming IEEE 802.11e extension.

In this thesis, we will evaluate the performances of Immediate Burst Ack Mechanism and Enhanced Distributed Coordination Function (EDCF) that were proposed in the current draft of IEEE 802.11e. Specifically, we will simulate the resultant system throughput, queuing delay and system packet loss rate of these proposed mechanisms, and examine the pro-and-con of adopting them as part of the present IEEE 802.11 WLAN system. Their power-saving efficiency over the ad hoc networks will also be investigated. Concluding remarks will be made based on our simulations.

Acknowledgements

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 A Brief of IEEE 802.11 standard

In 1997, IEEE 802.11 standard body announced the IEEE 802.11 standard that defines the Media Access Control (MAC) and Physical (PHY) layers to support data transmission up to 2 Mbps at 2.4GHz band. As pushing by the demand of higher data transmission rate, the IEEE 802.11a and IEEE 802.11b were later developed. The IEEE 802.11b standard defines 1∼11 Mbps data transmission rate at 2.4GHz ISM band, and the IEEE 802.11a describes a new OFDM modulation scheme that supports up to 54 Mbps at 5GHz UNII band. Further enhancement on these standards is still on-going.

The IEEE 802.11 MAC protocol supports two access methods, which are respectively named DCF (Distributed Coordination Function) and PCF (Point Coordination Function). The compulsory DCF access method adopts CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) mechanism to provide services for asynchronous data transmission. The optional PCF access method incorporates a polling coordinator that locates at the AP (Access Point), and is proposed for real-time traffic. The basic MAC architecture is depicted in Fig. 1.1, and a timing diagram for DCF is illustrated in Fig. 1.2.

In the CSMA/CA mechanism on which the IEEE 802.11 DCF is based, a station must

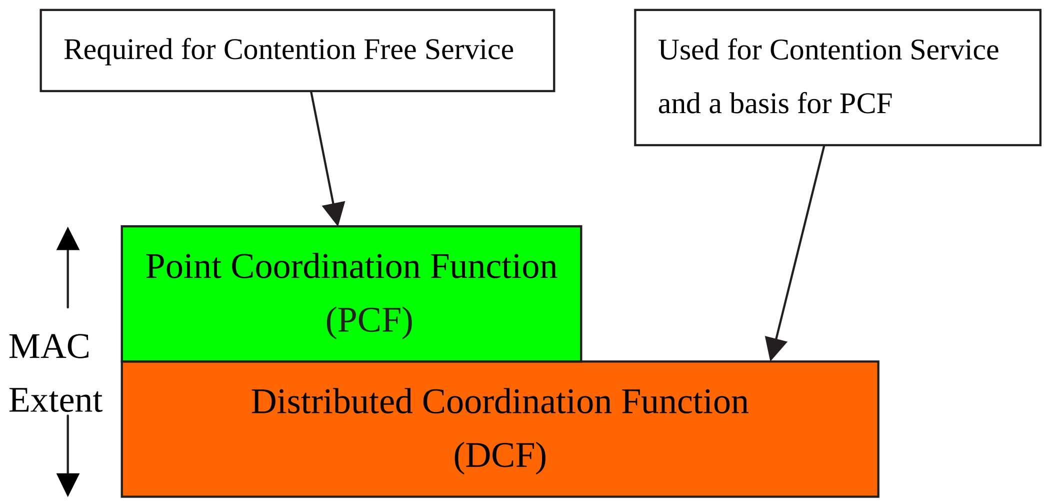


Figure 1.1: The IEEE 802.11 MAC Architecture [1].

backoff for a certain period after detecting the channel as being idle for a duration called DCF Interframe Space time (DIFS). The length of the backoff period is equal to the time slot times a number selected according to a uniform distribution over $\{0, 1, \ldots, \mathrm{CW}\}$, where CW represents the present Contention Window. After the backoff period expires, a station can start delivering packets if the channel is sensed idle.

According to 1999 edition of ANSI/IEEE Std 802.11, the CW values shall be an integer power of 2 minus 1, beginning from $\mathrm{CW}_{\mathrm{min}}$ and continuing up to $\mathrm{CW}_{\mathrm{max}}$.[1] This constraint, however, is released in IEEE 802.11e, in which the CW values are only required to be an unsigned (non-negative) integer. Such a random backoff process improves the stability of the access protocol under high load condition. An example of exponential increase of CW is depicted as Fig. 1.3.

By including a Network Allocation Vector (NAV) into the packet header, the IEEE 802.11

[1]The standard wrote in Section 9.2.4 that "The set of CW values shall be sequentially ascending integer powers of 2, minus 1, beginning with a PHYspecific aCWmin value, and continuing up to and including a PHY-specific aCWmax value."

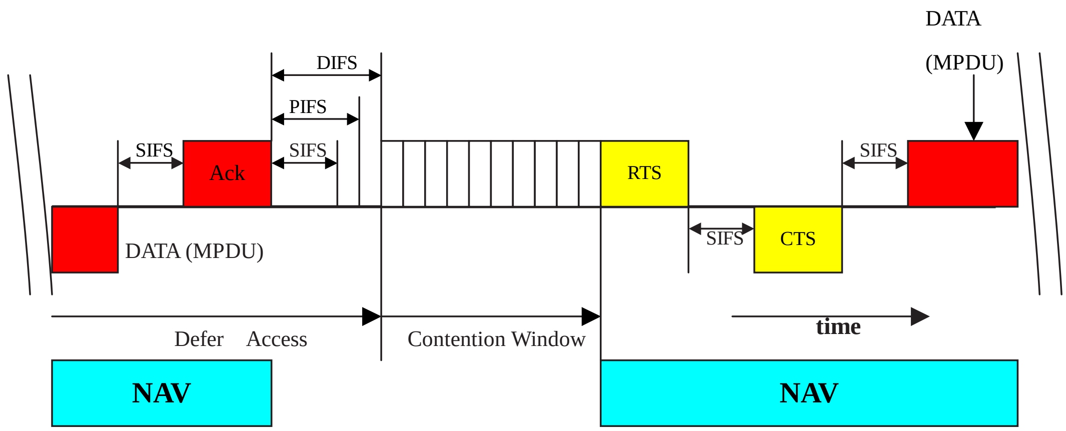


Figure 1.2: IEEE 802.11 DCF scheme [1].

MAC provides a so-called *virtual carrier sense* mechanism. The NAV information is a number (in milliseconds) indicating the length of the current transmission burst. Therefore, it can be used by the other stations to resolve the channel statue—busy or idle—without making the true channel assessment. Specifically, the other stations, upon receipt of a NAV information, may set a timer equal to this NAV time, and count down the timer (during which period the channel shall be used by the current transmission burst) until it reduced to 0 (indicating the end of the current transmission burst).

Next, we brief the PCF access method. As shown in Fig. 1.4, the contention-free period (CFP) repetition interval is divided into two periods: a CFP used by the PCF access method and a CP governed by the DCF access method. During CFP, a Point Coordinator (PC) that locates at an AP is responsible for the polling of CF-Pollable stations, and only the station that is just polled has the right to return a packet.

1.2 A Brief of IEEE 802.11e standard

Recently, research efforts over wireless LAN are gradually diverted to the provision of Quality of Service (QoS) for real-time multimedia services [3, 6]. Several QoS enhancement proposals

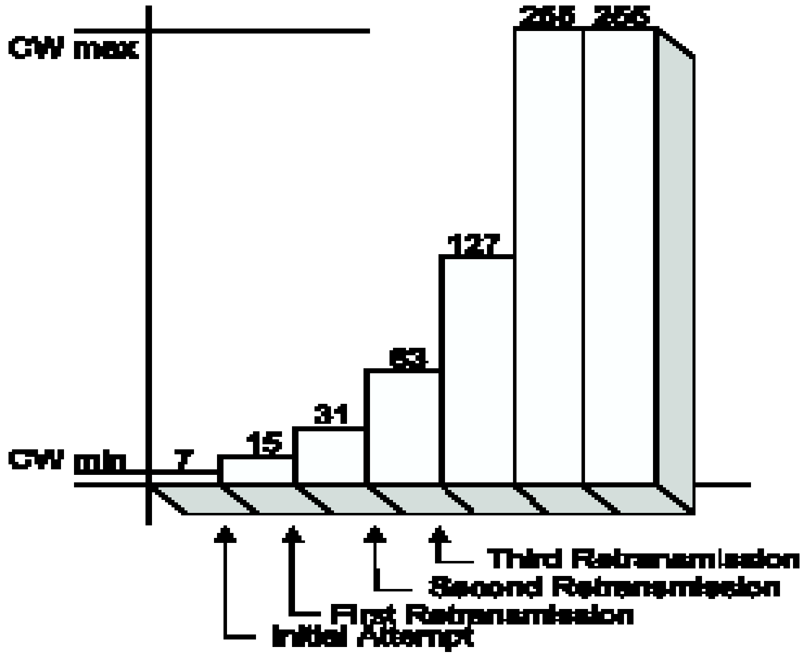


Figure 1.3: An example of exponential increase of CW [1].

were submitted, and are currently under evaluation of the IEEE 802.11 Task Group E. It is expected that these proposals will be concluded into a new QoS supplement standard to the existing IEEE 802.11 standard, enumerated as IEEE 802.11e.

In its draft, the IEEE 802.11e standard includes the Enhanced DCF access method (EDCF) [4], the Hybrid Coordination Function (HCF) [4], the Direct Link Protocol (DLP) [2], and the Burst ACK Mechanism [5]. Details of these QoS provisions that are pertinent to this thesis will be introduced in Chapter 2.

In this thesis, we will focus on the performance evaluation of the EDCF and Burst ACK mechanism, and remark on their effectiveness in performance improvement. In our opinion, these two mechanisms are the most essential to the upcoming IEEE 802.11e standard. Besides, power management is also an important issue for the mobile devices and we'll investigate the efficiency of the power management in an ad hoc IEEE802.11b or IEEE 802.11e network. We will describe these mechanisms such as EDCF, Burst ACK Mechanism, power

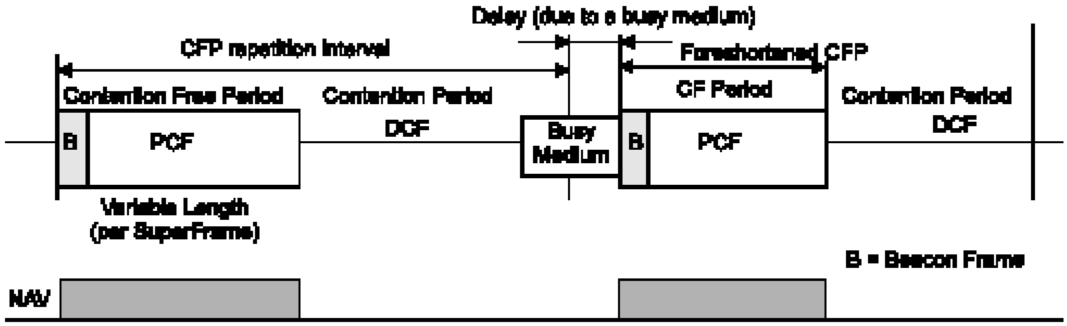


Figure 1.4: Alternation of CFP and CP in IEEE 802.11 MAC scheme [1].

management in more detail in Chapter 2.

1.3 Thesis Overview

The thesis is organized as follows:

In Chapter 2, we describe the mechanisms of IEEE 802.11e, which are pertinent to this thesis. In Chapter 3, we introduce our simulation models and simulation flows. In Chapter 4, simulation results that compare the system performances between legacy IEEE 802.11 with and without IEEE 802.11e enhancement are presented. Chapter 5 concludes the thesis.

Chapter 2

Mechanisms of IEEE 802.11e

The IEEE 802.11e mechanisms that are pertinent to this thesis are briefed in this chapter.

2.1 Enhanced Distributed Coordination Function

The Enhanced Distributed Coordination Function (EDCF) mechanism of IEEE 802.11e is the basis of the Hybrid Coordination Function (HCF)[4]. It is also a contention-based mechanism like the DCF in IEEE 802.11. According to the draft, each QoS station (QSTA) may maintain its packets using multiple queues, each of which belongs to different Access Category (AC) and hence has different User Priority (UP). The Access Category (AC) is parameterized by AC-specific parameters such as CW_{max}, CW_{min} and Arbitration Interframe Space (AIFS). During a contention period (CP), each AC within a station contends for a Transmission Opportunity (TXOP) by independently starting its own backoff mechanism after detecting and assuring channel idle for an AIFS time. A TXOP is an interval during which an AC has the right to initiate transmissions, and is defined by a starting time and a maximum duration. The AIFS shall be no smaller than DIFS, and can be enlarged individually according to the User Priority (UP) of each AC. Similarly, CW_{max} and CW_{min} can be varied according to the UP of each AC. The mapping between the Access Categories and User Priorities as defined in IEEE 802.11D is listed in Tab. 2.1. The reference implementation model provided by 802.11e is quoted in Fig. 2.1. The timing diagram of EDCF is illustrated in Fig. 2.2.

Table 2.1: Mapping of IEEE 802.1D User Priority to Access Category.

User Priority (IEEE 802.11D Priority)	IEEE 802.11D Designation	Access Category	Designation (Informative)
0	BE	0	Best Effort
1	BK	0	Best Effort
2	—	0	Best Effort
3	EE	1	Video Probe
4	CL	2	Video
5	VI	2	Video
6	VO	3	Voice
7	NC	3	Voice

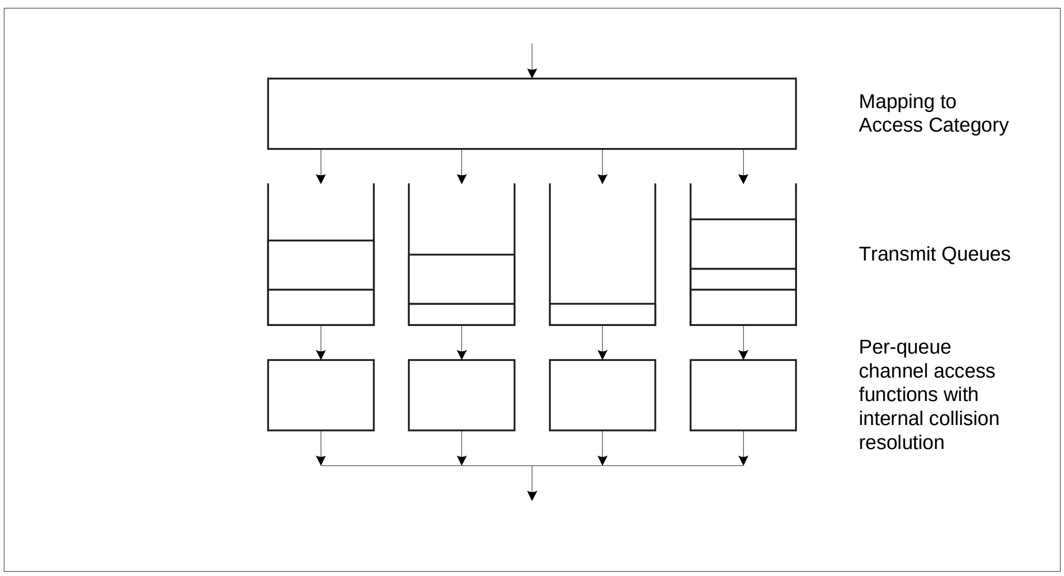


Figure 2.1: Reference Implementation Model of IEEE 802.11e.

2.2 Burst Acknowledgement Mechanism

The Burst Acknowledgement mechanism allows a burst of QoS data packets to be transmitted consecutively, only separated by a SIFS (short Interframe Space) period[5]. The mechanism

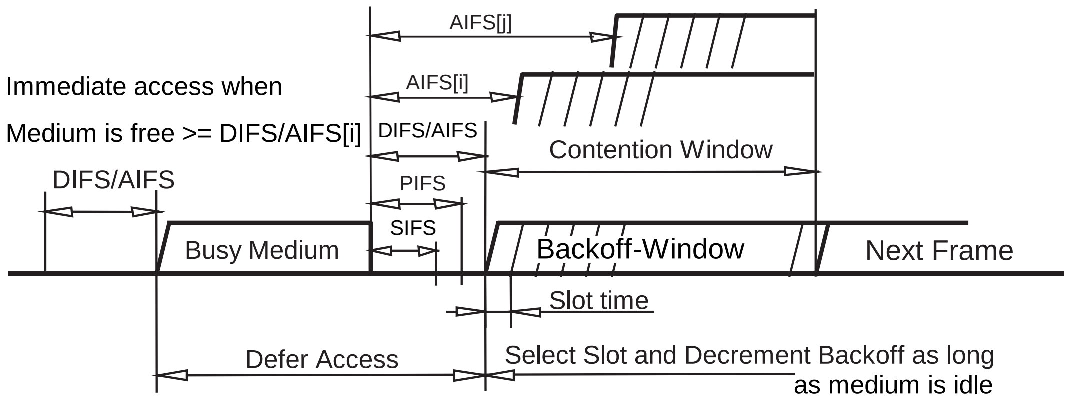


Figure 2.2: The IEEE 802.11e EDCF scheme.

improves the channel efficiency by aggregating several ACK frames into one Burst ACK frame. It consists of three stages:

1. Setup;
2. Data and Burst ACK;
3. Tear Down.

The three stages are depicted in Fig. 2.3.

In order to initiate a Burst ACK mechanism, a sender must win the contention under EDCF or polled by the QAP under HCF. During the setup stage, the Burst ACK mechanism originator initially sends a Define Burst ACK Request frame to negotiate with the recipient. The recipient who receives the Define Burst ACK Request frame first returns an ACK frame to the originator to acknowledge its reception of such request. If the recipient accepts and agrees the Burst ACK request, it returns a Define Burst ACK Response frame to signify to the originator that the burst transmission of multiple data frames can be initiated.

During the Data & Burst ACK stage, a pre-contracted number of packets are transmitted in sequence by the originator without waiting for any ACK frames. At the end of the packet

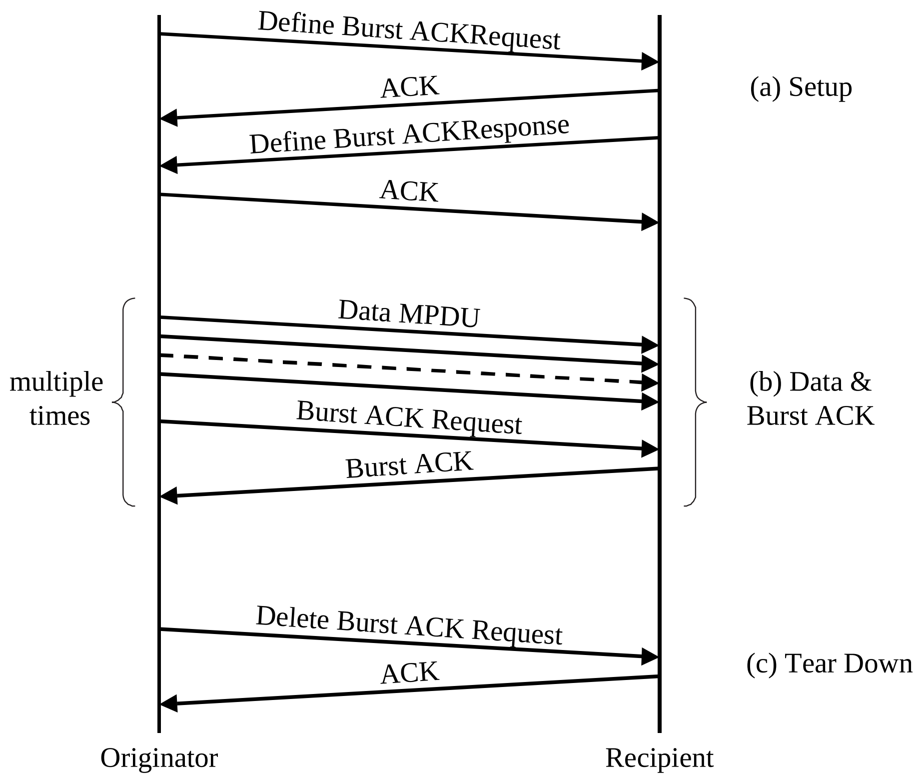


Figure 2.3: The Burst ACK Mechanism.

burst, the originator sends out a Burst ACK Request frame to request for a Burst ACK frame from the recipient. The Burst ACK frame will contain the information of reception status—success or failure—for each individual data frame so that the originator knows which data frame needs to be re-transmitted. This process can be repeated several times until all the packets are successfully transmitted.

After finishing the transmission of all data packets, the originator sends a Delete Burst ACK Request frame to request for a tear-down of the burst ACK link. An ACK frame from the recipient then ends the Burst ACK mechanism.

2.3 Power Saving In An Ad Hoc Network

Power consumption is a significant issue for mobile devices like PDA or notebooks. In accordance with this, the IEEE 802.11b standard has set up a power management mechanism for power-saving stations in both infrastructure and ad hoc topologies. In this thesis, we only consider the ad hoc topology.

Under the environment of ad hoc networks, each station contends to send the beacon frame at the target beacon time (cf. Figs. 2.4 and also 2.5). Thus, a power-saving station shall wake up prior to the commencement of the target beacon time to first contend for beacon transmission, and secondly synchronize according to the received beacon if the other station wins the beacon contention. Thereafter, all stations in the same IBSS (Independent Basic Service Set) shall remain awake for a beacon-specified duration, named Announcement Traffic Indication Message (ATIM) window. During the ATIM window, stations with data to transmit has to contend for ATIM frame transmission to indicate to the aimed receiver (possibly a power-saving station) to ensure that it will stay awake to receive data after the ATIM window. As anticipated, stations, which have no data to transmit, and which receive no ATIM frames, can enter the dose mode to save powers after the expiration of the ATIM window. The ATIM frame transmission also follows the random backoff procedure, and receivers of ATIM frames must acknowledge it by sending an ACK frame to ATIM frame originator. An exemplified power-saving operation is depicted in Fig. 2.5.

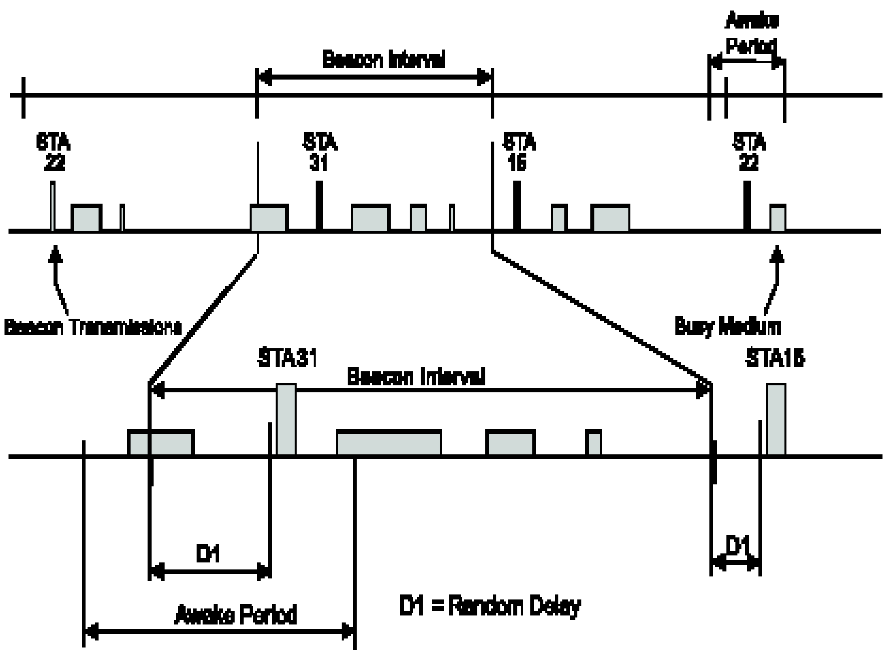


Figure 2.4: Beacon transmission in an IBSS [1].

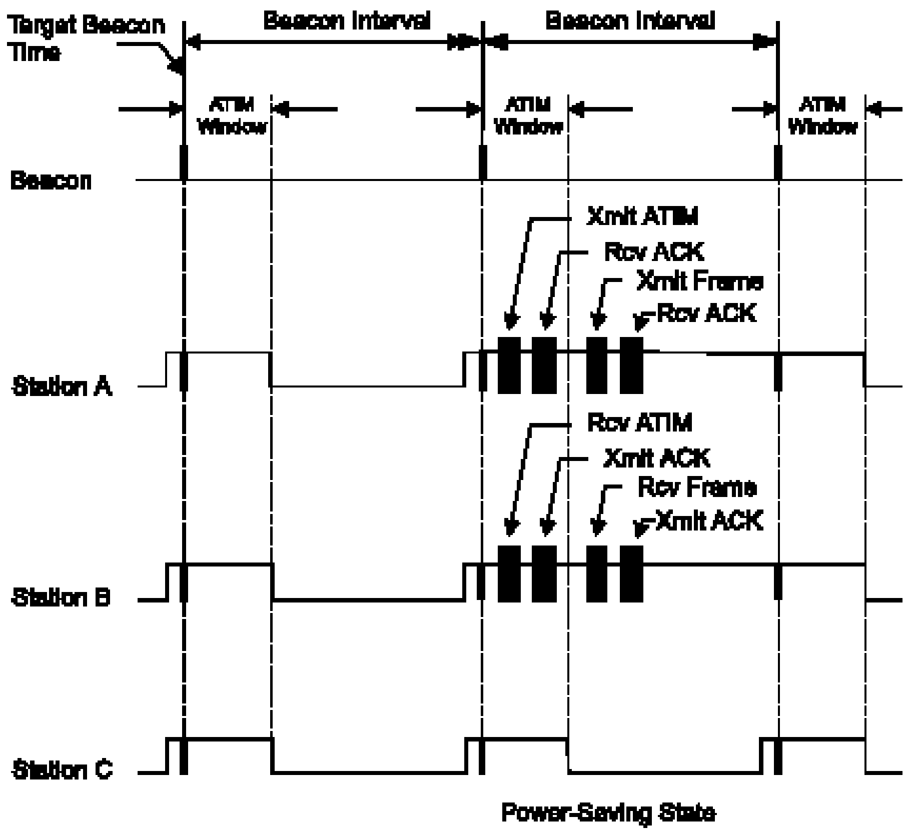


Figure 2.5: Basic operation of power-saving stations in the same IBSS [1].

Chapter 3

Simulation Scenario

3.1 Scenario of the Burst ACK Mechanism

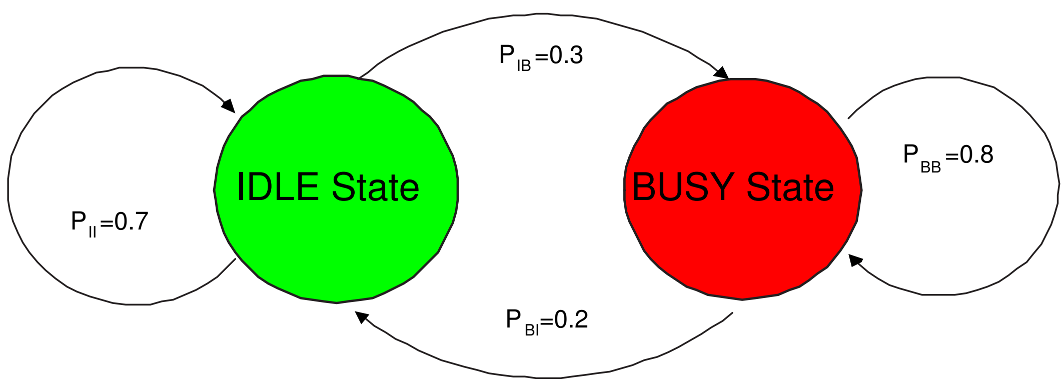


Figure 3.1: The Markov-Modulated Poisson Process.

In our system, we use the Markov-Modulated Poisson Process (MMPP) to simulate the arrival traffic of each station. As depicted in Fig. 3.1, the MMPP has two states: idle state and busy state. In idle state, no packets are generated, namely, the arrival data rate is exactly zero. In busy state, packets arrive the queue according to a Poisson distribution with mean data arrival rate $\lambda = 0.003$ packet/10us (equivalently, $\lambda = 300$ packet/second). The transition probability from busy state to idle state P_{BI} is 0.2, and the probability to remain in the busy state is thus $P_{BB} = 1 - P_{BI} = 0.8$. On the other hand, the transition probability from idle state to busy state P_{IB} is 0.3, and P_{II} which represents the probability from idle state to idle state is therefore equal to 0.7.

Two scenarios are considered in our simulation of the Burst ACK Mechanism. The first one considers no RTS/CTS exchange, while the second one includes the RTS/CTS exchange. In addition, only ac hoc topology is investigated in our research.

In our ad hoc network system, all the QSTAs are assumed to be in the same QBSS, and are within the radio range of all the other QSTAs; so the hidden node problem is excluded. Furthermore, all the QSTAs are operated in awake mode, namely no power-saving QSTAs reside in the QBSS, and are equipped with Burst ACK mechanism.

The channel is presumed to be error-free; hence, there is no packet loss or packet error due to interference or multipath effect. For simplicity, the receiving queue of each QSTA is supposed infinite in length, and the transmission time of ACK frames is assumed negligible, if being compared to the transmission time of the data frames. Also neglected in our performance calculation is the *setup stage* during which the originator and the recipient exchanged Define Burst ACK frames to handshake the system setting. The nominal data rate is set to 10 Mbps and the length of each packet is 1,000 bytes. According to the standard, the suggested values of SIFS and slot time for Direct Sequence Spread Spectrum (DSSS) PHY are 10 us and 20 us, respectively. In total, 200,000 packets of length 1000 bytes are sent during the entire simulation.

The performance impact of three parameters are studied. They are the number of QSTAs, the transmitting queue size and length of TXOP (burst length). Their ranges, as well as the aforementioned fixed setting, are listed in Tab. 3.1. As shown in the table, the number of the QSTAs ranges from 2 to 40, and the transmitting queue size varies from 16 KBytes to 32768 KBytes. The concerned burst length lies within 1 packet to 16 packets. The simulation flow chart of the Burst ACK Mechanism is depicted in Fig. 3.2.

Table 3.1: The parameters used in the Burst ACK Mechanism simulation. Notably, according to ANSI/IEEE Std 802.11, 1999Edition, $CW_{min} = 31$ and $CW_{max} = 1023$ for DSSS PHY. We however replace these two parameters by $CW_{min} = 7$ and $CW_{max} = 255$ for simulation convenience. Similar change is taken on the data rate for which the standard gives 11 Mbps but we use 10 Mbps.

Data Rate (Mbps)	10
A SIFS Time (us)	10
A DIFS Time (us)	50
A Slot Time (us)	20
CW_{min} (slots)	7
CW values in between (slots)	15, 31, 63, 127
CW_{max} (slots)	255
Packet Size (byte)	1000
Number of QSTAs	2∼30
TX Queue Size (Kbyte or 1000 bytes)	16∼32768
Burst Length (packets)	1∼16

3.2 Scenario of the Enhance Distributed Coordination Function (EDCF)

In our EDCF simulation, we restrict our consideration to a situation in which each QSTA only consists of one AC (i.e., only has one priority). We then evaluate the system performance of an ad hoc wireless LAN with QSTAs of different priorities.

In total, 200,000 packets of length 1000 bytes are sent during the entire simulation. Each QSTA sends out one packet whenever it wins the contention. (Here, we consider no Burst ACK Mechanism for simplicity.) The AIFS, CW_{max}, and CW_{min} parameters for each User Priority (UP) are listed in Tab. 3.2. There are 8 QSTAs in our QBSS, and each of them are within the radio range of all others. Among these 8 QSTAs, two have their UP equal 0, two have their UP equal 1, two have their UP equal 2, and two have their UP equal 3. Other system parameters, such as data rate, SIFS, DIFS, slot time and packet size, are the same as those used in the Burst ACK Mechanism Simulation (cf. Tab. 3.1). The TX queue size is set to be 1,024 Kbytes, and RX queue size is assumed infinite. We depict the system simulation flow chart of the EDCF in Fig. 3.3.

Table 3.2: The CW values (in slot times) of QSTAs.

Priority	AIFS (us)	CW_{min}	CW used inbetween				CW_{max}
0	50	7	15	31	63	127	255
1	70	9	19	39	79	159	319
2	90	11	23	47	95	191	383
3	110	13	27	55	111	223	447

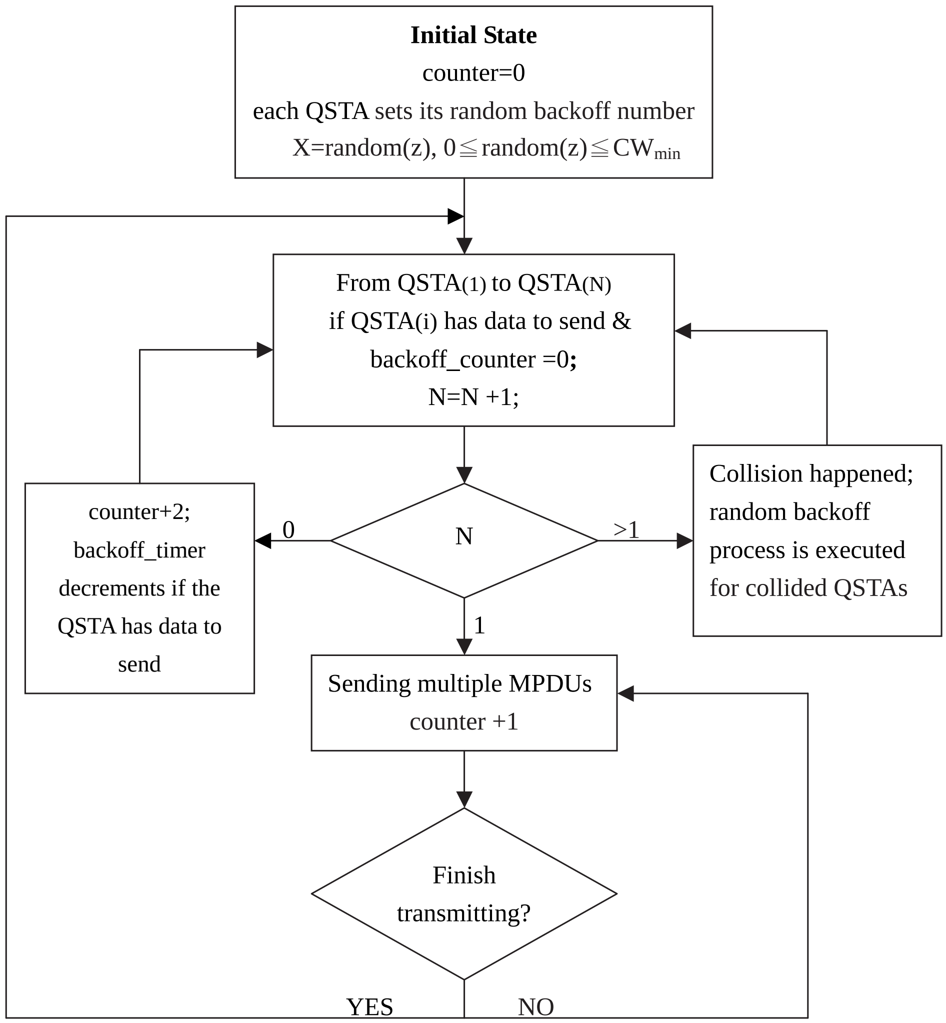
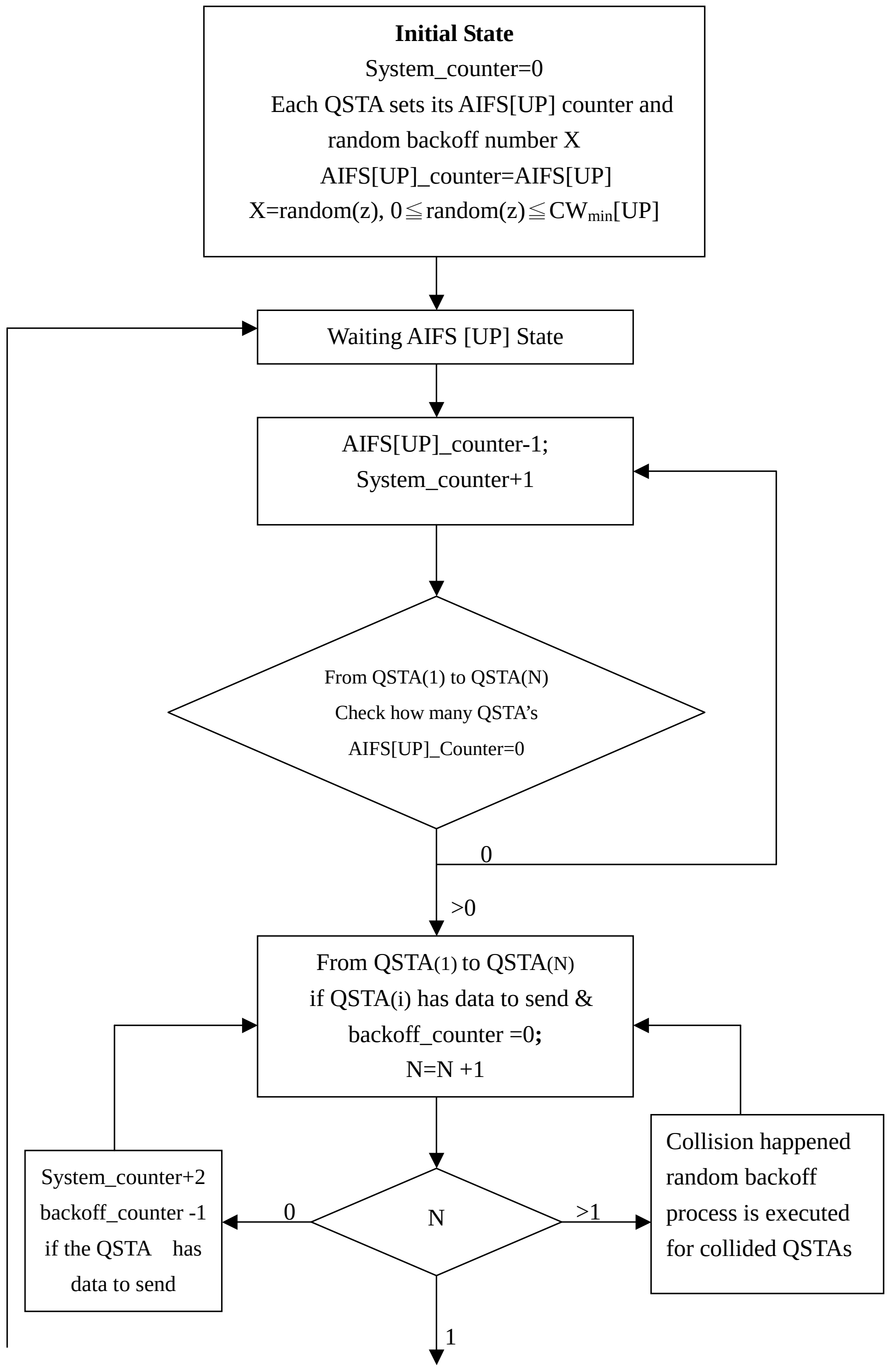


Figure 3.2: The Simulation Flow Chart of the Burst ACK Mechanism. In our simulation, one count = 10 us.



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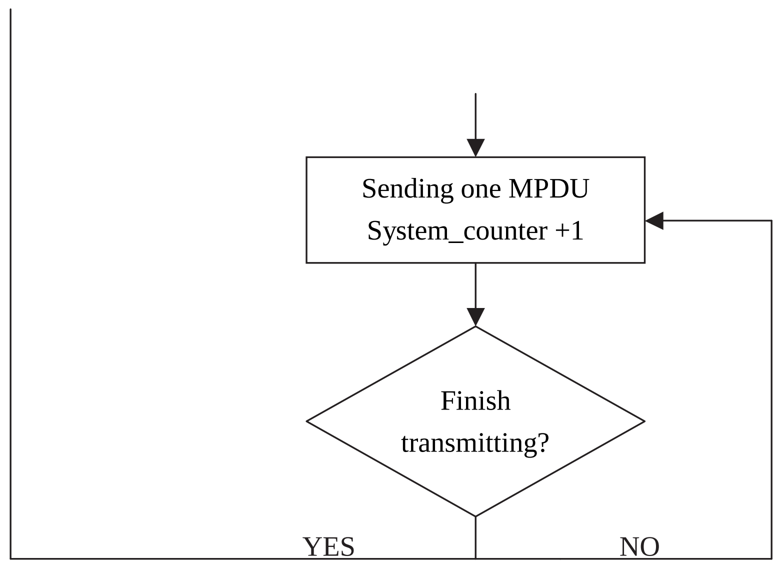
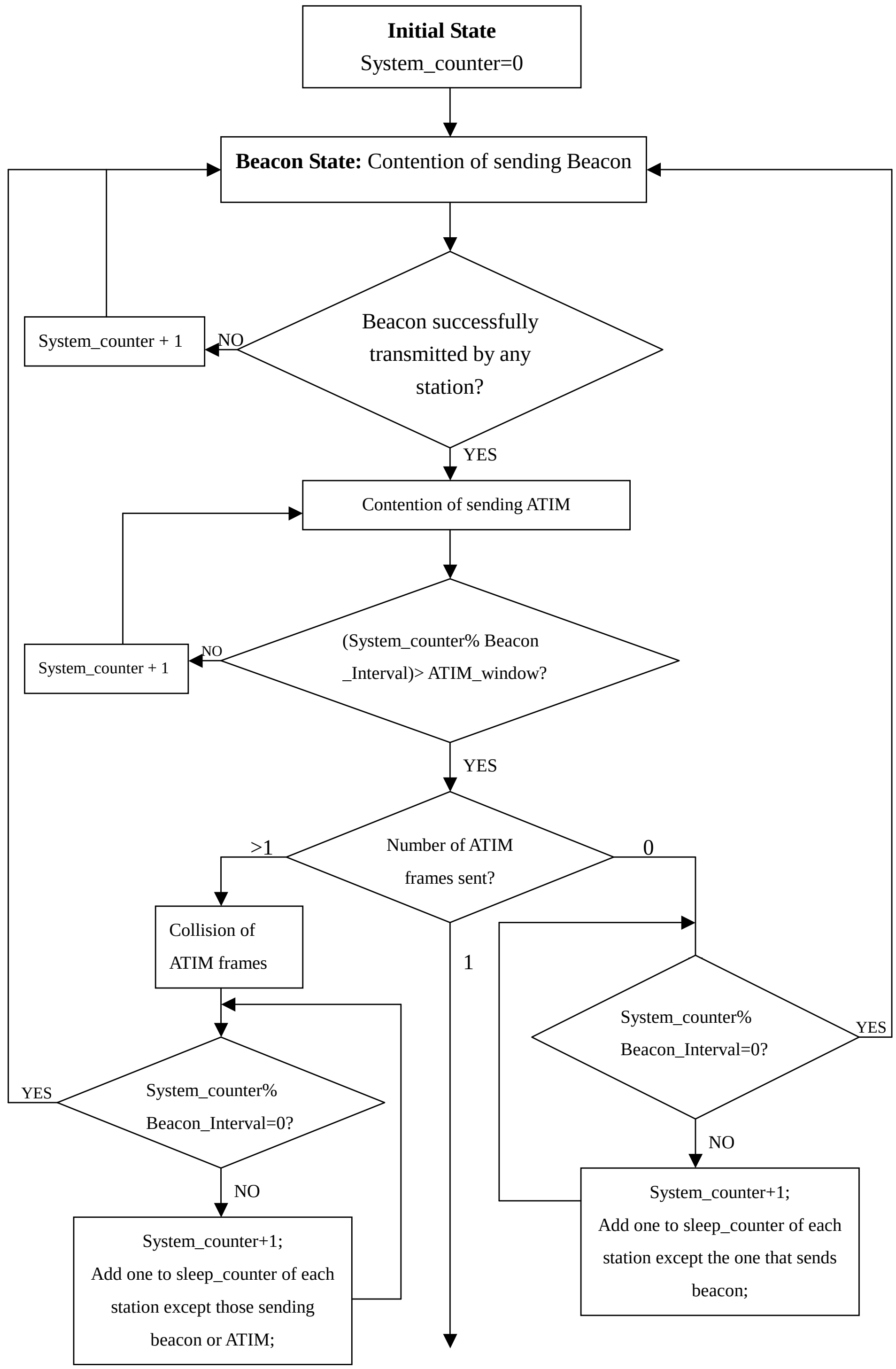


Figure 3.3: The Simulation Flow Chart of the EDCF.

3.3 Scenario of the Power Management Mechanism in an Ad Hoc Network

Consider an ad hoc network that is composed of several power-saving stations. Some system parameters in our consideration, such as slot time, SIFS, DIFS, packet size, data rate, data arrival rate, TX queue size and RX queue size, are all the same as those in the considered EDCF scenario. The Beacon Interval and ATIM window are assumed 1.5 milliseconds and 0.5 milliseconds, respectively. The $CW_{\text{min,ATIM}}$ and $CW_{\text{max,ATIM}}$ used in the backoff procedure in transmitting ATIM frames are set to 15 and 63 slot times, respectively. Besides, the $CW_{\text{min,data}}$ and $CW_{\text{max,data}}$ for the transmission of data frames are set to 7 and 255 slot times, respectively.

Our focus in this simulation scenario is to examine the power-saving efficiency of the IEEE 802.11e Burst ACK Mechanism. For the burst length of two packets, the Beacon Interval is 2.5 milliseconds. When the burst length increases to three packets, the Beacon Interval is 3.5 milliseconds. The ATIM window, however, remains the same as 0.5 milliseconds, independent of the burst length taken. The simulation flow in this scenario is depicted in Fig. 3.4.



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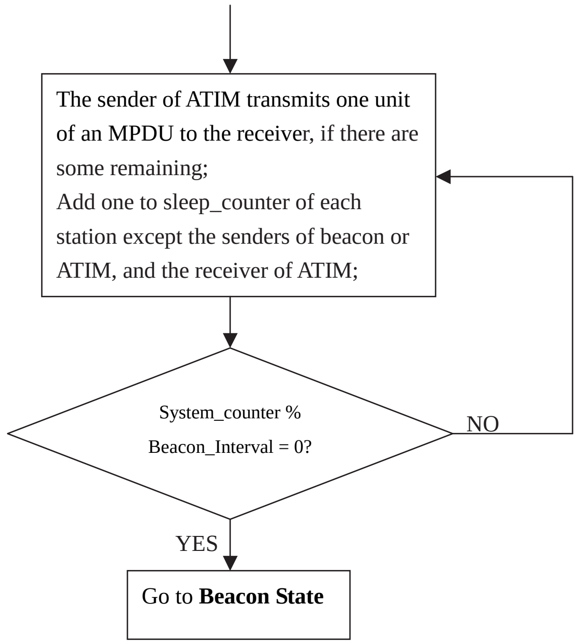

Figure 3.4: Simulation Flow Chart of the Burst ACK Mechanism under power management. Notably, since the duration of an ATIM frame plus an SIFS plus an ACK frame is equal to $206 + 10 + 199 = 415$ us, only one ATIM frame sequence can be successfully transmitted within our specified ATIM window (500 us). The collision of ATIM frames can therefore be simply examined by “more than one ATIM frames are transmitted” or “Number of ATIM frames sent > 1.”

Chapter 4

Simulation Results

4.1 Simulation Results for the Burst ACK Mechanism

In this chapter, we present our simulation results of the Burst ACK Mechanism with/without RTS/CTS, and those of the EDCF. Our investigation focuses on three performance indices: system throughput T (kbps), average queueing delay D (ms) and average packet loss rate L.

4.1.1 Performance of The Burst ACK Mechanism Without RTS/CTS

In the subsection, we varied three parameters regarding the Burst ACK Mechanism without RTS/CTS in our simulations to understand their performance impact over an ad hoc wireless LAN system. These three parameters are the number S of the QSTAs, the TX queue size Q (Kbytes) in each QSTA, and the burst length B (packets) of each transmission.

First, we fixed the TX queue size to be 1024 Kbytes, which can accommodate 1024 packets of length 1000 bytes. The burst length of one transmission is limited by 10 packets, and is equal to this number only when there are more than 10 packets in the TX queue at the time a QSTA wins the contention. In comparison, we also simulated the IEEE 802.11b system without the enhancement of any IEEE 802.11e functions, in which only one packet is allowed per transmission.[1] As mentioned in Chapter 3, there are 200,000 packets transmitted throughout each simulation with respect to one QSTA number.

Figures 4.1, 4.2 and 4.3 respectively depict the system throughput T (kbps), average queueing delay D (ms) and average packet loss rate L as a function of the number S of QSTAs. We found from these three figures that we can approximate the performance curves by using least-square approximation as:[2]

$$T_{\text{802.11b}}(S,Q,B) \approx \begin{cases} 2381, & \text{for } 2 \leq S \leq 3; \\ 8731.7\, S^{-1.1258}, & \text{for } S \geq 4, \end{cases} \tag{4.1}$$

$$T_{\text{B-Ack, No RTS/CTS}}(S,Q,B) \approx \begin{cases} 2385, & \text{for } 2 \leq S \leq 3; \\ 9165.9\, S^{-1.1112}, & \text{for } S \geq 4, \end{cases} \tag{4.2}$$

$$D_{\text{802.11b}}(S,Q,B) \approx \begin{cases} 0, & \text{for } 2 \leq S \leq 3; \\ 1532.9\, S - 2571.4, & \text{for } S \geq 4, \end{cases} \tag{4.3}$$

$$D_{\text{B-Ack, No RTS/CTS}}(S,Q,B) \approx \begin{cases} 0, & \text{for } 2 \leq S \leq 3; \\ 1428.2\, S - 2758.4, & \text{for } S \geq 4, \end{cases} \tag{4.4}$$

$$L_{\text{802.11b}}(S,Q,B) \approx \begin{cases} 0, & \text{for } 2 \leq S \leq 3; \\ 0.5247 \ln S - 0.4742, & \text{for } 10 \geq S \geq 4; \\ 0.1887 \ln S + 0.2786, & \text{for } S > 10, \end{cases} \tag{4.5}$$

and

$$L_{\text{B-Ack, No RTS/CTS}}(S,Q,B) \approx \begin{cases} 0, & \text{for } 2 \leq S \leq 3; \\ 0.5833 \ln S - 0.6318, & \text{for } 10 \geq S \geq 4; \\ 0.2041 \ln S + 0.2184, & \text{for } S > 10, \end{cases} \tag{4.6}$$

where $Q = 1024$ (Kbytes), $B = 10$ (packets), subscripts "802.11b" and "B-Ack, No RTS/CTS" represent the results with respect to IEEE 802.11b system without IEEE 802.11e enhancement functions and Burst ACK Mechanism without RTS/CTS, respectively.

[1] We ignore the fragmentation mechanism because the key different between IEEE 802.11b systems with and without Burst ACK mechanism is the transmission burst length. Such a key difference remains even with the fragmentation mechanism being enabled. So the inclusion of the fragmentation mechanism only complicates the simulation, but provides no apparent change in simulation conclusion.

[2] We use "Fit[data, functions, variables]" command in Mathematica to obtain these approximations. The command finds the least square fit to a list of data as a linear combination of the designated functions of variables.

From these approximations, we can see that the system throughput, average queueing delay and average packet loss remain almost the same when the number of stations is less than or equal to 3. This is because almost no collision occurs when station number S is no larger than 3. When the number of stations further increases, system throughput decreases dramatically due to collisions. However, the average queueing delay only increases linearly with respect to the number of stations. The average packet loss is approximately proportional to logarithm of the number of stations. These figures conclude that the Burst ACK Mechanism without RTS/CTS performs better in all three performance indices than the IEEE 802.11b system when the number of stations is moderately large (≥ 4). Such superiority of the Burst ACK Mechanism without RTS/CTS is not limited to the main terms in the approximation formulas (specifically, $S^{-1.1258}$ versus $S^{-1.1112}$ in system throughput, $1532.9\,S$ versus $1428.2\,S$ in average queueing delay, and $0.0167485\ln(S)$ versus $0.015872\ln(S)$ in average packet loss rate) but also extend to the constant terms (specifically, 8731.7 versus 9165.9 in system throughput, $-2571.4\,S$ versus -2758.4 in average queueing delay, and -0.01483 versus -0.015665 in average packet loss).

Next, we investigated the performance impact of varying TX queue size. The maximum burst length of a single transmission is 5. The numbers of QSTAs are fixed at 3, 5, 7 and 9, respectively. The simulation results are summarized in Figs. 4.4, 4.5 and 4.6. Again, we

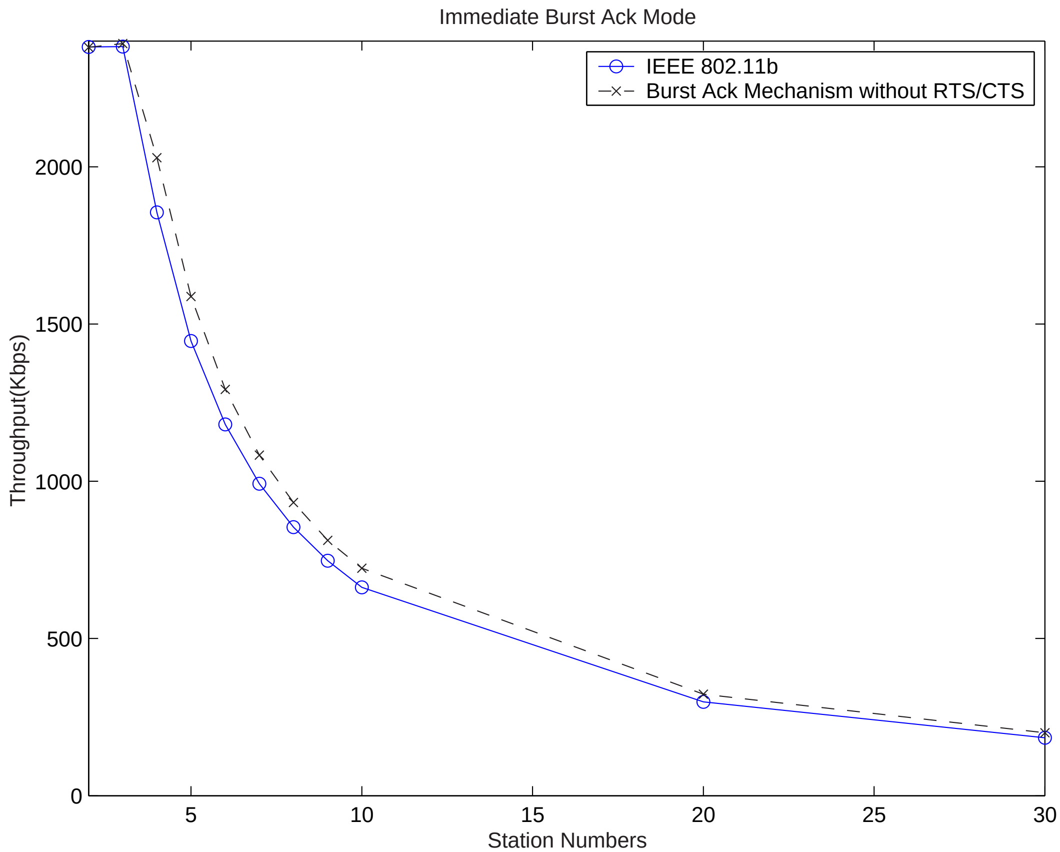

Figure 4.1: The system throughput versus the number of QSTAs.

approximated the curves obtained by simulations as follows.

$$T_{802.11b}(5, Q, 5) \approx 1447, \tag{4.7}$$

$$T_{\text{B-Ack, No RTS/CTS}}(5, Q, 5) \approx 1565, \tag{4.8}$$

$$D_{802.11b}(5, Q, 5) \approx \begin{cases} 4.4193\,Q + 80.42, & \text{for } Q \leq 1024; \\ 1939.7\,\ln Q - 8655.8, & \text{for } 1024 < Q \leq 4096; \\ 7100, & \text{for } Q > 4096, \end{cases} \tag{4.9}$$

$$D_{\text{B-Ack, No RTS/CTS}}(5, Q, 5) \approx \begin{cases} 3.8456\,Q + 45.39, & \text{for } Q \leq 1024; \\ 1027.2\,\ln Q - 3041, & \text{for } 1024 < Q \leq 4096; \\ 5400, & \text{for } Q > 4096, \end{cases} \tag{4.10}$$

$$L_{802.11b}(5, Q, 5) \approx \begin{cases} -0.0001\,Q + 0.3922, & \text{for } Q \leq 2848; \\ 0, & \text{for } Q > 2848, \end{cases} \tag{4.11}$$

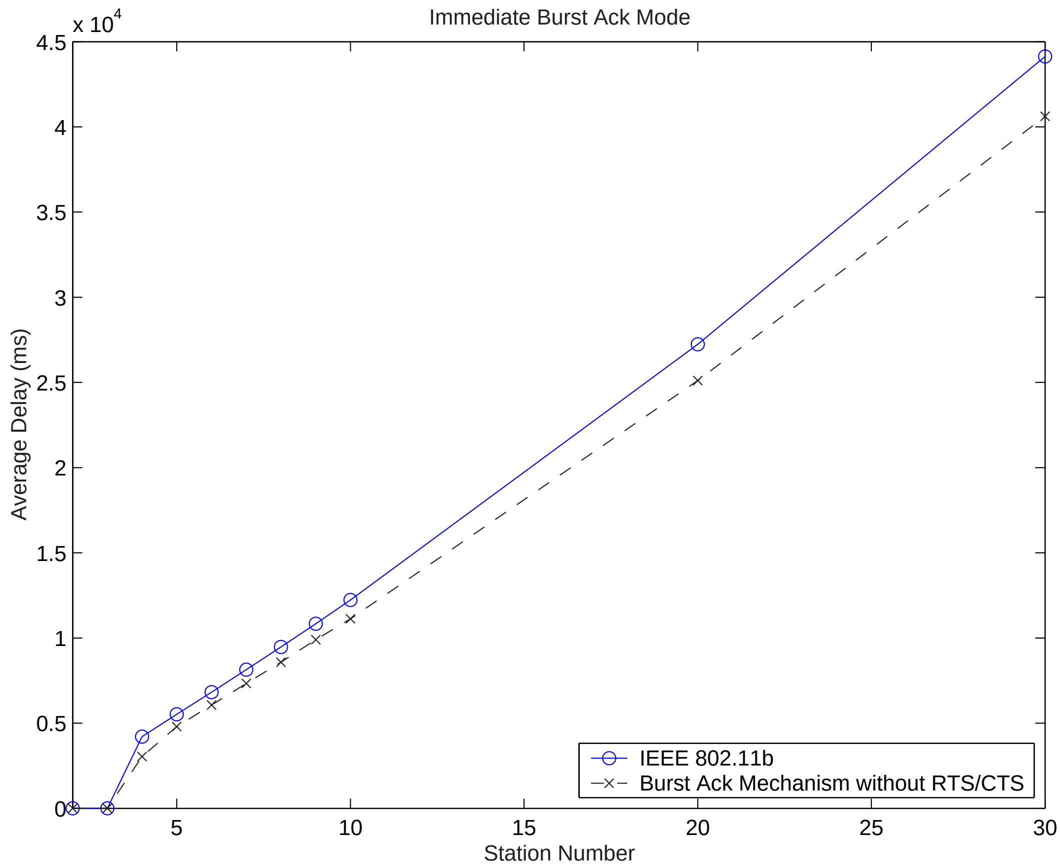

Figure 4.2: The average queueing delay versus the number of QSTAs.

and

$$L_{\text{B-Ack, No RTS/CTS}}(5, Q, 5) \approx \begin{cases} -0.0001\,Q + 0.344, & \text{for } Q \leq 2848; \\ 0, & \text{for } Q > 2848, \end{cases} \tag{4.12}$$

where the first argument 5 is the number of QSTAs, and the third argument 5 is the maximum burst length of a single transmission.

Figure 4.4 suggests that the system throughput is almost independent of the TX queue size; so the system throughput is more dominant by the other factors such as the number of QSTAs or the effect of collision. Figure 4.5 indicates that the average queueing delay increases rapidly when the TX queue size is small, and remains constant when the TX queue size is large. This is because that some packets are lost due to inadequately small queue

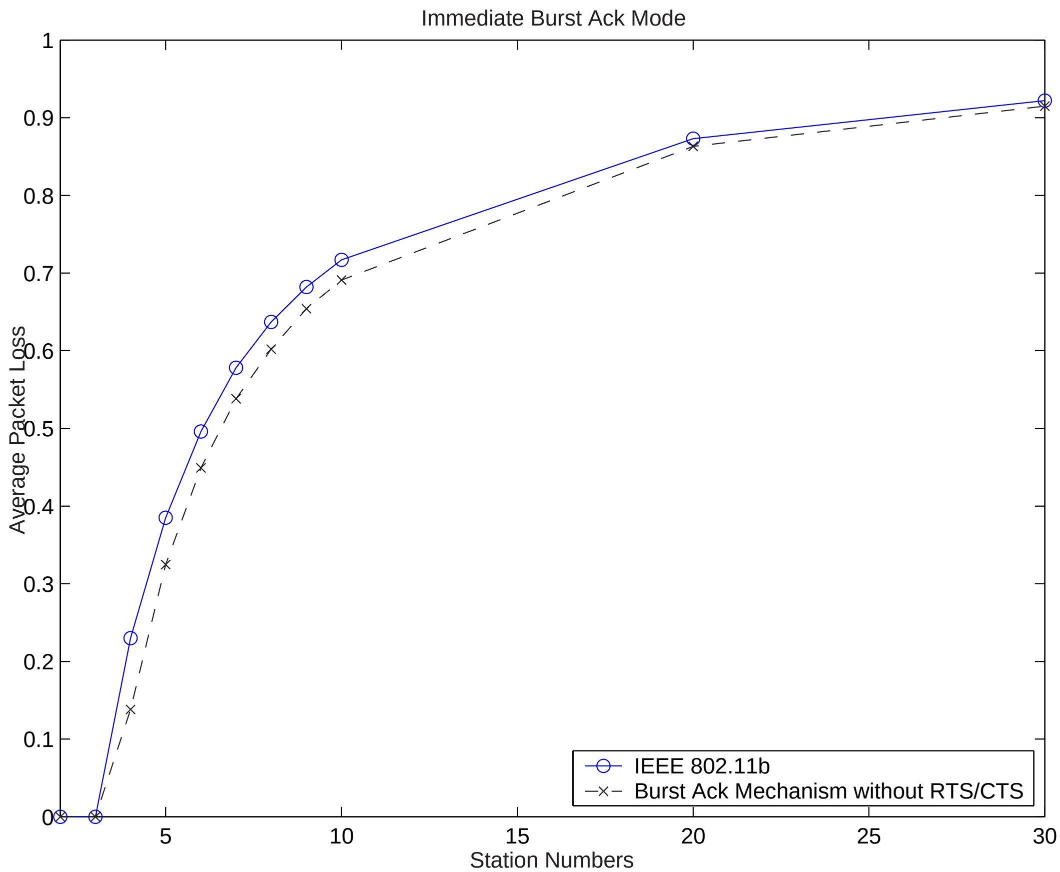

Figure 4.3: The packet loss rate versus the number of QSTAs.

size; in this situation, a larger queue size straightforwardly results in larger queueing delay. However, when the queue size is large enough to eliminate packet loss, in which case the queue utilization is strictly less than 100%, no further increase of queueing delay is caused by further increase of queueing size. This phenomenon can be observed from Fig. 4.6, where the packet loss rate reduces to almost zero, after the queue size exceed certain quantity. Figure 4.6 actually hints that the average packet loss rate is inversely proportional to the TX queue size.[3] We conclude from Figs. 4.4, 4.5 and 4.6 that the improvement of the Burst

[3]In Figs. 4.4 and 4.5, the simulated Queue Sizes are 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384, 32768 Kbytes. In Fig. 4.6, additional values of Queue Sizes are added to the bottom 5 curves as 2248, 2448, 2648, 2848, 3048, 3248, 3448, 3648, 3848 Kbytes. With these additional values, the point at which the packet loos rate reduces to zero can be better approximated.

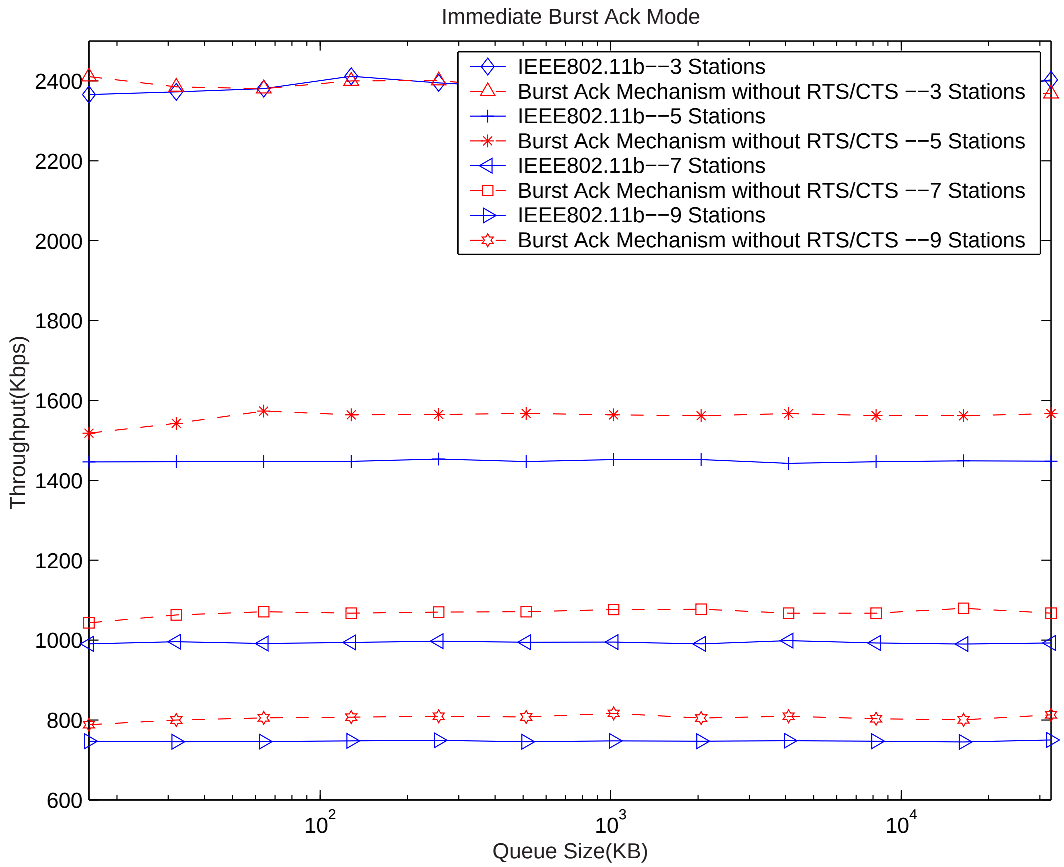

Figure 4.4: The system throughput versus the TX queue size.

ACK Mechanism without RTS/CTS over IEEE 802.11b is more evident when the number of stations increase.

Finally, we adjusted the burst length of each transmission from 1 to 16 packets to study its performance impact. The numbers of QSTAs are fixed at 5 and 10. The TX queue size of each QSTA is 1024 Kbytes in size. The system throughput, average queueing delay and the average packet loss rate as a function of the burst length are depicted in Figs. 4.7, 4.8 and 4.9, respectively. The least-square-fit formulas for the curves with respect to 5 QSTAs

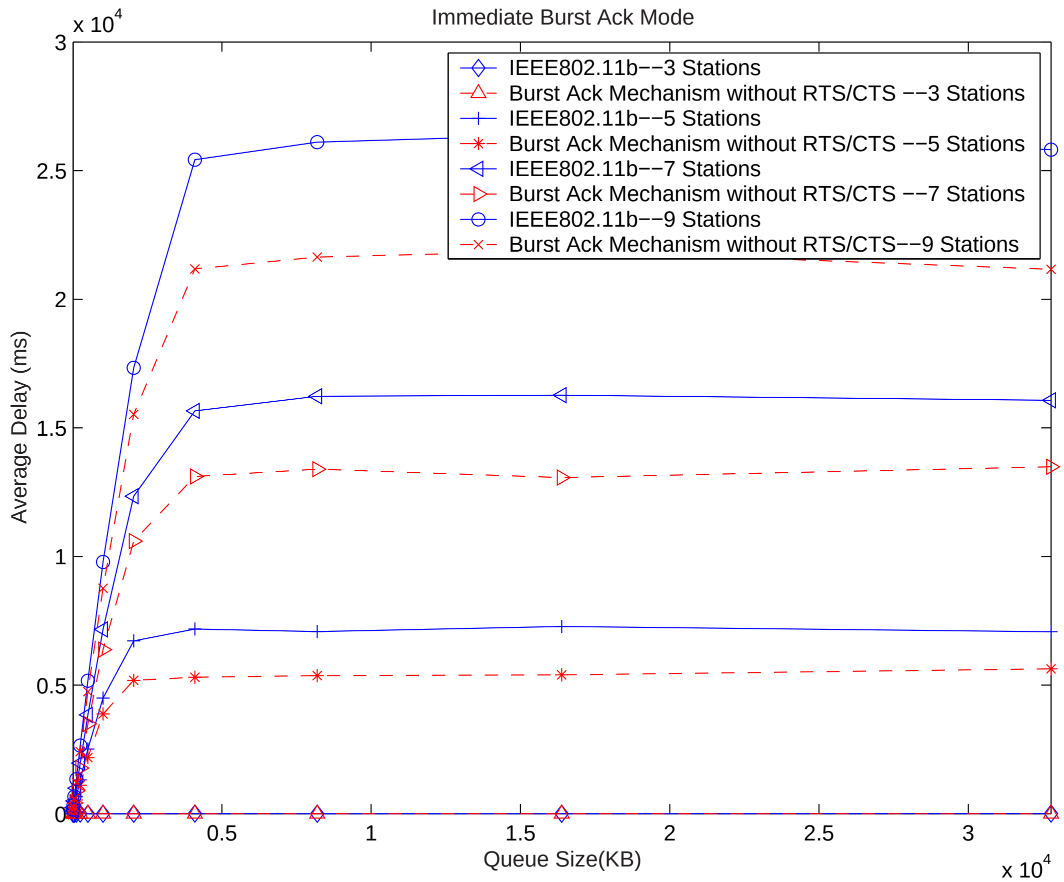

Figure 4.5: The average queueing delay versus the TX queue size.

are:

$$T_{\text{B-Ack, No RTS/CTS}}(5, 1024, B) \approx \begin{cases} 81.1 \ln B + 1452.5 & \text{for } 1 \leq B \leq 5; \\ 1590, & \text{for } B > 5, \end{cases} \tag{4.13}$$

$$D_{\text{B-Ack, No RTS/CTS}}(5, 1024, B) \approx 5481.2B^{-0.0613} \tag{4.14}$$

$$L_{\text{B-Ack, No RTS/CTS}}(5, 1024, B) \approx 0.3603B^{-0.0479}. \tag{4.15}$$

From Figs. 4.7, 4.8 and 4.9, we observed that the system throughput increases about 10% as the burst length grows from 1 to 5 packets. In the same region, the average queueing delay decreases about 20%, and the average packet loss rate reduces about 35%. However, further increase of burst length is ineffective to further improve the system throughput, average

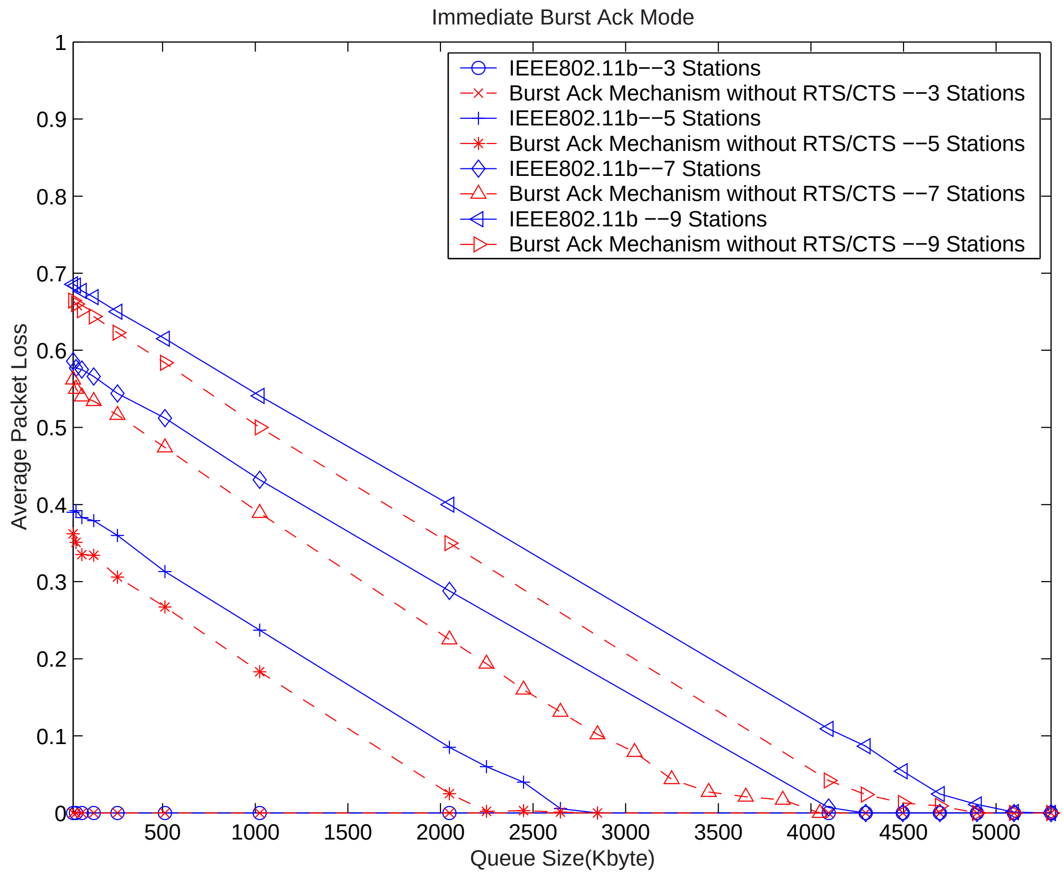

Figure 4.6: The packet loss rate versus the TX queue size.

queueing delay and average packet loss rate.

To summarize, we found that increasing the burst length, which is claimed to be the key merit of Burst ACK Mechanism, only has limited improvement in system performance when no RTS/CTS is implemented. The entire system performance is still dominantly decided by the number of QSTAs and the queueing size taken.

4.1.2 Performance of The Burst ACK Mechanism With RTS/CTS

In this section, we empirically evaluate the performance of the Burst ACK Mechanism with RTS/CTS. The system parameters and setting are the same as those taken in Figs. 4.1,

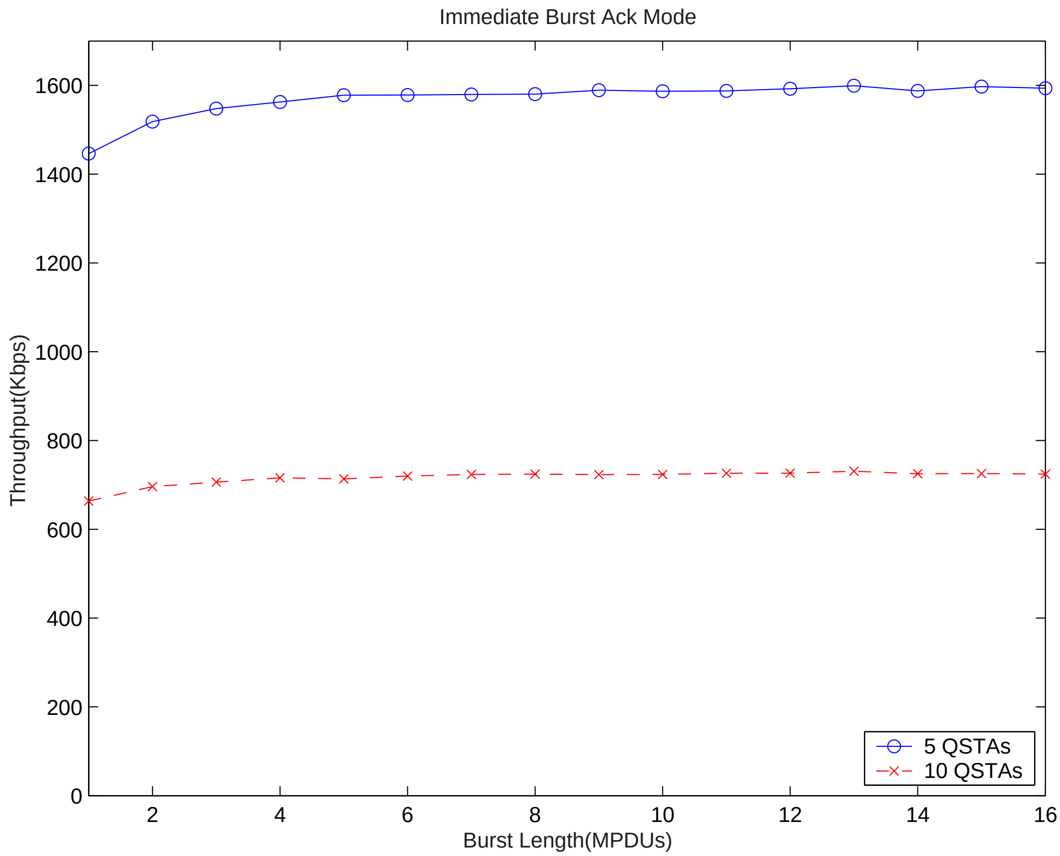

Figure 4.7: The system throughput versus the burst length.

4.2 and 4.3. The simulation results for performance indices of system throughput, queueing delay and average packet loss rate are summarized in Figs. 4.10, 4.11 and 4.12, respectively. The approximation formulas for the Burst ACK Mechanism with RTS/CTS are given by:

$$T_{\text{B-Ack, RTS/CTS}}(S, 1024, 10) \approx \begin{cases} 2385, & \text{for } 2 \leq S \leq 4; \\ 9643.4\, S^{-0.9928} & \text{for } S \geq 5, \end{cases} \tag{4.16}$$

$$D_{\text{B-Ack, RTS/CTS}}(S, 1024, 10) \approx \begin{cases} 0 & \text{for } 2 \leq S \leq 4 \\ 828.43\, S - 777.36 & \text{for } S \geq 5 \end{cases} \tag{4.17}$$

$$L_{\text{B-Ack, RTS/CTS}}(S, 1024, 10) \approx \begin{cases} 0 & \text{for } 2 \leq S \leq 4 \\ 0.6231 \ln S - 0.8436 & \text{for } 10 \geq S \geq 5 \\ 0.2565 \ln S - 0.0174 & \text{for } S > 10. \end{cases} \tag{4.18}$$

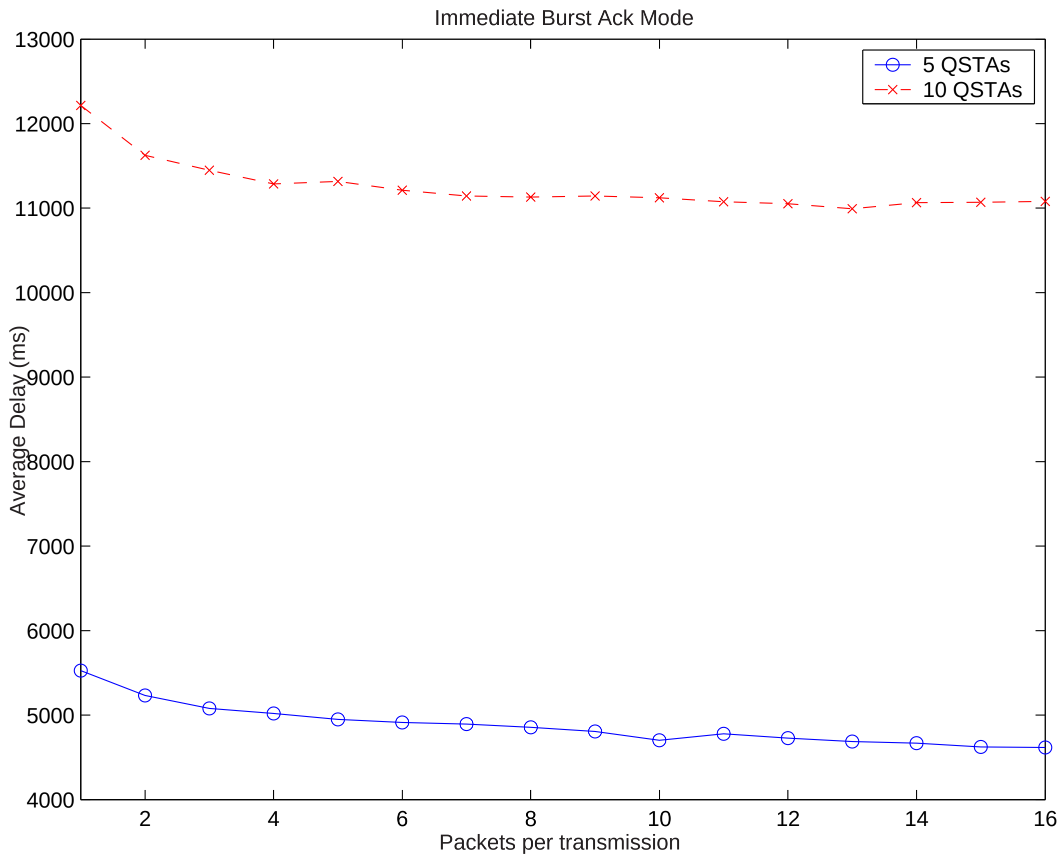

Figure 4.8: The average queueing delay versus the burst length.

From the figures (or the formulas), we observe that the performance of the Burst ACK Mechanism with RTS/CTS improves considerably than that without RTS/CTS. This is because RTS/CTS exchange can pre-resolve the collision beforehand in a much shorter time that a true burst transmission; so a QSTA does not need to waste a burst transmission time to resolve a collision (or to learn that a collision occurs by an Burst ACK timeout). The other performance indices such as average queueing delay and average packet loss rate also greatly improve when Burst ACK mechanism and RTS/CTS mechanism are both enabled.

From the above results, we conclude that the performance of the Burst ACK Mechanism with RTS/CTS is considerably better than that of the Burst ACK Mechanism without RTS/CTS or the IEEE 802.11b.

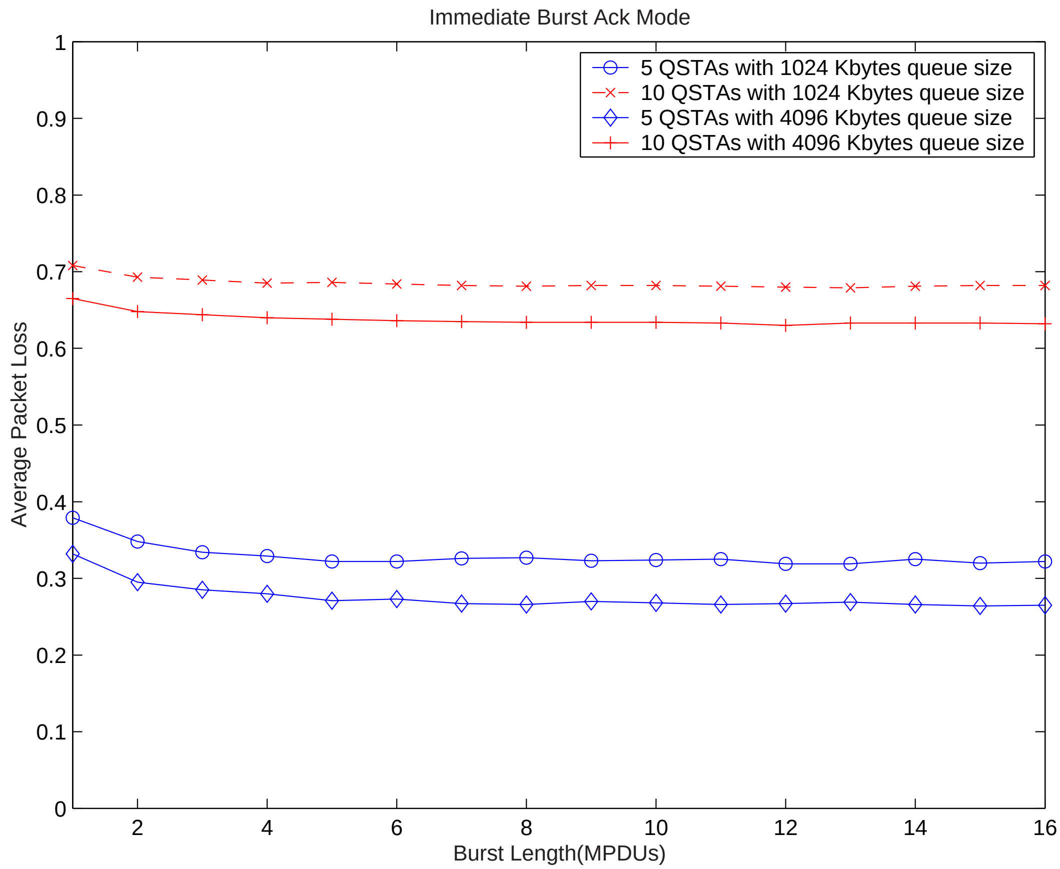

Figure 4.9: The packet loss rate versus the burst length.

4.2 Performance of the Enhanced Distributed Coordination Function

In this section, we evaluate the performance impact of the EDCF. The simulation results are summarized in Tabs. 4.1, 4.2 and 4.3.

The results show that the QSTAs with higher priority get larger throughput, smaller queueing delay and less packet loss. Although we simulated the EDCF by assuming that each QSTA consists of only one AC, it can be applicable to a multiple-queue with different priorities within a QSTA. Hence, one can adjust the CW_{max}, CW_{min} and AIFS to fulfill different service requirements. In addition, we only change the AIFS to 50, 100, 150, 200us

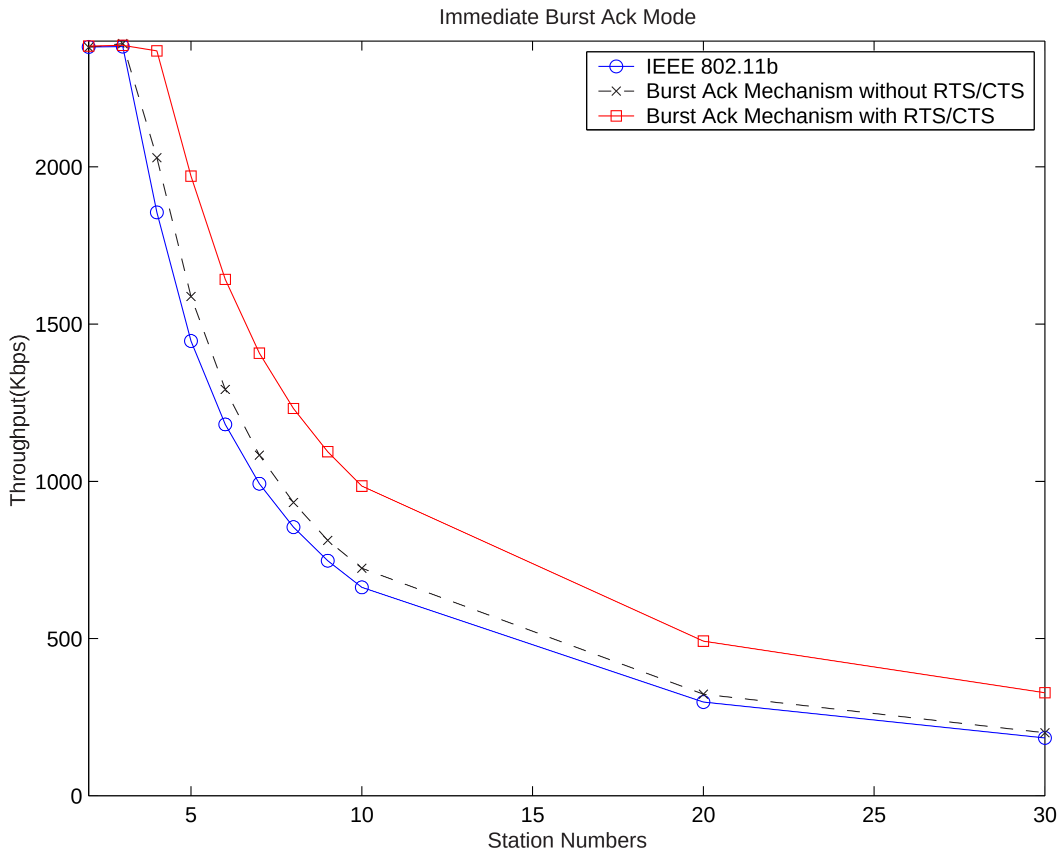

Figure 4.10: The system throughput versus the number of QSTAs.

for priority 0 to 3 respectively, and the results are listed in Tabs. 4.4, 4.5 and 4.6. Besides, we adjust the CW values for different priorities as the Tab. 4.7 and the simulation results are listed in Tabs. 4.8, 4.9 and 4.10.

Specifically, the average throughput of QSTA 0 is about 14.5 times larger than that of QSTA 7; but the average queueing delay for QSTA 0 is much less than that for QSTA 7. Furthermore, there is almost no packet loss for QSTA 0; however, QSTA 7 encounters a markedly large packet loss rate due to queue overflow.

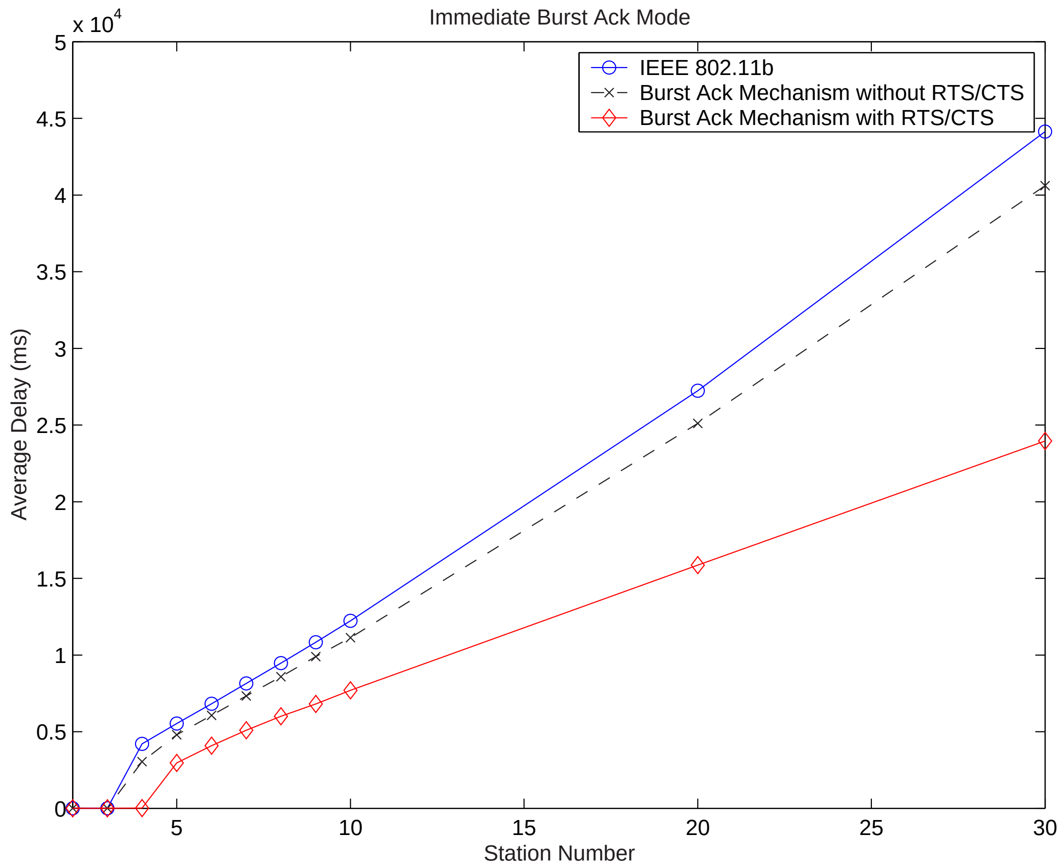

Figure 4.11: The average queueing delay versus the number of QSTAs.

4.3 Performance of the Burst ACK Mechanism over Ad Hoc Networks with Power Management Enabled

In this section, we examine the power efficiency of the Burst ACK mechanism in draft IEEE 802.11e. This situation is different from what has been studied in the previous sections, where no power-saving mode is allowed in any stations.

Figure 4.13 illustrates the system inactive ratio as a function of the station number. Here, the average inactive ratio is defined as the total time, during which stations enter inactive (namely, power-saving or dose) mode, against the total simulation time multiplying

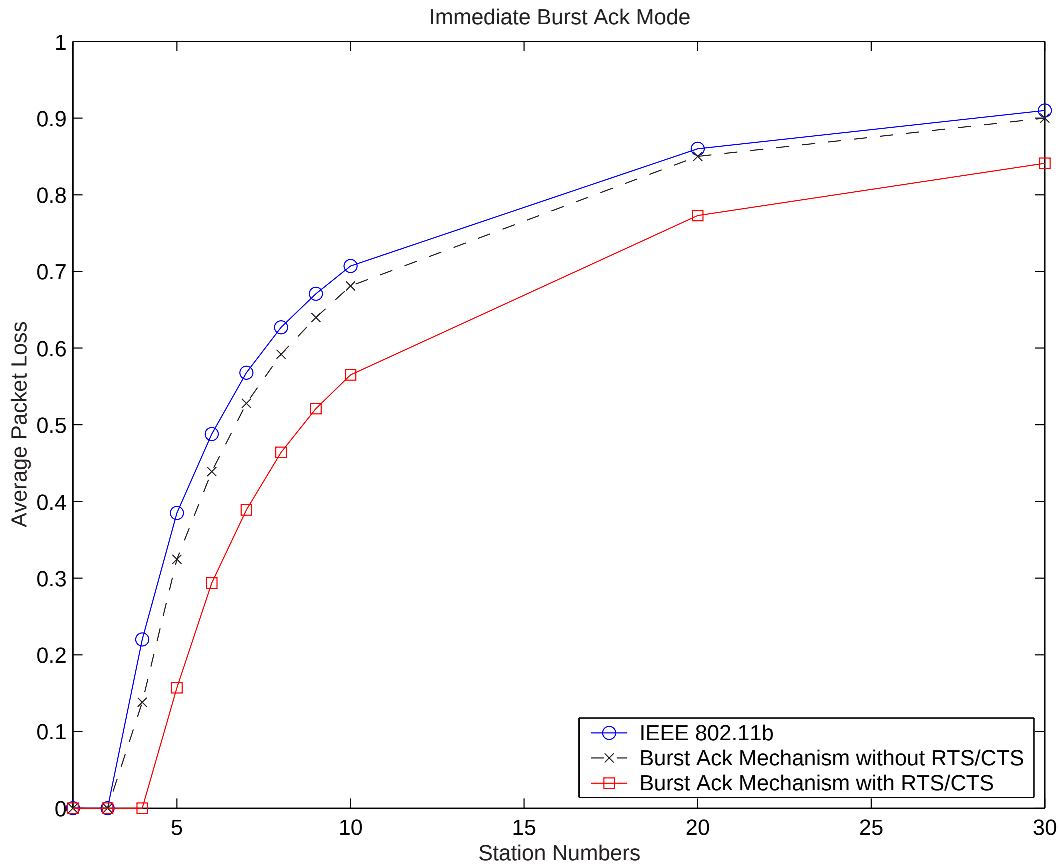

Figure 4.12: The average packet loss versus the number of QSTAs.

the station number. Again, we can find the least-square-fit of each curve in Fig. 4.13 as follows.

$$P_{\text{IEEE 802.11b}}(S, 1024, 1) \approx \begin{cases} 0.28 \ln S - 0.1692, & \text{for } 1 \le S \le 10; \\ 0.1201 \ln S + 0.1756, & \text{for } S > 10, \end{cases} \tag{4.19}$$

$$P_{\text{B-Ack, RTS/CTS}}(S, 1024, 3) \approx \begin{cases} 0.3213 \ln S - 0.1604, & \text{for } 1 \le S \le 10; \\ 0.1273 \ln S + 0.2637. & \text{for } S > 10, \end{cases} \tag{4.20}$$

where S represents the station number, 1024 Kbps is the TX queue size adopted, and the last argument is the burst length used in the simulation. Since the curves for burst lengths 2 and 3 in Fig. 4.13 are close, we only list the approximate equation for burst length 3.

In order to compare the power economy of different systems, we further use the *power*

Table 4.1: The throughput of the QSTAs with different priorities.

	Average throughput(Kbps)	Normalized to the average throughput of QSTA 7
QSTA 0(priority 0)	2371.723	14.5
QSTA 1(priority 0)	2393.956	14.6
QSTA 2(priority 1)	1395.085	8.5
QSTA 3(priority 1)	1348.988	8.2
QSTA 4(priority 2)	494.848	3.0
QSTA 5(priority 2)	475.923	2.9
QSTA 6(priority 3)	178.300	1.1
QSTA 7(priority 3)	163.611	1.0

Table 4.2: The average queueing delay of the QSTAs with different priorities.

	Average queueing delay(ms)	Normalized to the average queueing delay of QSTA 0
QSTA 0(priority 0)	11.47	1
QSTA 1(priority 0)	11.11	0.97
QSTA 2(priority 1)	6445.08	561.9
QSTA 3(priority 1)	6668.50	581.4
QSTA 4(priority 2)	18384.51	1602.8
QSTA 5(priority 2)	19125.55	1667.4
QSTA 6(priority 3)	51176.59	4461.8
QSTA 7(priority 3)	55727.88	4858.6

consumption ratio over average system throughput as a performance index. This performance index can be interpreted as the *average power used for a single transmission*. As a result, if the index value is smaller, then the power economy is better because each transmission consumes less power. It needs to be pointed out that the power consumption ratio is equal to 1 minus the power inactive ratio plotted in Fig. 4.13.

Figure 4.14 depicts the power-economy performance index as a function of station number. From the figure, we can observe that although taking burse length 2 has almost the same average system inactive ratio as taking burst length 3, the latter apparently has better

Table 4.3: The average packet loss rate of the QSTAs with different priorities.

	Average packet loss rate
QSTA 0(priority 0)	0
QSTA 1(priority 0)	0
QSTA 2(priority 1)	0.40
QSTA 3(priority 1)	0.42
QSTA 4(priority 2)	0.77
QSTA 5(priority 2)	0.78
QSTA 6(priority 3)	0.90
QSTA 7(priority 3)	0.91

Table 4.4: The throughput of the QSTAs with different priorities with different AIFS.

	Average throughput(Kbps)	Normalized to the average throughput of QSTA 7
QSTA 0(priority 0)	2389.918	59.4
QSTA 1(priority 0)	2366.206	58.8
QSTA 2(priority 1)	1644.220	40.9
QSTA 3(priority 1)	1646.081	40.9
QSTA 4(priority 2)	264.330	6.5
QSTA 5(priority 2)	266.277	6.6
QSTA 6(priority 3)	36.605	0.9
QSTA 7(priority 3)	40.196	1.0

power economy. This is because that one success of ATIM contention can cause a burst transmission of 3 packets, and hence, a higher throughput can be achieved. In addition, as the transmission of a longer burst proceeds, the other stations except the receiver and the sender of beacon frame can stay inactive (namely, in power-saved mode) longer, which makes the average power consumption ratio smaller. Accordingly, we conclude from our simulations that the power economy can be significantly improved by the Burst ACK Mechanism in draft IEEE 802.11e.

Table 4.5: The average queueing delay of the QSTAs with different priorities with different AIFS.

	Average queueing delay(ms)	Normalized to the average queueing delay of QSTA 0
QSTA 0(priority 0)	2.59	1
QSTA 1(priority 0)	2.58	0.99
QSTA 2(priority 1)	5517.16	2130.17
QSTA 3(priority 1)	5481.33	2116.3
QSTA 4(priority 2)	35042.20	13529.8
QSTA 5(priority 2)	34789.53	13432.2
QSTA 6(priority 3)	253330.23	97810.89
QSTA 7(priority 3)	230738.15	89088.08

Table 4.6: The average packet loss rate of the QSTAs with different priorities with different AIFS.

	Average packet loss rate
QSTA 0(priority 0)	0
QSTA 1(priority 0)	0
QSTA 2(priority 1)	0.29
QSTA 3(priority 1)	0.30
QSTA 4(priority 2)	0.88
QSTA 5(priority 2)	0.88
QSTA 6(priority 3)	0.98
QSTA 7(priority 3)	0.98

Table 4.7: The CW values (in slot times) of QSTAs.

Priority	AIFS (us)	CW_{min}	CW used inbetween				CW_{max}
0	50	31	63	127	255	511	1023
1	70	39	79	159	319	639	1279
2	90	47	95	191	383	767	1535
3	110	55	111	223	447	895	1791

Table 4.8: The throughput of the QSTAs with different priorities with different CW values.

	Average throughput(Kbps)	Normalized to the average throughput of QSTA 7
QSTA 0(priority 0)	1978.157	4.7
QSTA 1(priority 0)	1974.181	4.7
QSTA 2(priority 1)	1148.807	2.7
QSTA 3(priority 1)	1148.952	2.7
QSTA 4(priority 2)	685.421	1.6
QSTA 5(priority 2)	679.882	1.6
QSTA 6(priority 3)	426.866	1.0
QSTA 7(priority 3)	415.702	1.0

Table 4.9: The average queueing delay of the QSTAs with different priorities with different CW values.

	Average queueing delay(ms)	Normalized to the average queueing delay of QSTA 0
QSTA 0(priority 0)	4527.54	1
QSTA 1(priority 0)	4530.04	1
QSTA 2(priority 1)	8150.97	1.8
QSTA 3(priority 1)	8138.91	1.79
QSTA 4(priority 2)	13712.26	3.02
QSTA 5(priority 2)	13824.37	3.05
QSTA 6(priority 3)	22057.24	4.87
QSTA 7(priority 3)	22671.68	5.00

Table 4.10: The average packet loss rate of the QSTAs with different priorities with different CW values.

	Average packet loss rate
QSTA 0(priority 0)	0.15
QSTA 1(priority 0)	0.15
QSTA 2(priority 1)	0.50
QSTA 3(priority 1)	0.49
QSTA 4(priority 2)	0.69
QSTA 5(priority 2)	0.69
QSTA 6(priority 3)	0.80
QSTA 7(priority 3)	0.80

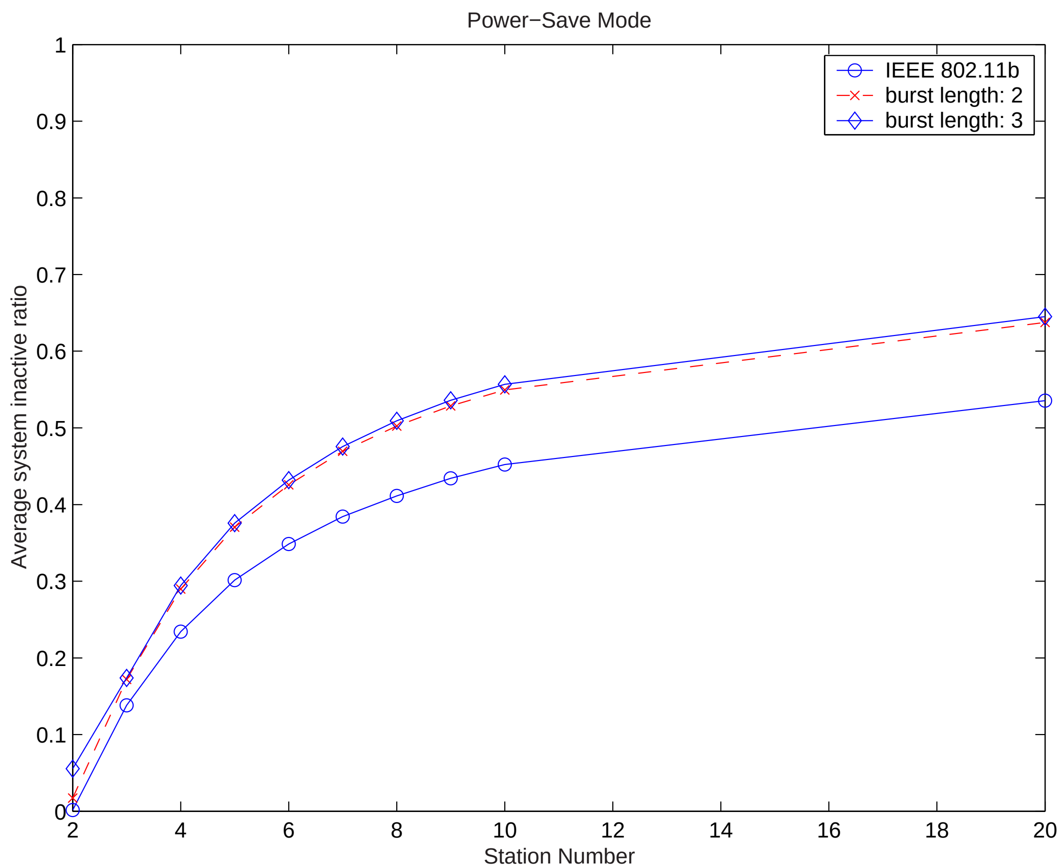

Figure 4.13: Average system inactive ratio versus the number of QSTAs.

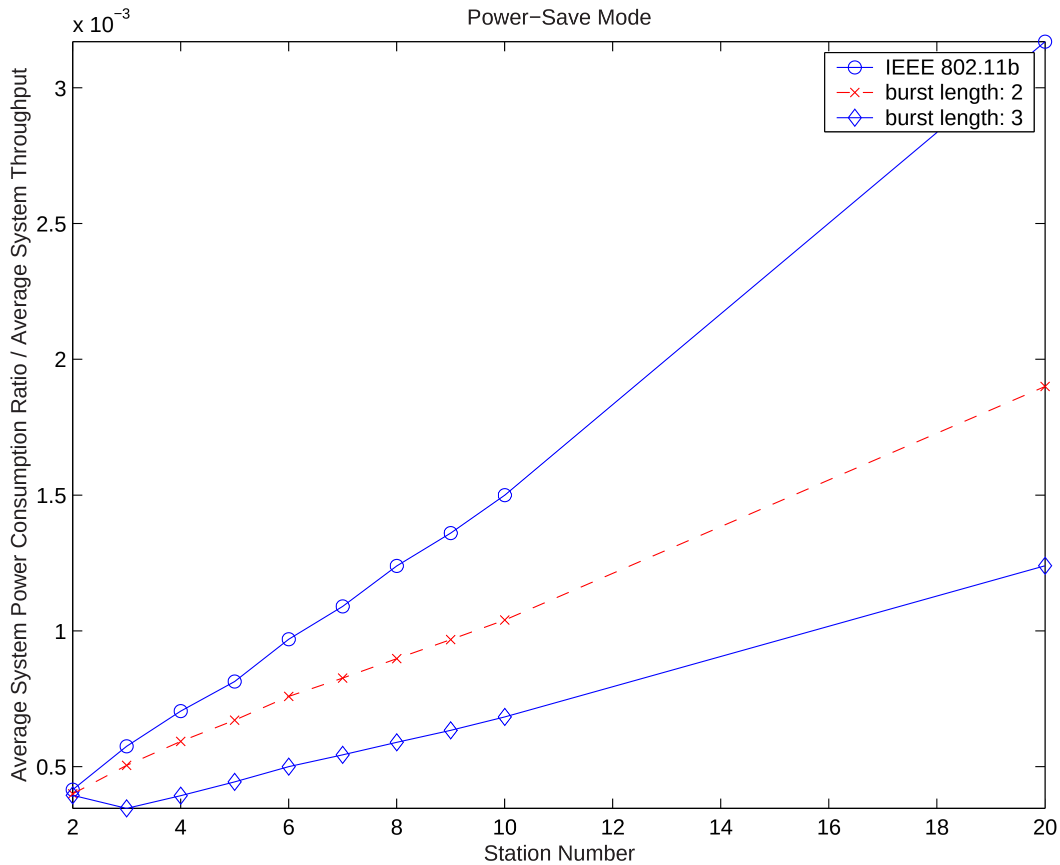

Figure 4.14: Average system power consumption ratio over average system throughput versus the number of QSTAs.

Chapter 5

Conclusions and Future Works

From the simulation results in Chapter 4, we can conclude that the immediate Burst ACK Mechanism without RTS/CTS improves the performance of the legacy IEEE 802.11 network in all three performance indices, although limited. A marked improvement can be obtained if the RTS/CTS exchange is additionally enabled. The simulations on the EDCF imply that by a proper adjustment of CW_{max}, CW_{min} and AIFS, we may statistically fulfill the needs of services with different QoS requirements. In addition, we surprisingly found that the immediate Burst ACK Mechanism with RTS/CTS is indeed more power efficient than the conventional IEEE 802.11b in an ad hoc network.

A straightforward future work is to investigate the performance impact of the HCF and the DLP mechanisms in the draft IEEE 802.11e, which were not completed in this thesis. Further, we can examine the performance of various combination of all these proposed mechanisms, and provide more insight suggestions to future standard.

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