Performance Analysis of Distributed MAC Protocols for Wireless Networks

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

How to improve the radio resource utilization and provide better quality-of-service (QoS) is an everlasting challenge to the designers of wireless networks. As an indispensable element of the solution to the above task, medium access control (MAC) protocols coordinate the stations and resolve the channel access contentions so that the scarce radio resources are shared fairly and efficiently among the participating users. With a given physical layer, a properly designed MAC protocol is the key to desired system performance, and directly affects the perceived QoS of end users.

Distributed random access protocols are widely used MAC protocols in both infrastructure-based and infrastructureless wireless networks. To understand the characteristics of these protocols, there have been enormous efforts on their performance study by means of analytical modeling in the literature. However, the existing approaches are inflexible to adapt to different protocol variants and traffic situations, due to either many unrealistic assumptions or high complexity.

In this thesis, we propose a simple and scalable generic performance analysis framework for a family of carrier sense multiple access with collision avoidance (CSMA/CA) based distributed MAC protocols, regardless of the detailed backoff and channel access policies, with more realistic and fewer assumptions. It provides a systematic approach to the performance study and comparison of diverse MAC protocols in various situations. Developed from the viewpoint of a tagged station, the proposed framework focuses on modeling the backoff and channel access behavior of an individual station. A set of fixed point equations is obtained based on a novel three-level renewal process concept, which leads to the fundamental MAC performance metric, average frame service time. With this result, the important network saturation throughput is then obtained straightforwardly. The above distinctive approach makes the proposed analytical framework unified for both saturated and unsaturated stations.

The proposed framework is successfully applied to study and compare the performance of three representative distributed MAC protocols: the legacy p-persistent CSMA/CA protocol, the IEEE 802.15.4 contention access period MAC protocol, and the IEEE 802.11 distributed coordination function, in a network with homogeneous service. It is also extended naturally to study the effects of three prevalent mechanisms for prioritized channel access in a network with service differentiation. In particular, the novel concepts of “virtual backoff event” and “pre-backoff waiting periods” greatly simplify the analysis of the arbitration interframe space mechanism, which is the most challenging one among the three, as shown in the previous works reported in the literature. The comparison with comprehensive simulations shows that the proposed analytical framework provides accurate performance predictions in a broad range of stations. The results obtained provide many helpful insights into how to improve the performance of current protocols and design better new ones.

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Chapter 1

Introduction

1.1 Wireless Communication Networks

Driven by the vision of communications from anywhere, anytime, various wireless networks such as nation- or continent-wide cellular networks, wireless metropolitan area networks (WMANs) and wireless local area networks (WLANs) have been deployed almost ubiquitously in recent years. Meanwhile, as the Internet has evolved to a worldwide information transport platform, many wireless networks serve as access networks to the Internet. The combination of these two types of networks have greatly promoted the rapid growth of wireless communications and mobile computing around the world.

As the most popular wireless network, cellular networks can provide wide area coverage and seamless roaming. Evolved from the analog technology based first generation (1G), digital technology based second generation (2G) to the current wideband code division multiple access (CDMA) technology based third generation (3G), cellular networks can now provide 144kbps-2Mbps data rate to users in different environments. The next generation (4G) cellular networks may be based on the orthogonal frequency division multiplex (OFDM) technology [64], and are expected to provide high transmission rate of 100 Mbps [35].

The representative WMAN is the emerging worldwide interoperability for microwave access (WiMAX) network [34]. Based on the IEEE 802.16 series standards [47], WiMax networks use the orthogonal frequency division multiple access (OFDMA) and multiple input multiple output (MIMO) technologies [108] and can support data rates up to 75 Mbps in a 20 MHz channel.

Compared with the above two types of networks, WLANs are much easier and cheaper[1] to set up, and usually cover small hotspot areas such as airports, malls, offices, hotels and residential homes. Due to its great success in the past years, the IEEE 802.11 series standards [45] are the *de facto* standards for present WLANs. The current main stream IEEE 802.11g standard uses OFDM technology to provide up to 54 Mbps data rate at the 2.4 GHz band. The next generation WLAN standard, IEEE 802.11n, is expected to provide data rate as high as 200 Mbps using OFDM and MIMO [107]. High data rate WLANs are expected to have higher market share in the next a few years [114].

The above networks with increasingly higher data rates have or will contribute to meeting the rapid growth of demand for wireless access to the Internet. In the development of these networks, the common challenge of how to further improve the resource utilization efficiency and provide better quality-of-service (QoS) attracts great efforts from both industry and academia. Medium access control (MAC) protocols play a critical role in determining the performance of these wireless networks, which directly affects the perceived QoS of end users. In the next section, we give an overview of the prominent wireless MAC protocols.

[1]WLANs operate in the unlicensed Industrial, Scientific and Medical (ISM) bands.

1.2 Wireless Medium Access Control Protocols

A medium access control (MAC) protocol coordinates the nodes in a network and resolves the contention among their accessing the shared medium (the wireless channel in wireless networks) so that the scarce system resources are shared fairly and efficiently [75]. With a given physical layer, a properly designed MAC protocol is the key to desired system performance such as high throughput and short delay.

Wireless MAC protocols can be classified into three categories [16]: random access, guaranteed access and hybrid access protocols. Random access protocols are distributed contention-based protocols that are quite suitable for networks with stations carrying bursty traffic. Classic random access protocols include ALOHA [2], slotted ALOHA [80], and non/p/1-persistent CSMA [55]. To avoid the possible continuous collisions, random backoff policies (e.g., uniform backoff, geometric backoff, binary exponential backoff) have been added to the classic protocols[2]. One resulting protocol family is the various CSMA/CA protocols widely used in WLANs, WPANs and WSNs, etc. The main advantage of the random access protocol are that it does not require a central controller and its relatively simple implementation; while the main disadvantage is that channel idle periods and frame collisions are inevitable, which wastes the valuable channel bandwidth. Guaranteed access are contention-free protocols with which stations access the channel in an orderly manner (via polling or scheduling), and thus a certain level of QoS can be provided. The main overhead

[2]Stations in wireless systems are usually operating in half-duplex mode. Due to the fact that a large fraction of transmitting energy leaks into the receiving path, it is very difficult for a node to receive data reliably when its transmitter is transmitting unless the transmission and reception use different frequency bands. As a result, collision detection is almost impossible and carrier sense multiple access with collision avoidance (CSMA/CA) instead of with collision detection (CSMA/CD) is usually deployed in wireless systems.

of guaranteed access protocols incurs when the polled or scheduled station has no need to use the medium at the moment, which usually occurs to stations with bursty traffic. A hybrid access protocol normally combines the advantages of the random access and guaranteed access protocols to achieve flexibility, efficiency and QoS provisioning [16]. With the hybrid protocols, each station sends a request, using a random access protocol, to the central controller (e.g., the base station in a cellular system or the access point in a WLAN) indicating the time or bandwidth required for its future transmissions. After a request is received, usually the admission control scheme (if exists) decides whether to grant it or not. For the former, the controller allocates time slots and notifies the requesting stations the start time and duration assigned. Later transmissions from these stations are then collision-free. Hybrid MAC protocols are normally deployed in infrastructure-based networks to support a variety of delay-sensitive multimedia applications with satisfactory QoS provisioning.

Due to its flexibility, random access protocols may be used alone in infrastructure-less wireless networks (e.g., mobile ad hoc networks or ad hoc mode WLANs) or be used as part of the hybrid protocols in infrastructure-based wireless networks (e.g., uplinks of cellular or WiMAX systems). In addition, random access protocols can easily incorporate some mechanisms to provide prioritized channel access to different stations [1], which is indispensable for networks providing service differentiation. Since the MAC protocol adopted is critical to not only the system performance but also the perceived QoS of end users in a wireless network, it is important to fully understand the characteristics of the widely used random access protocols. In this thesis, we focus mainly on studying the performance of CSMA/CA based distributed MAC protocols in various wireless networks.

1.3 Performance Modeling Approaches for Distributed MAC Protocols

Performance evaluation of MAC protocols is usually carried out by simulations/field measurements or theoretical modeling approach. While simulation/field measurement studies, usually time consuming, may only address particular scenarios under specific conditions, analytical modeling enables one to gain deeper insight into the characteristics of the protocol.

The performance of MAC protocols is traditionally analyzed by developing stochastic models, often with various assumptions and approximations. In the literature, there are mainly three techniques commonly used in this area, as briefly discussed below. More details of the related work will be given in Chapters 4 and 5.

1.3.1 The *S*-*G* Analysis

The so-called "S-G" approach [87], where S is the carried load and G is the offered load, was widely used in the 1970's-90's to analyze the throughput-delay performance of both slotted and non-slotted multiple access protocols such as ALOHA and CSMA [55, 96, 97, 91, 4, 88, 83]. It assumes an infinite number of nodes collectively generate traffic equivalent to an independent Poisson source with an aggregate mean packet generating rate of S packets per slot, and the aggregated new transmissions and retransmissions are approximated as a Poisson process with rate of G packets per slot. The scenario considered is mainly of theoretical interest in the sense that a practical system has just a finite number of users, each of which usually has a buffer size larger than one as assumed in the S-G analysis. In addition, this technique is usually used only for a homogeneous network.

1.3.2 The Equilibrium Point Analysis

Equilibrium point analysis (EPA) is a fluid-type approximation analysis usually applied to systems in steady state [32, 91]. It assumes that the system always works at its equilibrium point so that the number of users in any working mode is always fixed, i.e., the expected increase in the number of stations in each mode is zero at this point. For its analysis, it requires a set of nonlinear equations, the number of which equals the number of the working modes (e.g., different backoff stages [79, 106] or the frame queue length in the buffer [90, 17]) in the system. When the number of working modes increases, e.g., considering both the backoff stages and the queue lengths, the computing complexity of the EPA approach increases quickly even just for a homogeneous network, which is similar to that of the Markov analysis discussed next.

1.3.3 The Markov Analysis

Compared with the previous two techniques, the Markov analysis is the most widely used one in the performance modeling of MAC protocols. It has been used mainly from two different perspectives:

- *Modeling the system state* — The early works in this category (e.g., [54, 95]) usually consider a simple MAC protocol for a homogeneous system in which the stations have only two states: 1) backlogged, in which a frame is waiting in the buffer for transmission; and 2) thinking, in which the buffer is empty and a frame will be generated according to a Bernoulli experiment. Therefore, those works usually take the number of backlogged stations as the system state to form a one-dimensional Markov chain, and thus the size of the state space equals the number of stations. When the MAC protocols become more complicated, multi-dimensional Markov chains are introduced. For instance, when some multi-stage backoff policies are included in the protocol, a multi-dimensional Markov chain with each dimension representing the number of stations in a corresponding backoff stage can be developed as in [79]. On the other hand, if the protocol defines different behavior for different classes of stations, each dimension of the Markov chain may represent the number of stations in an individual class (e.g., [109] for integrated voice and data system with packet reservation multiple access (PRMA) [37]. Furthermore, Markov analysis may also be extended to consider the buffer status of each station, but only limited to a homogeneous network with a very small number of stations and small buffer sizes [87].

- *Modeling the state of an individual station* — This type of usage of the Markov analysis becomes popular after it appears in the saturation throughput analysis of the IEEE 802.11 DCF in [5, 6]. In this model, the backoff stage and the backoff counter value are combined together to form the state space of the two-dimensional discrete time Markov chain that models the backoff procedure of an individual station in the WLAN. Numerous variants of this model have been proposed for the performance study of DCF (e.g., [110, 15, 104, 19, 31]) and many other protocols such as the IEEE 802.11e EDCA [48, 115, 82, 56], IEEE 802.15.4 [46, 68, 76, 89] and HomePlug [60, 51].

For the Markov analysis, the state transition probabilities of the Markov chain must be found to solve the model. To determine the state transition probabilities, usually the traffic is assumed to be Poisson or Bernoulli so that the memoryless characteristic of the Markov chain is maintained, or the stations are assumed to be saturated as always having at least one frame waiting for transmission. Even with such simplifying assumptions, a common issue in all the above models is the complexity involved in deciding the transition probability matrix for the single- or multi-dimensional Markov chain, especially when the number of states is large. The state space of the Markovian model increases with both the complexity of the protocol studied and the number of stations in the system, which hinders its usage in systems with large station population.

1.4 Motivations and Objectives

Performance study of MAC protocols by means of analytical modeling is helpful for researchers to understand the complex relationships among protocol parameters, find the bottleneck and improve the protocol performance. All these also shed light to future protocol design. It is desirable to have a systematic approach of analyzing the diverse MAC protocols so that their performance can be studied and compared in an efficient manner. However, the existing performance modeling approaches discussed in the previous section are inflexible to adapt to different protocol variants, due to either the many unrealistic assumptions or the high complexity. The main objective of this thesis is to propose a simple and scalable generic performance analysis framework for various CSMA/CA based distributed MAC protocols regardless of the detailed backoff and channel access policies, with more realistic and fewer assumptions, and provide accurate performance predictions. In particular, the objectives of this thesis are to

- extract the common essence of various CSMA/CA based distributed MAC protocols;
- propose a general framework to reflect the common essence of these protocols;

- provide an analytical approach for performance modeling of both saturated and unsaturated stations, with general arrival traffic distributions;
- apply the proposed framework to study the performance of representative distributed MAC protocols in networks with homogeneous service or service differentiation, in terms of average frame service time and network saturation throughput;

1.5 Main Contributions

The main contributions of this thesis are listed as follows:

- Proposal of a three-level renewal process method to model the backoff and channel access behavior of a tagged station in a wireless network with CSMA/CA based MAC protocols;
- Development of a generic analysis framework based on the above method for the performance study of such MAC protocols; the computational complexity of this framework does not scale up with the complexity of the backoff and channel access policies as in other models (e.g., Markov analysis based models in Section 1.3);
- Proposal of a performance modeling approach for unsaturated stations operating in practical networks; the approach also naturally covers the saturated stations as a special case. In addition, it is applicable to station traffic with general frame arrival process. On the contrary, other existing approaches mainly focus on saturated stations that rarely work in reality, and the few reported extensions to those approaches can only handle limited traffic models.

- Performance analysis and comparison of three representative distributed MAC protocols; possible improvements are suggested; the intrinsic relationship among the protocols is also revealed;

- Insights of the different effects of popular service differentiation mechanisms in networks supporting multi-service or with multiple classes of stations; especially, within one framework, different effects of the same mechanism in different traffic situations are revealed for the first time in the open literature. The insights provided by this work will help wireless network designers and operators to select proper service differentiation mechanism(s) for their specific requirements.

1.6 Outline of the Thesis

The remainder of this thesis is organized as follows. Chapter 2 describes the system model, including the wireless networks under consideration and the distributed MAC protocols to be studied. The generic analytical framework for CSMA/CA based distributed MAC protocols is presented in Chapter 3. In Chapter 4, we analyze the performance of three representative distributed MAC protocols in networks with homogeneous service, demonstrating the applications of the proposed framework. Three commonly used service differentiation mechanisms in wireless LANs are analyzed in Chapter 5. Finally, concluding remarks and discussion on future work are given in Chapter 6. The content of this thesis is disseminated in papers [131]–[137].

Chapter 2

System Model

In this chapter, we first present the basic network model that will be used in Chapters 3 and 4, followed by the extended network model that will be studied in Chapter 5. Four representative distributed MAC protocols (three for homogeneous service and one for heterogeneous service) are introduced in the Section 2.2.

2.1 Network Model

A basic network is considered in Chapter 3 for the development of the generic performance model and in Chapter 4 for the analysis of networks with homogeneous service. It is a single-hop wireless network consisting of N functionally identical stations and an optional receiving-only central receiver[1]. Specifically, all the stations are within the transmission range of one another so there are no hidden terminals in the network. The time axis is slotted, and all the stations are synchronized so that all stations start their transmissions only at the beginning of a slot. In addition, all the stations can

[1]This optional central receiver can be the base station in a cellular network (note only uplink is considered), or a data sink in a sensor network, etc.

correctly sense the channel status. Ideal wireless channel without transmission error is assumed so that all transmitted frames may be lost only due to collisions caused by simultaneous transmissions from multiple stations. All MAC frames are assumed to have the same fixed length, which is a widely adopted assumption in MAC protocol analysis [4], and can be easily achieved in practice by commonly used link layer functions, such as fragmentation or concatenation of the upper layer packets. A short acknowledgment (ACK) frame is transmitted by the receiver immediately after every successful MAC frame transmissions, and a negative ACK (NACK) frame is transmitted in respond to a collision. Alternatively, the sending stations will determine that there is a collision if the ACK frame is not received within a timeout period, in which no station other than the receiver is allowed to transmit. In this case, the timeout period can be deemed as if it is occupied by a virtual negative ACK (NACK) frame transmitted by the central receiver. The aggregate transmission time of the MAC frame and the associated ACK or NACK is L slots, and no new transmission from any station will start during this period.

The basic network model described above is extended to a *multi-service* network in Chapter 5 when service differentiation mechanisms are studied. The multi-service network consists of S classes of stations, with N_s stations in each class. MAC frame lengths or the physical layer data rates used by each class may be different. For stations in the same class, the incoming traffic is the same and they receive the same type of service from the network. The optional central receiver in the basic network model can be naturally included in the extended network model, say, as a station of its own class. Thus, the extended network model can represent either an infrastructure-based or an infrastructureless wireless network, and can be used to study networks with a broad range of traffic situations: peer-to-peer traffic only as in an ad hoc network, all uplink traffic over a wireless access channel in a cellular or WiMax network, or either symmetric or asymmetric to-and-from AP traffic in a WLAN [11].

In this thesis, two important performance metrics of MAC protocols are of our primary interest: the average frame service time of an individual station and the network throughput. The former is the most important metric in evaluating the perceived QoS of each station, since it directly determines the service rate for the MAC frames of the station. The latter is obtained as the aggregation of the per station throughput, which can be derived easily if the average frame service time is given. In particular, for the network throughput, we concentrate mainly on the *saturation case* in which every station always has at least one frame in the MAC buffer waiting for transmission. The throughput in this case, *saturation throughput*, is a fundamental performance figure defined as the limit reached by the system throughput as the offered load increases, and represents the maximum load that the system can carry in stable conditions [6]. On the contrary, the network throughput is trivially given by the total incoming traffic load in the *unsaturation case* where none of the stations in the network is saturated. The average frame service time is always studied in both saturation and unsaturation cases.

All the MAC protocols studied in this article belong to the CSMA/CA family. In the sequel, for ease of presentation, a successful channel sensing refers to the event that a station senses the channel and the channel is idle. In contrast, a failed channel sensing or channel sensing failure refers to the event that a station senses the channel which is busy due to transmission(s) from other station(s).

2.2 Four Representative Distributed MAC Protocols

In this thesis, four representative distributed MAC protocols that are widely used in current wireless networks will be studied, and they are briefly reviewed one by one in this section.

2.2.1 The p-persistent CSMA/CA Protocol

As a simple but highly efficient multiple access protocol, the slotted p-persistent CSMA/CA protocol was first proposed in [55]. Since then it has been widely used and its application can still be found nowadays in various networks such as mobile ad hoc network (MANET) [50], vehicular networks [98, 120] and factory control networks [69].

In the slotted p-persistent CSMA/CA protocol, a station will sense the channel when it has a frame for transmission. If the channel is idle, the station transmits the frame with probability p. With probability $1-p$, the station will defer its decision of frame transmission by one slot. If the channel is still idle in the next slot, the station will repeat the above procedure. When the channel is sensed busy, the station waits until the channel becomes idle again and then operates as above. This probabilistic channel access rule can be deemed as that the station follows a geometric backoff policy, and the backoff procedure stops when there is a transmission from other stations and restarts itself after the transmissions ends. From this perspective, this protocol is an exact fit for the proposed analytical model (presented in Chapter 3), and it will be used as a basic example to illustrate the details of the model in Section 4.1.

2.2.2 The IEEE 802.15.4 MAC

The fast growth of public interest in wireless sensor networks and wireless personal area networks (WPAN) in recent years has led to the standardization of the IEEE 802.15.4-2003 [46], which contains a protocol stack targeting at low-power low-rate wireless networks. The standard has been quickly accepted by industry, and many products have appeared in the market since its ratification. In this subsection, we briefly review the MAC protocol specified in the IEEE 802.15.4-2003 standard. More details of the protocol, such as specific parameter settings or physical layer related information, can be found in [46, 127].

The MAC layer in the IEEE 802.15.4 standard specifies two operating modes: an ad hoc non-beacon-enabled mode and a beacon-enabled mode. In the ad hoc mode, nodes in the network use a non-slotted CSMA with collision avoidance (CSMA/CA) mechanism to contend for channel access. If the channel is sensed to be idle, the transmission of a frame will begin immediately; otherwise the node will backoff and try to access the channel in a future slot. This mechanism has been extensively studied in the literature and its performance is well understood [55, 4]. In the beacon-enabled mode, a personal area network (PAN) coordinator transmits a beacon periodically to form the so-called "superframe" time structure, as shown in Figure 2.1. A superframe consists of a beacon that enables the beacon-enabled mode, contention access period (CAP), contention free period (CFP), and an optional inactive portion in which all the nodes may enter a sleep mode to reduce power consumption. The CAP and CFP together form the active portion of the superframe, during which all communication among the nodes should take place. In the CFP, the network coordinator alone controls entirely the contention-free channel access by assigning guaranteed time slots (GTS) to those nodes with their GTS requests granted. The assignment of the GTS to those nodes is determined by the scheduling scheme adopted by the network coordi-

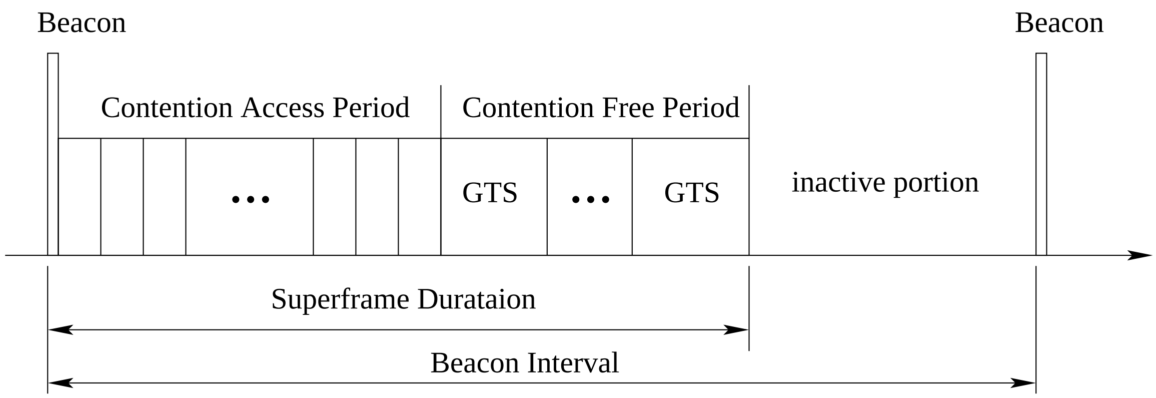


Figure 2.1: IEEE 802.15.4 superframe structure in the beacon-enabled mode

nator, which is open in the standard. Therefore, depending on the specific scheduling scheme used, the performance analysis of CFP is actually the same as that of the well-studied centralized scheduling schemes in cellular systems (e.g., [52, 119]).

In the CAP, a non-persistent slotted CSMA/CA with binary exponential backoff multiple access protocol is defined in the standard. Three variables need to be maintained for each frame before it is successfully transmitted. They are respectively the number of random backoff stages experienced (NB), the current backoff exponent (BE), and the contention window (CW)[2]. According to this protocol, a node with a frame waiting for transmission at the MAC buffer is required to backoff a random number of slots first, with CW set at a value of two. At the end of this backoff stage, the node will do the first channel clear assessment (CCA). If the channel is sensed idle, CW is decremented by one and the node will do the second CCA in the next slot. Only when both CCAs indicate an idle channel (thus CW reaches zero), will the node start the transmission in the next slot; otherwise, it will enter the next backoff

[2]The term *contention window* is the number of slots that the channel has to be sensed idle by a node before its transmission of a frame, which is completely different from the contention window defined in the IEEE 802.11 DCF.

stage and reset CW to two.

The number of backoff slots in stage $NB, 0 \leq NB \leq NB_{\max}$, is drawn from a uniform distribution over $[0, 2^{\mathrm{BE}_{NB}} - 1]$, where $BE_0 = macMinBE$ is the initial and minimum backoff exponent for each frame. $BE_{NB+1} = BE_{NB} + 1$ is upper-bounded by *aMaxBE* which is the default maximum value of backoff exponent, and $NB_{\max}$ is the maximum number of backoff stages allowed for a frame. If all the $NB_{\max}$ backoff stages end up with a busy channel indicated by the associated CCAs, a *Channel Access Failure* event will be reported to the upper layer; the node may then start the above procedure again for the next frame. The standard specifies the following default parameter values: $macMinBE = 3, aMaxBE = 5$ and $NB_{\max} = 5$. Their impact on the protocol performance will be discussed in Section 4.2.5. During the backoff procedure, if the node succeeds in accessing the channel, it will reset the three parameters NB, BE and CW to the default values for initial transmission of the next frame.

In this study, we focus on the contention access period only to illustrate the protocol performance by the proposed analytical model, i.e., the inactive portion and the contention free period in the active portion will not be considered in the superframe time structure. With this protocol, termed CAP-MAC in the sequel, a node will always contend for channel access according to the protocol for CAP, whenever it has a frame to transmit. Therefore, the superframe contains equal-size time slots with fixed length, which is normalized to unit time in the sequel for presentation simplicity. In fact, since the contention access related activities such as backoff counter decrement occurs only in the CAPs and freeze in the CFPs and inactive portion of the superframes, the impact of these two periods on the MAC performance can be taken into our proposed model as having a constant time cost (equal to the aggregate length of the CFP and the inactive portion of a superframe) associated to every A slots, where A is the length of each CAP in units of slots. A similar approach is used in [76], but for generating low duty cycle constant rate traffic as a special case of unsaturated nodes.

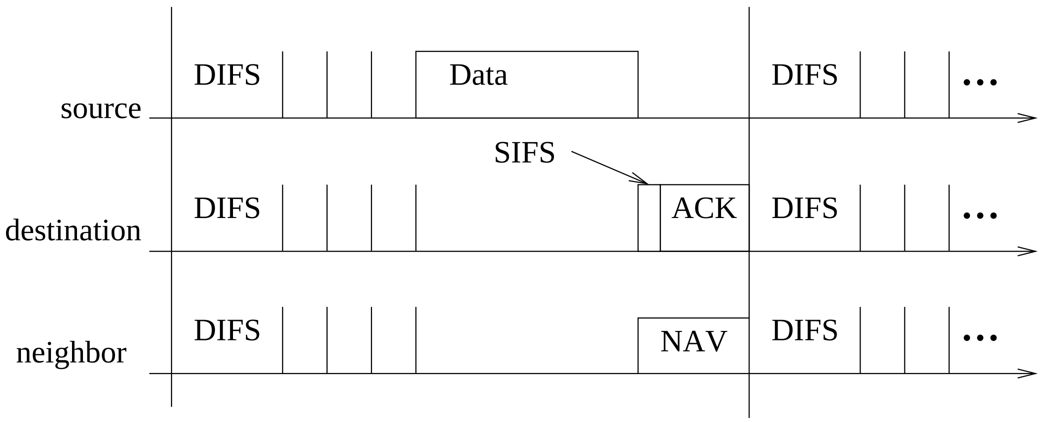
2.2.3 The IEEE 802.11 Distributed Coordination Function

The recent popularity of WLAN is mainly due to the simple and robust MAC protocol specified in the IEEE 802.11 standard, which defines two modes: the mandatory distributed coordination function (DCF) and the optional point coordination function (PCF). Although the PCF is designed for real-time traffic [23, 101], it is not widely deployed due to its inefficient polling schemes, limited QoS provisioning, and implementation complexity [11]. In practice, most of the WLANs deploy DCF as the MAC protocol. Therefore, we will focus on the DCF only in the following.

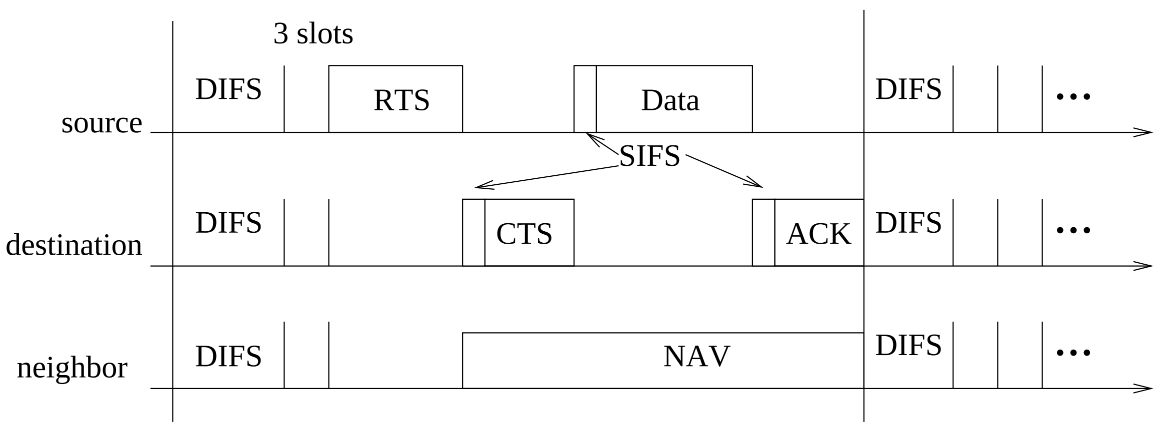
In the standard, DCF specifies the channel access method as follows. Every station adopts the CSMA/CA principle. When a station has a frame at the MAC sublayer buffer, it will first sense the channel. If the channel is busy, it will backoff with a randomly chosen number BO_{slot} of time slots, where BO_{slot} is uniformly distributed over $[0, CW_r)$, and CW_r is the contention window for retransmission stage r. After the channel becomes idle for a duration of DCF-interframe-space (DIFS), the backoff counter counts down for each time slot when the channel is idle. Different from the CAP-MAC described previously, in DCF the backoff counter (BC) freezes when the channel is busy due to a successful transmission or collisions from other stations, and it resumes after the channel turns idle again. When the BC reaches zero, the station will transmit immediately. A station resets its CW to the minimum value $CW_{min} = 32$ after each successful transmission. If two or more stations transmit at the same time slot, a collision occurs and all involved stations will double their CWs, which is upper-bounded by $CW_{max} = 1024$ in the standard, and backoff again. The frame will be discarded if retransmission fails after a pre-defined retry limit, which depends on the frame length.

Usually a sender transmits data frames directly when its backoff counter reaches zero, and the receiver will reply with an explicit acknowledgment (ACK) after a duration of short interframe space (SIFS) if the data frame is successfully decoded (see Figure 2.2(a)). This is called the basic access mode. To improve the efficiency of transmitting long frames, the standard also defines an optional request-to-send/clear-to-send (RTS/CTS) access mode. When the frame length is larger than a threshold, the source station will send out an RTS frame to its intended destination station, which will reply with a CTS frame if the RTS is correctly decoded. After that, the source will transmit the data frame and wait for the corresponding ACK frame from the destination. There are periods of short-interframe-space (SIFS) in between the RTS, CTS, data and ACK frames (see Figure 2.2(b)). As DIFS is longer than SIFS, an ongoing transmission sequence as described above will not be interrupted by a new transmission. In case of a collision, the source stations in the basic mode will wait for duration of $(ACK\_timeout + DIFS)$ before resuming their backoff procedure; in the RTS/CTS mode, the source stations wait a duration with the same length because the CTS frame has the same length as the ACK frame. In both the basic and the RTS/CTS access modes, neighboring stations that detect a collision will defer a duration of extended-interframe-space (EIFS) before resuming their backoff procedure. The EIFS equals the summation of SIFS, DIFS and the transmission time of the CTS or ACK frame with the lowest mandatory transmission rate so that all the stations will resume their backoff procedure at the same time. The CTS/ACK timeout and EIFS mechanism serves as an implicit NACK in DCF. The above timing relationship is illustrated in Figure 2.2(c).

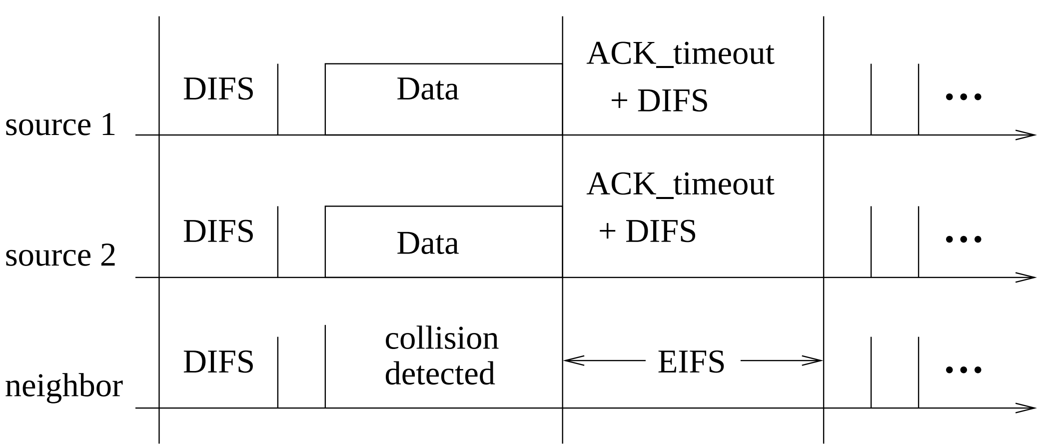
In addition to the above physical carrier sense (PCS) mechanism, a virtual carrier



(a)



(b)



(c)

Figure 2.2: The IEEE 802.11 DCF channel access mechanisms

sense (VCS) mechanism is also introduced in the DCF. It is implemented by means of the so-called network allocation vector (NAV), which is maintained by every station that is not currently involved in any transmission or reception of frames. Each such station may set the NAV according to the information in the Duration/ID field of the RTS or Data frame. In the RTS/CTS mode, stations may reset its NAV (to zero) if a transmission does not start during a period with a duration of $(2\,SIFS{+}CTS{+}2\,Slot)$ after the NAV is set according to the duration value of the RTS frame[3]. Before the NAV expires, the station may stop the physical carrier sensing activity to save energy.

2.2.4 The IEEE 802.11e Enhanced Distributed Channel Access Mechanisms

In the widely deployed IEEE 802.11 based WLANs, DCF is the dominant MAC protocol, which guarantees an equal long term channel access probability to all stations [41]. When heterogeneous applications coexist in a WLAN, the DCF MAC is inefficient in protecting Quality-of-Service (QoS)-critical applications (e.g., real-time voice sessions or teleconferences) from the QoS-resilient applications (e.g., emails). Aiming to enhance the QoS provisioning demanded by multimedia services in WLANs, the IEEE 802.11e amendment [48] to the legacy IEEE 802.11 standard was released recently. In this standard, the newly defined enhanced distributed channel access (EDCA) supports service differentiation mainly by distributed prioritized channel access among different access categories (ACs) with three AC-dependent parameters: contention window (CW), transmission opportunity (TXOP) and arbitration interframe space (AIFS). The details of their usage are given below and their service differentiation

[3]This does not occur in the single-hop network studied in this work because all the neighboring stations either correctly set the NAV and the source station will surely transmit within the specified duration, or the NAV is not set due to a collision.

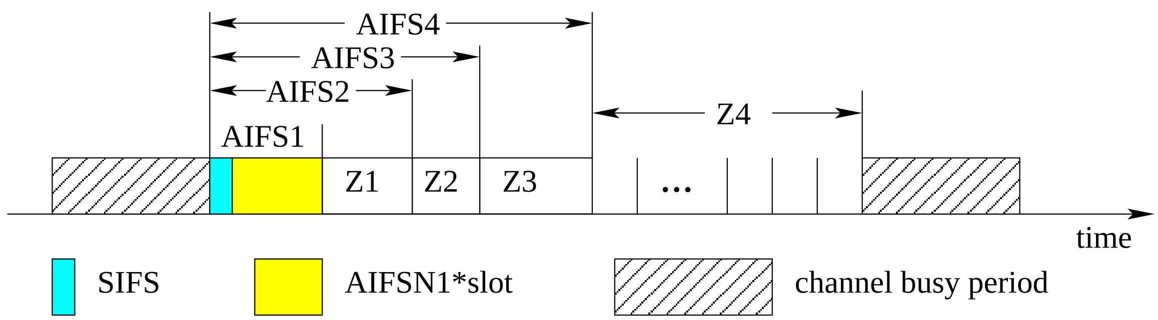


Figure 2.3: An illustration of prioritized channel access for different station classes

effects are analyzed in Chapter 5.

In the EDCA, user traffic is first classified into multiple ACs, such as voice, video, best-effort and background. Each station regulates its frame transmission using the contention parameters associated with each AC. When a station has a frame at the MAC sublayer buffer, it will first sense the channel. If the channel is busy, it performs the backoff procedure by first setting the backoff counter to an integer sampled from the minimum CW size. Therefore the first differentiation mechanism is to assign higher priority ACs with a smaller value of minimum CW size such that higher priority ACs statistically spend less time on backoff. After the channel becomes idle for the AC-dependent AIFS, the station can count down the backoff counter at the beginning of each idle slot and also the first slot of a channel busy period. Since the higher priority ACs are assigned with smaller value AIFS, they obtain higher chances to access the channel than low priority ACs. Fig. 2.3 shows an example of four ACs, where AC_1 has the highest priority. To illustrate the effect of different AIFS lengths, the time between two busy periods, except $AIFS_1$, is divided into four contention zones, $Z_i, i = 1, 2, 3, 4$. In Z_1, only AC_1 stations are allowed to contend for channel access, while in Z_2 the contentions are between AC_1 and AC_2, i.e., contentions in Z_i involve $AC_j, j \leq i$. Consequently, each AC encounters different contentions in its allowable contention zones. After one station succeeds in contending for channel access, it can transmit for a duration up to the TXOP. Different TXOP durations can be assigned to different ACs to further differentiate the service. The three mechanisms may be used individually or be combined together.

Chapter 3

A Generic Performance Analysis Framework for Distributed MAC Protocols

3.1 Introduction

A simple yet accurate analytical model is proposed in this chapter to analyze the performance of a family of carrier sense multiple access with collision avoidance (CSMA/CA) based MAC protocols commonly used in wireless networks. We model the behavior of an individual station instead of modeling the channel. The proposed model is based on a novel concept of *three-level renewal process*, the key parameter of which can be solved by the fixed point technique. The new modeling approach significantly simplifies the mathematical analysis, where the important performance metrics of MAC throughput (of individual station or the whole network) and the average frame service time can be directly obtained. The proposed model is a general framework which is applicable to CSMA/CA based MAC protocols with various backoff procedures and channel access policies.

In the remainder of this chapter, we first present the three-level renewal process which is the core of the analytical framework. Following that, the MAC performance analysis based on it is given. Finally, we present two extensions of the basic framework.

3.2 Renewal Process Based Framework

In a steady state network with a CSMA/CA based MAC protocol as described in Chapter 2, a randomly tagged station contends for the channel access following the same rule for each frame, *i.e.*, it uses the same initial parameters pertaining to the backoff, transmitting and possible retransmitting processes for each frame. Therefore, the channel access process of an individual station is regenerative with respect to the time instants of the completion of its each successful frame transmission. The period between two consecutive successful frame transmissions from the same station thus forms a renewal cycle in a renewal process [70], which directly relates to some important MAC performance metrics such as MAC throughput and average frame service time. This key observation inspires the derivation of the basic analytical model presented below.

3.2.1 Three-Level Renewal Process

For many CSMA/CA based MAC protocols, a hierarchical three-level renewal process, as illustrated in Fig. 3.1, can model precisely the behavior of a tagged station. A common characteristic of these protocols is that a certain form of backoff procedure is required before a station can access the channel, and the backoff procedure may be

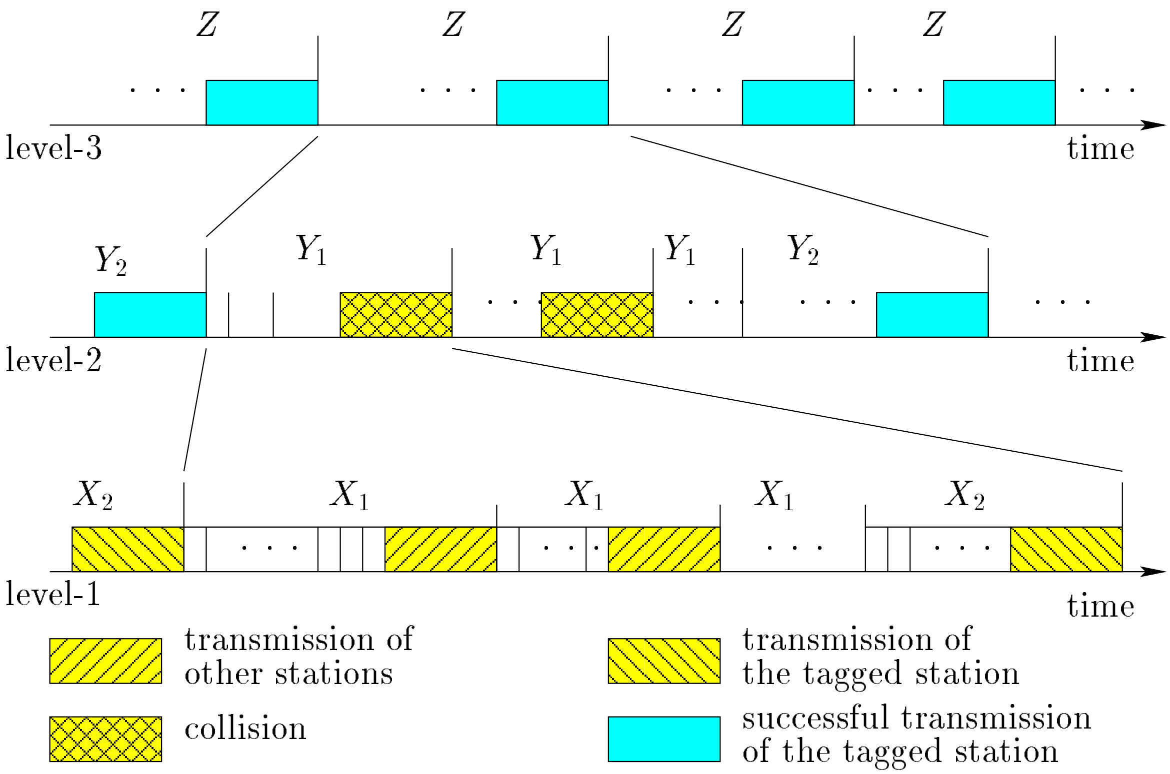


Figure 3.1: Illustration of the concept of 3-level renewal process

interrupted usually by transmissions from other stations and resume after the channel becomes idle again. The time instants that the backoff procedure resumes (or restarts itself) can naturally be viewed as basic renewal points. Over a larger time scale, the end of each transmission from the tagged station is a higher level of renewal point of the frame service process. If the time scale is even larger, the renewal points can also be set at the end of each *successful* transmission from the tagged station, which delimit the important highest level renewal cycle as identified earlier.

In Figure 3.1, a level-1 renewal cycle X is defined as the period between the end of a channel busy event to the end of the next one. There may be a number of idle slots in which no station transmits between two consecutive channel busy events.

From the viewpoint of the tagged station, a level-1 cycle is of type X_1 if the busy channel is caused by transmission from other stations, and it will be of type X_2 if its own transmission causes the channel busy. Notice that the transmission in an X_2 level-1 cycle may be a successful transmission or a collision due to the simultaneous transmissions from other stations.

A level-2 renewal cycle Y is from the end of an X_2 cycle to the end of the next X_2 cycle. As shown in Fig. 3.1, there can be U ($U \geq 0$) X_1-cycles before the X_2-cycle. Depending on the result of transmission in the X_2-cycle included, a level-2 cycle can be either of type Y_1, in which the transmission results in a collision, or of type Y_2, in which the transmission succeeds.

Finally, a level-3 renewal cycle Z is from the end of a Y_2 level-2 cycle to the end of the next Y_2 cycle. Similarly, there can be $V, V \geq 0$, Y_1 cycles before the Y_2 cycle. Therefore, the successful transmission of a frame in the Z cycle can be viewed as the reward for the level-3 renewal cycle. The throughput of the tagged station can thus be obtained as the average reward in a Z cycle.

3.2.2 MAC Performance Analysis

As an important MAC performance metric, the average frame service time (or access delay) ζ, is defined as the average duration from the instant that a frame becomes the head-of-line at the MAC buffer to the end of its successful transmission. As can be seen, ζ is exactly the average length of the level-3 renewal cycle in the proposed analytical model. The normalized throughput obtained by an individual station, per station MAC throughput, is the ratio of the transmission time of the MAC frame over ζ, and the saturation throughput of the network is thus simply the aggregation of the per station throughput.

To obtain the average length of the level-3 cycle, we need to find out the characteristics of the random variables that determine the structure of the whole hierarchical renewal process. Depending on the specific channel access policies, the basic fixed point equations extracted from the analysis of level-1 cycles may be slightly different for different MAC protocols. After the average length of a level-1 cycle $E[X]$ has been obtained, however, the analysis of the other two levels is shared by different protocols, which is one of the advantages of the proposed framework.

As shown in Figure 3.1, a level-2 cycle contains a number U of type X_1 cycles and an ending X_2 cycle, where U follows a geometric distribution with parameter P_{tx}, which is the probability that a level-1 cycle is of type X_2. Therefore, the average length of a level-2 cycle is

$$E[Y] = \frac{E[X]}{P_{tx}}. \tag{3.1}$$

Similar to the case in a Y cycle, the number of level-2 cycles contained in a level-3 cycle also follows a geometric distribution, but with parameter P_{suc}, which is the probability that a transmission from the tagged station is successful. Thus, the average length of a level-3 cycle is

$$E[Z] = \frac{E[Y]}{P_{suc}}. \tag{3.2}$$

Notice that $E[Z]$ equals the average frame service time ζ. Therefore, in the remainder of this dissertation, $E[Z]$ and ζ will be used interchangeably. Since there is only one successful MAC frame transmission from the tagged station during a level-3 cycle, the normalized per station throughput is directly given by

$$\eta_s = \frac{L}{E[Z]}, \tag{3.3}$$

and the aggregated throughput in a homogeneous network is thus

$$\eta = N\eta_s. \tag{3.4}$$

In the above analysis, the detailed expressions of P_{tx} and P_{suc} depend on the specific backoff procedure and channel access policy defined in the protocol being studied. Since there is no assumption on the backoff procedure, the proposed analytical framework is applicable to protocols with various backoff procedures as long as the procedure restarts itself for each MAC frame.

3.3 Discussion

To simplify the presentation of the development of the above framework, we have implicitly assumed that the network is composed of saturated stations with only one type of service. In what follows, we discuss two extensions of the framework with this assumption relaxed.

3.3.1 Modeling Unsaturated Stations

The above analysis is directly applicable for a network with saturated stations. The throughput in this case, *saturation throughput*, is a fundamental performance figure defined as the limit reached by the system throughput as the offered load increases, and represents the maximum load that the system can carry in stable conditions [6]. It is of theoretical importance to obtain this MAC performance metric. In practice, a network with saturated stations corresponds to the case when some delay-insensitive data applications (such as bulk file transfer through FTP) running on the stations.

With multimedia applications that usually generate bursty traffic, a station may work in the unsaturated situation in which the MAC buffer may be empty from time to time. The proposed analytical framework can also be applied to the analysis of unsaturated stations. In this case, a station will contend to access the channel only when it has a frame in the buffer waiting for transmission, which occurs with the probability of having a non-empty buffer. For a station usually having a MAC buffer that can accommodate tens of frames (which is in effect almost a lossless queueing

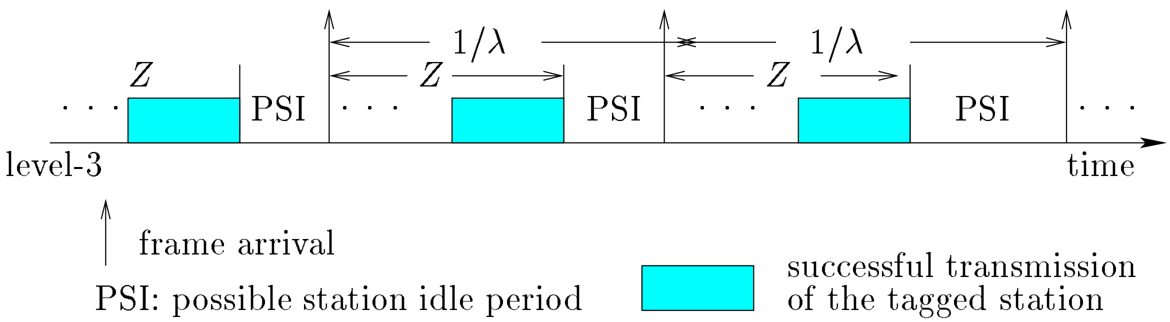


Figure 3.2: The level-3 cycle for unsaturated stations

system in practice), this probability can be satisfactorily approximated by the ratio of the average frame service time ζ' over a given average frame inter-arrival time $1/\lambda$. Since the proposed framework is developed from the viewpoint of a busy station, *i.e.*, it does have a frame in service, ζ' can be obtained from the above analysis for saturated stations with just slight changes reflecting the effects of the aforementioned probability to the contention behavior of other stations. The details of this extension can be found in the application instances in Chapter 4.

More specifically, the level-3 cycle for an unsaturated station is slightly different from the one for a saturated station. As shown in Figure 3.2, the level-3 cycle Z is changed to the period between the instant of a frame arrival to the one when it is successfully transmitted. Between two Z cycles, there exists a possible station idle period (PSI) if the MAC buffer becomes empty after the current frame is transmitted. The PSI can be of length zero, *e.g.*, when at least one more frame is waiting in the buffer. Since the tagged station is always busy in a Z cycle, the same structure of the lower two level renewal cycles still applies to the Z cycles as in the basic model in Figure 3.1.

3.3.2 Modeling Networks with Service Differentiation

The analysis and discussion up to this point are for networks with homogeneous services in which all the stations carry the same type of traffic and follow the same backoff and channel access policy with same relevant parameters. In practice, wireless networks are usually designed and operated to provide heterogeneous services to users. In addition, service differentiation is either a required or desired feature. In such networks, stations may carry different types of traffic, with backoff and channel access policies using different parameters determined by their service requirements.

The proposed analytical framework can be readily extended to the analysis of networks with service differentiation. We may select one tagged station from each service class and analyze them respectively according to the proposed framework. This is because the framework is developed from the viewpoint of any tagged station, and the effect of all the other stations are effectively reflected by the success or failure of the frames transmitted and the channel status seen by the tagged station. As explained earlier, usually a set of fixed point equations can be obtained for one tagged station. For K classes of stations, we may obtain K sets of equations which are interconnected among one another. These equations can be solved numerically to obtain the key parameters for further derivation of the desired MAC performance metrics. Several types of service differential mechanisms commonly used in current wireless networks are studied in Chapter 5.

3.4 Summary

We have proposed a simple yet accurate (as will be shown in later chapters) analytical framework for CSMA/CA based MAC protocols. By proposing a novel hierarchical three-level renewal process mechanism, we can describe and analyze the protocols in a straightforward manner. Two important MAC protocol performance metrics, the per station throughput and the average frame service time, are obtained immediately, due to the direct relationship between the level-3 renewal cycle and the frame service time. We have also discussed the extension of this framework to the analysis of networks with unsaturated stations and/or with service differentiation. The only assumption made in developing the proposed analytical framework is that a station restarts its backoff procedure upon serving a new MAC frame, regardless of the detailed parameter changing mechanisms of the backoff procedures. Therefore, the framework has a wide applicability to a family of CSMA/CA based MAC protocols. In the next chapter, application instances are given for networks with homogeneous service to show the usage details of the framework.

Chapter 4

Networks with Homogeneous Service

For CSMA/CA based protocols, the hierarchical three-level renewal process based analytical framework proposed in Chapter 3 makes the performance analysis easy to follow. The representative protocol is the legacy slotted p-persistent CSMA/CA [55]. Other good examples include the MAC protocol for the contention access periods of the IEEE 802.15.4 standard [46], and the *de facto* standard MAC protocol for WLANs, IEEE 802.11 distributed coordination function (DCF).

In the remainder of this chapter, we first study the legacy slotted p-persistent CSMA/CA protocol, followed by the analysis of the IEEE 802.15.4 MAC and the IEEE 802.11 DCF, respectively. We then compare the performance of the three protocols with same input traffic in Section 4.5. In each of the first three sections, the basic analysis for saturated stations is given first, followed by the analysis for unsaturated stations and some numerical results for performance evaluation.

For presentation simplicity, we will use the same notations for the key variables such as $E[X], E[Y], E[Z], P_{tx}$, and P_{suc} in the analysis of the different protocols when there is no confusion from the context. Self-explanatory subscripts are applied to the variables in Section 4.5 to avoid ambiguity.

4.1 The p-persistent CSMA/CA Protocol

According to the protocol description in Section 2.2.2, the probabilistic channel access rule of the p-persistent CSMA/CA protocol can be deemed as that the station adopts a geometric backoff policy. This backoff procedure stops when there is a transmission from other stations and restarts itself after the transmissions ends. A level-1 cycle is thus the period between the two instants when the backoff procedure restarts. From this perspective, this protocol is an exact fit for the proposed three-level renewal process model. With the given parameter p, the mean length of a level-1 cycle can be obtained straightforwardly, and so do the average lengths of level-2 and level-3 cycles by following the approach outlined in Section 3.2.2.

4.1.1 Analysis of Saturated Stations

As explained above, starting from the first idle slot after a channel busy period either caused by a successful frame transmission or a collision, the stations will backoff according to the geometric backoff procedure with the parameter p. The channel is sensed idle in a slot only when none of the stations transmits, which occurs with probability

$$q = (1 - p)^N, \tag{4.1}$$

otherwise the channel becomes busy. Therefore, the number of consecutive idle slots preceding the channel busy period follows a geometric distribution with parameter

$1-q$. The average number $E[I]$ of idle slots *preceding a busy slot* is thus given by

$$E[I] = \frac{q}{1-q}. \tag{4.2}$$

Notice that the ending part of a level-1 cycle is a busy channel period with length of L slots. The average length of a level-1 cycle is thus given by

$$\begin{aligned} E[X] &= E[I] + L \\ &= \frac{L-(L-1)(1-p)^N}{1-(1-p)^N}. \end{aligned} \tag{4.3}$$

As explained in Section 3.2.1, a level-1 cycle is of type X_2 if the ending transmission block involves a transmission from the tagged station. Given that there is at least one station transmits, the conditional probability that the tagged station transmits in a level-1 cycle is

$$\begin{aligned} P_{tx} &= \Pr\{\text{the tagged station transmits} \mid \text{at least one station transmits}\} \\ &= \frac{\Pr\{\text{the tagged station transmits, at least one station transmits}\}}{\Pr\{\text{at least one station transmits}\}} \\ &= \frac{p}{1-(1-p)^N}. \end{aligned} \tag{4.4}$$

Among the level-2 cycles, the transmission from the tagged station will be successful only when none of the other $N-1$ stations transmits in the same slot. This occurs with probability

$$P_{suc} = (1-p)^{N-1}. \tag{4.5}$$

Substituting (4.3) – (4.5) into (3.1) – (3.4), we obtain the average length of the level-3 cycle

$$E[Z] = \frac{L-(L-1)(1-p)^N}{p(1-p)^{N-1}}, \tag{4.6}$$

the per station throughput

$$\eta_s = \frac{Lp(1-p)^{N-1}}{L-(L-1)(1-p)^N}, \tag{4.7}$$

and the network throughput

$$\eta = \frac{NLp(1-p)^{N-1}}{L-(L-1)(1-p)^N}. \tag{4.8}$$

4.1.2 Analysis of Unsaturated Stations

For unsaturated stations, the following analysis is carried out as outlined in Section 3.3.1. In the sequel, the superscript $'$ will be added to relevant variables to indicate the unsaturated analysis.

Consider a generally distributed traffic with average frame inter-arrival time $1/\lambda$ slots at the MAC layer buffer of a station. Denote $E[Z']$ the average frame service time in slots. The key is that an unsaturated station will contend for channel access only with probability

$$\rho = \lceil \lambda \cdot \zeta' \rceil^1 = \lceil \lambda \cdot E[Z'] \rceil^1, \tag{4.9}$$

where $\lceil x \rceil^1$ is the smaller of x or one, which is necessary because ρ can reach its upper bound of one if the frame service time is longer than the average frame inter-arrival time, which corresponds to the saturated case analyzed previously.

Notice that the three-level renewal process model is developed from the tagged station's viewpoint, with the condition that the station is serving a frame, *i.e.*, it is contending for channel access with other busy stations. With this condition taken into consideration, the channel is idle in a slot with probability

$$q' = (1-p)(1-p\rho)^{N-1}. \tag{4.10}$$

Accordingly, the average length of a level-1 cycle is changed to

$$E[X'] = \frac{L-(L-1)(1-p)(1-p\rho)^{N-1}}{1-p(1-p\rho)^{N-1}}. \tag{4.11}$$

Given that the tagged station is contending for channel access, the conditional probability that it transmits in a level-1 cycle is given by

$$P'_{tx} = \frac{p}{1 - (1-p)(1-p\rho)^{N-1}}, \tag{4.12}$$

and the probability of successful transmission is

$$P'_{suc} = (1-p\rho)^{N-1}. \tag{4.13}$$

With the above results, we can obtain the average length of the level-3 cycle as

$$E[Z'] = \frac{L - (L-1)(1-p)(1-p\rho)^{N-1}}{p(1-p\rho)^{N-1}}, \tag{4.14}$$

and the per station throughput

$$\eta'_s = \frac{Lp(1-p\rho)^{N-1}}{L - (L-1)(1-p)(1-p\rho)^{N-1}}. \tag{4.15}$$

Since the stations are unsaturated, the network throughput is not the summation of per station throughput as for the saturated stations, but equals the total incoming traffic, *i.e.*,

$$\eta' = NL\lambda. \tag{4.16}$$

Given N, L, λ and p, equations (4.9) and (4.14) can be solved numerically. If λ is too large such that the average frame service time $\zeta' = E[Z']$ becomes larger than the average frame inter-arrival time $1/\lambda$, the station enters the saturated situation, *i.e.*, ρ will be set to one and equations (4.10) – (4.15) reduce to their corresponding versions for saturated stations (4.1) – (4.7).

4.1.3 Numerical Results

In order to verify the accuracy of the analytical results given by the proposed framework, computer simulations[1] have been conducted and simulation results are compared to analytical ones. The network simulated is basically the same as described in

[1] The simulator is written in C language.

Chapter 2. We have simulated an ideal channel without transmission errors, mainly because the effect of such errors to the performance is not studied in our work[2]. The assumption of an unbreakable channel busy period of L slots caused by the frame and ACK/NACK transmissions is slightly relaxed in the sense that L can be a non-integer in the simulation. The stations are synchronized again at the end of each L slots, so the time slot boundaries are not always fixed-length apart as in the analysis. For unsaturated stations, we have tested Poisson and constant bit rate (CBR) arrival traffic with the same average inter-arrival time in each case simulated. In particular, the initiating times for the CBR traffic are uniformly distributed over the average inter-arrival time period in different simulation rounds. For all the simulation results presented in this thesis, each data point shown in the figures is the mean result of at least 20 rounds of simulations with different random number generator seeds, and each round of simulation lasts for successful transmission of at least $100,000$ frames.

We have run two groups of simulations to verify the accuracy of the analysis for the p-persistent CSMA/CA protocol with saturated stations. One group is for $L = 10$ and the other group is for $L = 100$. The number of stations in the network varies from $N = 5$ to 60, with three different values of $p:$ 0.005, 0.01 and 0.05, respectively.

The normalized network throughput η is shown in Figure 4.1. With the same pair of p and N, the network throughputs of $L = 10$ and $L = 100$ are remarkably different. For instance, with $p = 0.005$, the throughput for the former increases with N when $N < 60$ while that for the latter increases only when $N < 35$ and then starts to decrease. In addition, the maximum network throughput that can be achieved by different L differs as well. From the figure, the maximum η for $L = 10$ is about 0.63 while that for $L = 100$ can reach about 0.9. We will study the maximum network throughput of p-persistent CSMA/CA protocol in detail in Section 4.5.1.

[2] It can be easily included in our framework following the approach in [24, 128]

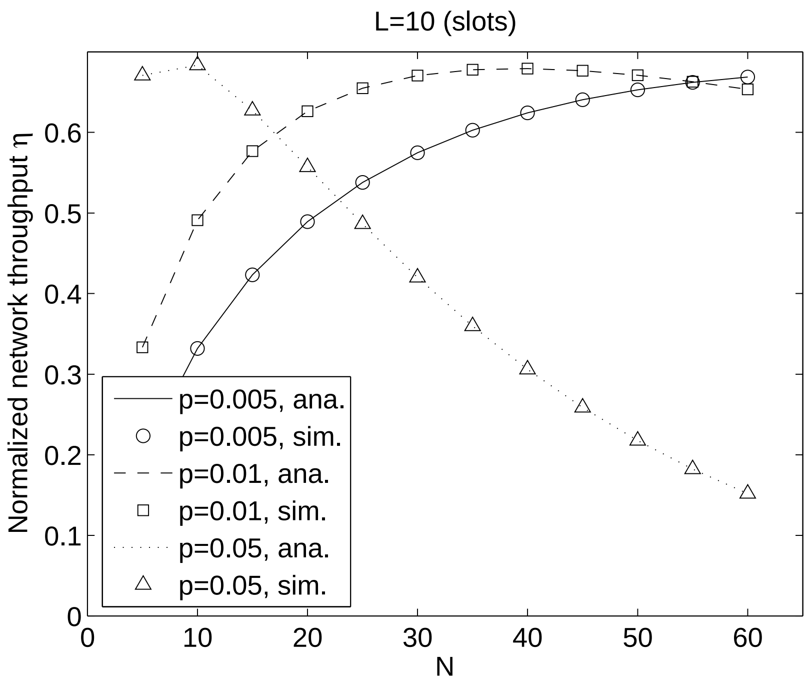
The average MAC frame service time ζ is shown in Figure 4.2. It can be observed that, in contrast to the network throughput, ζ always increases with N for a given pair of p and L. In addition, ζ for $L = 100$ is always larger than $L = 10$ for any given pair of p and N, which is in fact clearly shown in (4.6).

The above results show that a larger L leads to a higher network throughput, but the frame service time will increases as well, which is usually undesirable in practice. Therefore, a proper trade-off between network throughput and average frame service time of individual station should be made, with the requirements from both network service provider and end users taken into consideration.

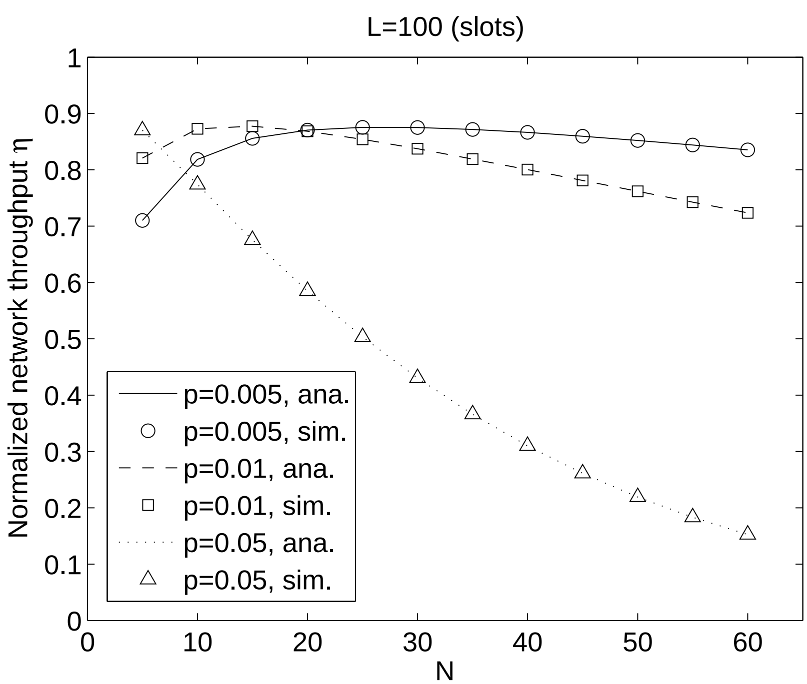
We have also studied the protocol performance when the stations are unsaturated. In the simulations, each station in the network carries a Poisson arrival traffic with mean rate λ frames/slot, although the analysis is valid for a general arrival traffic type.

Figure 4.3(a) shows the average frame service time ζ' versus the average traffic arrival rate λ with $L = 10$ and $p = 0.05$ for station population $N = 10$ and 20, respectively. Define the maximum average traffic arrival rate that keeps the stations in the unsaturated state, *i.e.*, $\lambda\zeta' < 1$, as the *sustainable rate*. For the same L and p, the sustainable rate is roughly halved when N is doubled. In addition, when λ approaches the sustainable rate, the average frame service time ζ' increases steeply for $N = 20$. In contrast, a gradual increase of ζ' in the corresponding situation is observed for the case of $N = 10$. This is because the increment of λ for an individual station brings the network traffic increment proportional to N. The heavier the network traffic load, the severer the channel contention, and thus the longer average frame service time.

Figure 4.3(b) shows the relationship between ζ' and N when different L and λ are given. Compared with the case of a small L, a steeper increase of ζ' is observed for

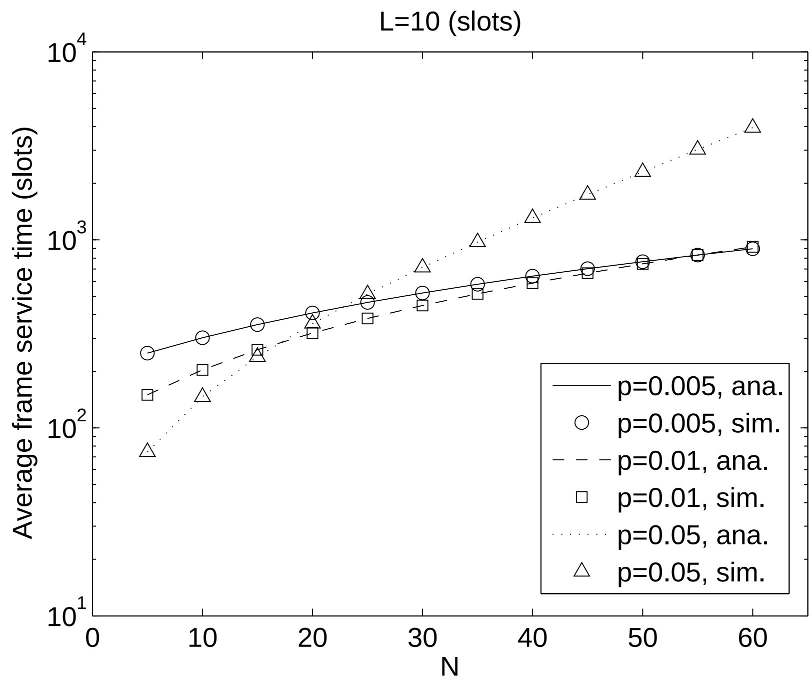


(a)

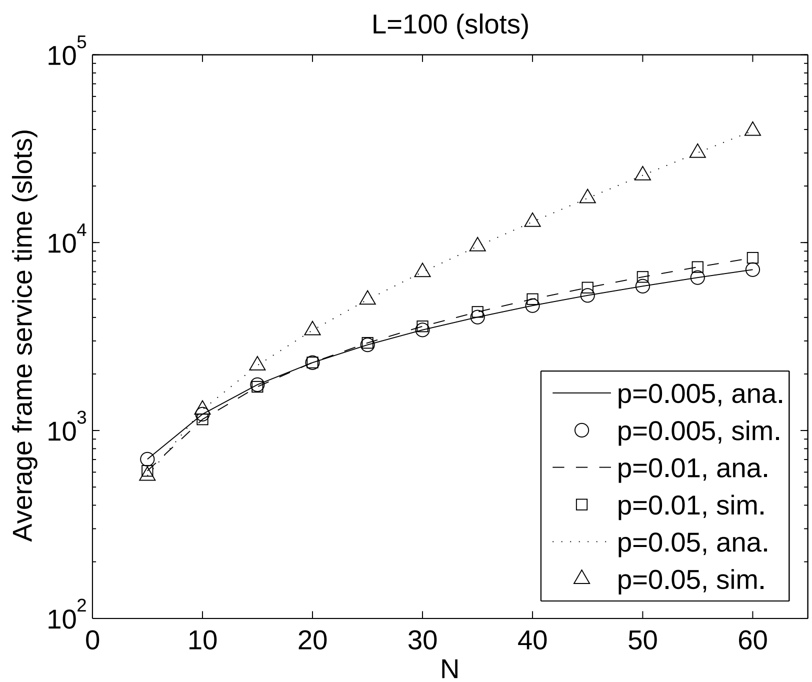


(b)

Figure 4.1: Saturation throughput of p-persistent CSMA/CA protocol

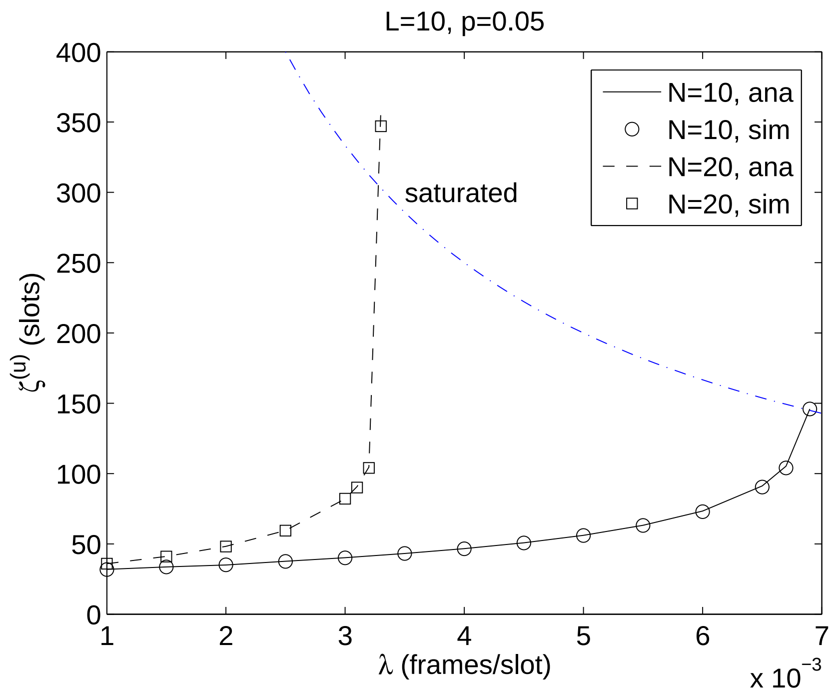


(a)

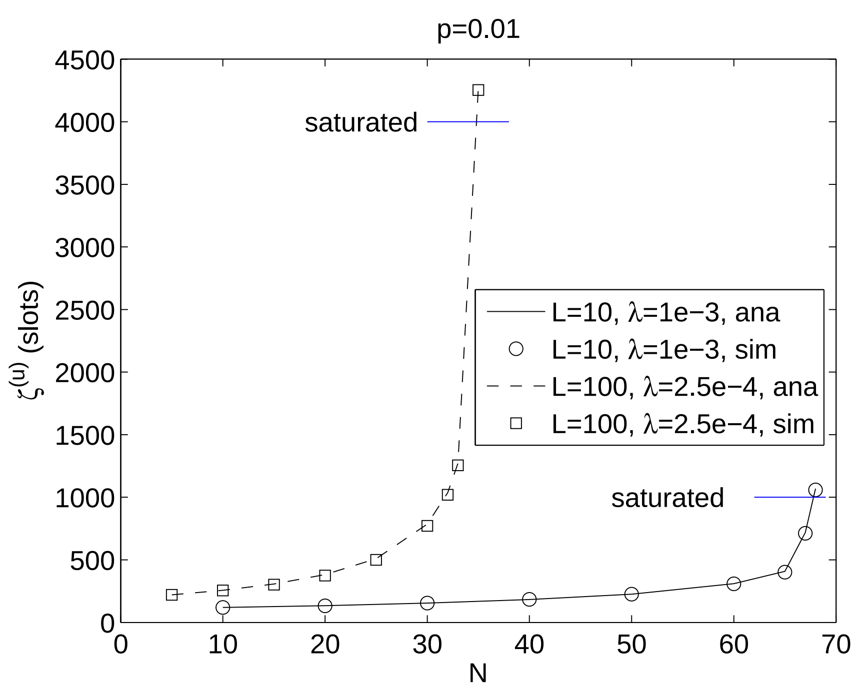


(b)

Figure 4.2: Average frame service time for saturated stations with p-persistent CSMA/CA protocol



(a)



(b)

Figure 4.3: Average frame service time in unsaturated case of p-persistent CSMA/CA protocol

a large L, even with reduced λ and smaller N.

In fact, two applications of the proposed analytical model for unsaturated stations have been demonstrated in Figure 4.3. For a network with given number of stations, we can obtain the sustainable rate for each station, as shown in Figure 4.3(a). On the other hand, with a given per station average traffic arrival rate, we can also determine the maximum number of stations that can be admitted into a network (usually called *admission region*), as shown in Figure 4.3(b). Such results are very useful to the design of the call admission control scheme, which is usually an indispensable element in a network with QoS provisioning capability.

Inspection of Figures 4.1-4.3 shows that the analytical results approximate the simulation results very well in all cases, even though the analytical and simulation models are not identical, as mentioned earlier in this subsection. The reason for this can be attributed to the fact that the performances shown are average values. Therefore, for the p-persistent CSMA/CA protocol, analytical results will be given without further comparison to simulation results in the remainder of the this chapter.

4.2 The CAP-MAC in IEEE 802.15.4

4.2.1 The Basic Analysis

According to the channel access policy of this protocol (see Section 2.2.2), the renewal point of the level-1 renewal cycle can be set when a station resets its contention window to the minimum value after each transmission trial (regardless of the result) or when it senses a busy channel at the end of the Mth backoff stage. Correspondingly, in Figure 4.4, a level-1 renewal cycle is defined as the period between the two adjacent time instants that the tagged station starts a stage 0 backoff. Although the renewal points are different from those in the model for the slotted p-persistent CSMA/CA

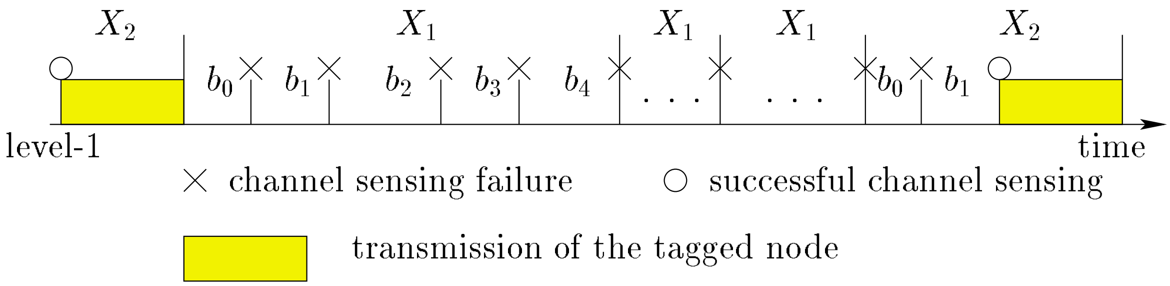


Figure 4.4: The level-1 renewal cycle for IEEE 802.15.4 MAC

protocol, level-1 renewal cycles in this case can still be classified into two types, as illustrated in Figure 4.4. The X_1 type is a cycle that includes no transmission from the tagged station, resulting from M channel sensing failures. In contrast, the X_2 type is a cycle that contains a period L of transmission from the tagged station, after experiencing m backoff stages, $0 \leq m \leq M$. Again, the ending points of the X_2 cycles delimit the level-2 cycles as in the basic model. Also, the transmission in an X_2 cycle may be a successful transmission or a collision due to the simultaneous transmissions from other stations. Thus, the level-2 and level-3 renewal cycles remain the same as in the basic model (Figure 3.1). Note that the difference in the level-1 cycle modeling from the one for p-persistent CSMA/CA results from the fact that the backoff period of the tagged station overlaps with the transmission time from other stations in the CAP-MAC, which means that there is no explicit L in its X_1 cycles.

To analyze this variant of the model, the number of *channel sensing attempts* R conducted by the tagged station is viewed as a reward associated to a level-1 renewal cycle. For a homogeneous service network, the sensing failure probability α, defined as the probability of finding a busy channel when the tagged station senses the channel in a slot, is the same for all the channel sensing activities from all the stations. With a given α, the number of sensing attempts for one station in a level-1 renewal cycle follows a truncated[3] geometric distribution with parameters α and M. More specifically, with probability $1-\alpha$ the station succeeds in sensing an idle channel and transmits the frame by only one sensing attempt; with probability $\alpha(1-\alpha)$ the station succeeds in transmitting the frame by two sensing attempts, and so forth. The number of backoff stages contained in a level-1 cycle follows the same distribution. Therefore, the average length of a level-1 cycle can be obtained accordingly. By the renewal reward theorem [70], the channel sensing probability τ for the tagged station is given by the ratio of the average sensing attempts over the average length of the level-1 cycle, which is a function of α. On the other hand, the channel sensing failure probability α can be obtained as a function of τ by carefully studying the transition probabilities among the channel states (idle and busy). These two equations can be solved by the fixed point technique to obtain α and τ, which can then be used to derive the average lengths of the three-level cycles and, finally, the desired MAC performance metrics.

In what follows, we first consider a slightly simpler protocol to illustrate the essence of the above model, then extend to the double channel sensing (DS) case specified in the standard.

4.2.2 The Single-Sensing Case (One CCA)

In the single-sensing (SS) case, a station senses the channel once at the end of a backoff stage. If the channel is idle, the station transmits at the beginning of the next slot; otherwise, it enters the next backoff stage. This is the only difference between the SS and the DS.

According to the discussion in the previous subsection, with a given channel sensing failure probability α, the average number of sensing attempts for one station in a

[3] It is truncated because the maximum number of sensing attempts allowed in an X cycle is M.

level-1 renewal cycle is

$$\begin{aligned} E[R] &= (1-\alpha) + 2\alpha(1-\alpha) + 3\alpha^2(1-\alpha) + \cdots \\ &\quad + (M-1)\alpha^{M-2}(1-\alpha) + M\alpha^{M-1} \\ &= \sum_{m=0}^{M-1} \alpha^m, \end{aligned} \tag{4.17}$$

and the average length of a level-1 renewal cycle is

$$\begin{aligned} E[X] &= (1-\alpha)(b_0 + 1 + L) + \alpha(1-\alpha)(b_0 + b_1 + 2 + L) + \cdots \\ &\quad + \alpha^{M-1}(1-\alpha)(\sum_{m=0}^{M-1}(b_m+1) + L) + \alpha^M \sum_{m=0}^{M-1}(b_m+1) \\ &= \sum_{m=0}^{M-1} \alpha^m (b_m + 1) + (1-\alpha^M)L, \end{aligned} \tag{4.18}$$

where L is the duration of a frame transmission in units of slots, and $b_m, 0 \leq m \leq M$, is the average number of slots in backoff stage m. Note that at the end of each backoff stage, there is always one slot used for sensing the channel. In addition, with the probability of α^M, the tagged station encounters M contiguous sensing failures and thus ends up the current renewal cycle without a transmission period incurred. Therefore, a period of L is included in the level-1 renewal cycle only with probability $(1 - \alpha^M)$, which is reflected by the last term in (4.18).

According to the renewal reward theorem [70], the sensing attempt rate for the tagged station is given by $E[R]/E[X]$, *i.e.*, τ can be obtained as

$$\tau = \frac{E[R]}{E[X]} = \frac{\sum_{m=0}^{M-1} \alpha^m}{\sum_{m=0}^{M-1} \alpha^m (b_m+1) + (1-\alpha^M)L}. \tag{4.19}$$

Next we derive the sensing failure probability α. In a randomly chosen slot, the channel state is either idle with probability P_i or busy with probability $P_b = 1 - P_i$, depending on the behavior of the stations. To obtain P_i, consider the channel status for two consecutive slots. Using conditional probabilities, we have

$$P_i = P_{(i,i)} P_i + P_{(b,i)}(1 - P_i), \tag{4.20}$$

which yields

$$P_i = \frac{P_{(b,i)}}{1 + P_{(b,i)} - P_{(i,i)}}, \tag{4.21}$$

where $P_{(b,i)}$ $\left(P_{(i,i)}\right)$ is the conditional probability that the next channel state is idle given that the current channel state is busy (idle). Since a transmission lasts for L slots, a randomly chosen busy slot will end with probability $1/L$ in the next slot, which comes from

$$\begin{aligned} P_{(b,i)} = {} & \Pr\{\text{next slot is idle} \mid \text{current slot is the last busy slot}\}\times \\ & \quad \Pr\{\text{current slot is the last busy slot}\} \\ & + \Pr\{\text{next slot is idle} \mid \text{current slot is not the last busy slot}\}\times \\ & \quad \Pr\{\text{current slot is not the last busy slot}\} \\ = {} & 1 \times \frac{1}{L} + 0 \times \frac{L-1}{L} \\ = {} & \frac{1}{L}. \end{aligned} \tag{4.22}$$

On the other hand, considering the sensing probability independence assumption, the channel will remain in the idle state in slot $k+1$ when it is idle in slot k only if none of the stations starts to sense in slot k, where k is an arbitrary slot index. Thus, we have

$$P_{(i,i)} = (1 - \tau)^N. \tag{4.23}$$

Substituting $P_{(b,i)}$ and $P_{(i,i)}$ into (4.21), we obtain

$$P_i = \frac{1}{1 + L(1 - (1 - \tau)^N)}. \tag{4.24}$$

Thus, the sensing failure probability α is given by

$$\alpha = 1 - P_i = \frac{L(1-(1-\tau)^N)}{1+L(1-(1-\tau)^N)}. \tag{4.25}$$

With given L, N and b_m, the set of fixed-point equations (4.19) and (4.25) can be solved numerically to obtain α, τ and $E[X]$.

To complete the analysis, we need to obtain the parameters P_{tx} and P_{suc}. As shown in Figure 4.4, for every level-1 renewal cycle X, it contains a transmission of L slots (*i.e.*, it is a type X_2 cycle) with probability

$$P_{\text{tx}} = 1 - \alpha^M. \tag{4.26}$$

Furthermore, the conditional probability that a transmission from the tagged station is successful is

$$P_{\text{suc}} = (1-\tau)^{N-1}, \tag{4.27}$$

because none of the other $N-1$ stations should sense the channel in the same slot as the tagged station does.

Combining (4.18), (4.26), (4.27) and (3.1) – (3.4), we obtain the average length of level-3 cycles $E[Z]$ as:

$$E[Z] = \frac{1}{\tau(1-\tau)^{N-1}(1-\alpha)}, \tag{4.28}$$

which is also the average frame service time, ζ. Following the basic model, the throughput of an individual station is

$$\eta_s = \frac{L}{E[Z]} = L\tau(1-\tau)^{N-1}(1-\alpha). \tag{4.29}$$

For the homogeneous network, the throughput is

$$\eta = N\eta_s = NL\tau(1-\tau)^{N-1}(1-\alpha). \tag{4.30}$$

4.2.3 The Double-Sensing Case (Two CCAs)

In this subsection, we study the double-sensing channel access mechanism specified in the standard. Similar to the single sensing case, the analysis can be done with appropriate changes in the equations regarding α and τ. In the following, the superscript (d) is added to all the relevant variables for the double-sensing case.

Let p_1 denote the probability of sensing a busy channel in the first CCA, and p_2 the probability of sensing a busy channel in the second CCA given that the channel is idle in the first CCA. Let $\alpha^{(d)}$ denote the probability of sensing failure, which is defined as sensing a busy channel in either of the two CCA events. At the end of each backoff stage, the tagged station will either enter the next backoff stage with probability $\alpha^{(d)}$ or start a transmission with probability $1 - \alpha^{(d)}$. Therefore,

$$\alpha^{(d)} = p_1 + (1 - p_1)p_2. \tag{4.31}$$

In addition, for each backoff stage, a station must spend one slot for the first CCA, and spend another slot for the second CCA with probability $1 - p_1$. Hence, the average number of slots spent for channel sensing in each backoff stage ending up without a transmission is

$$c = 1 + (1 - p_1) = 2 - p_1. \tag{4.32}$$

In the situation that the station succeeds in starting a transmission at the end of a backoff stage, the two successful CCA events will occupy two slots. In summary, the average length of a level-1 renewal cycle for the double-sensing case is

$$\begin{aligned} E[X^{(d)}] &= (1-\alpha^{(d)})(b_0+2+L) + \alpha^{(d)}(1-\alpha^{(d)})(b_0+c+b_1+2+L) + \cdots \\ &\quad + (\alpha^{(d)})^{M-1}(1-\alpha^{(d)})(\sum_{m=0}^{M-1} b_m + (M-1)c + 2 + L) + (\alpha^{(d)})^M \sum_{m=0}^{M-1}(b_m+c) \\ &= \sum_{m=0}^{M-1}(\alpha^{(d)})^m b_m + c\sum_{m=1}^{M}(\alpha^{(d)})^m + (1-(\alpha^{(d)})^M)(2+L). \end{aligned} \tag{4.33}$$

Denote $\tau^{(d)}$ the counterpart of τ in the double-sensing case, which refers to the probability of starting the first CCA in a slot for the tagged station. We have

$$\tau^{(d)} = \frac{E[R^{(d)}]}{E[X^{(d)}]} = \frac{\sum_{m=0}^{M-1}(\alpha^{(d)})^m}{E[X^{(d)}]}, \tag{4.34}$$

where α in (4.17) is replaced with $\alpha^{(d)}$ to obtain $E[R^{(d)}]$ as the average number of attempts to start sensing[4] in the double-sensing case.

To compute $\tau^{(d)}$, we need to know $\alpha^{(d)}$, p_1 and p_2, which can be derived as follows. Let $P'_{(i,b)}$ denote the probability that the channel turns busy in slot $k+1$ given that it is idle in slot k, for an arbitrary slot index k. This can only occur when the channel in slot $k-1$ is idle and at least one station starts to sense the channel at that time, due to the requirement of two consecutive successful channel sensing events before a transmission. Hence,

$$P^{(d)}_{(i,b)} = [1-(1-\tau^{(d)})^N]P^{(d)}_{(i,i)}. \tag{4.35}$$

Also, since the channel is either idle or busy in any slot, we have

$$P^{(d)}_{(i,b)} = 1 - P^{(d)}_{(i,i)}. \tag{4.36}$$

[4]Note that only the first channel sensing activity is counted as the reward associated to a renewal cycle; the second one does not contribute to it.

Combining (4.35) and (4.36) and letting $t = 1 - (1 - \tau^{(d)})^N$, we obtain

$$P_{(i,i)}^{(d)} = \frac{1}{1+t}. \tag{4.37}$$

Note that the derivation of (4.21) does not rely on any specific assumption of the channel sensing mechanism, so the relationship among the relevant probabilities is also valid for the DS case. Substituting (4.37) into (the DS version of) (4.21), and noting that $P_{(b,i)}^{(d)} = 1/L$, we have

$$P_i^{(d)} = \frac{1+t}{1+(L+1)t}. \tag{4.38}$$

Then, the channel sensing failure probabilities for the two sensing attempts can be obtained as:

$$p_1 = 1 - P_i^{(d)} = \frac{Lt}{1+(L+1)t}, \tag{4.39}$$

$$p_2 = P_{(i,b)}^{(d)} = \frac{t}{1+t}. \tag{4.40}$$

Substituting the above two equations into (4.31), we obtain

$$\alpha^{(d)} = \frac{L(1-(1-\tau^{(d)})^N)}{1+L(1-(1-\tau^{(d)})^N)}. \tag{4.41}$$

Note that the channel sensing failure probability $\alpha^{(d)}$ for the DS case has a relationship to the channel sensing probability $\tau^{(d)}$ exactly same as that of α to τ in the SS case. However, $\tau^{(d)}$ as a function of $\alpha^{(d)}$ is different from τ as a function of α, due to the time cost of the second CCA slot in the DS case. This difference causes the lower throughput of the DS mechanism compared to the SS with the same protocol parameters, as will be shown in Sec. 4.2.5.

Similarly to the SS case, with $\alpha^{(d)}$ and $\tau^{(d)}$ we can obtain straightforwardly the performance metrics for the DS case. The average frame service time is

$$E[Z^{(d)}] = \frac{1}{\tau^{(d)}(1-\tau^{(d)})^{N-1}(1-\alpha^{(d)})}\ , \tag{4.42}$$

the MAC throughput of an individual station is

$$\eta_s^{(d)} = L\tau^{(d)}(1-\tau^{(d)})^{N-1}(1-\alpha^{(d)}), \tag{4.43}$$

and the network throughput is

$$\eta^{(d)} = N\eta_s^{(d)} = NL\tau^{(d)}(1-\tau^{(d)})^{N-1}(1-\alpha^{(d)}), \tag{4.44}$$

where $\tau^{(d)}$ and $\alpha^{(d)}$ are given in (4.34) and (4.41), respectively. Note that the network throughput $\eta^{(d)}$ is consistent with (29) in [76], which is obtained with a much more complicated Markov chain based approach.

4.2.4 Analysis of Unsaturated Stations

For presentation succinctness, we only give the analysis for unsaturated stations in the single-sensing case. The analysis is based on the key idea that a station will not attempt to *sense*[5] the channel when its MAC buffer is empty, *i.e.*, the station will contend to access the channel only when it has a frame in the buffer waiting for transmission, which occurs with probability $\rho = \lceil \lambda E[Z'] \rceil^1$. The sensing probability τ' for a busy station remains in the same format as in (4.19) except α is now α'. Thus, τ' is given by

$$\tau' = \frac{\sum_{m=0}^{M-1}(\alpha')^m}{\sum_{m=0}^{M-1}(\alpha')^m(b_m+1)+(1-(\alpha')^M)L}. \tag{4.45}$$

Consider the conditional probability that the channel will remain in the idle state in slot $k+1$ given that it is idle in slot k. Such an event will occur only when neither the tagged station nor any of the $n, 0 \le n \le N-1$, other busy stations starts to sense in slot k. Hence, we have

$$P'_{(i,i)} = (1-\tau')(1-\rho\tau')^{N-1} \tag{4.46}$$

[5] In fact, the station will not transmit in this case either.

Following the approach in Sec. 4.2.2, α' can be obtained as

$$\alpha' = \frac{L(1 - P'_{(i,i)})}{1 + L(1 - P'_{(i,i)})}, \tag{4.47}$$

and

$$E[Z'] = \frac{1}{\tau' P'_{(i,i)}(1 - \alpha')}, \tag{4.48}$$

$$\rho = \lceil \lambda E[Z'] \rceil^1, \tag{4.49}$$

With given λ, N and L, τ', $\alpha', E[Z']$ and ρ can be obtained from equations (4.45)–(4.63). Following the method given earlier, the throughput and average frame service time in the unsaturated case can be readily obtained from $E[Z']$.

4.2.5 Numerical Results

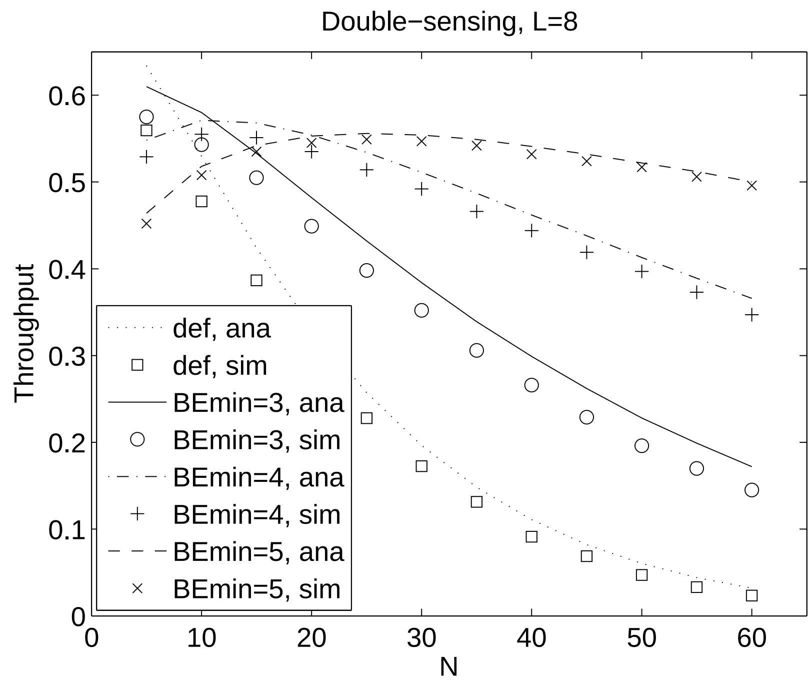
In this subsection, we present simulation results and compare them with the analytical ones to demonstrate the accuracy of the proposed analytical model. The simulator is written in the C language. In the following, the normalized throughput and average frame service time in units of slots are given, but they can be easily converted to actual throughput in units of bit per second and time in units of seconds with the parameter values given in the standard.

Performance of Default Parameters and Potential Improvements

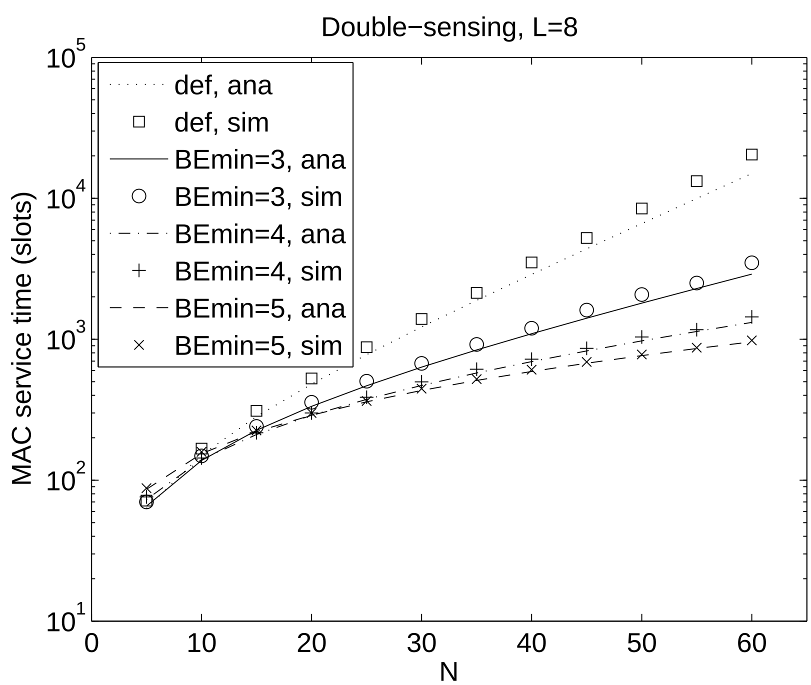
First, we study the performance of the MAC protocol with default parameter values given in the standard, *i.e.*, the minimum backoff exponent $BE_{min} = 3$, the maximum backoff exponent $BE_{max} = 5$, and the maximum allowed backoff stage for a frame $NB_{max} = 5$. The saturation throughput and average frame service time versus the number of stations N in the networks with the above default settings are shown in

Figure 4.5(a) and Figure 4.5(b), respectively, marked as "def" in the figures. The frame length is $L = 8$. It can be seen that the throughput decreases sharply with the number of stations while the average frame service time shows an opposite trend. This is because with small values of $BE_{min} = 3$ (corresponding to $b_0 = 3.5$) and $BE_{max} = 5$, the backoff slots are uniformly distributed over a relatively small range of $[0, 31]$, which causes the probability of simultaneous channel sensing conducted by multiple stations increases quickly with N. In contrast, the probability of finding the channel idle in the sensing slots decreases quickly when N increases. Therefore, a large portion of time is spent in backoff and thus the network throughput downgrades with the significantly increased frame service time. To overcome this issue, a straightforward solution is to remove the upper limit of maximum backoff exponent (or set it to a large number, e.g., 10 as in IEEE 802.11). That is, every time a station enters a new backoff stage, it simply increments the backoff exponent by one. In this way, the selection range of backoff slots is enlarged so that the probability of simultaneous channel sensing increases slower with N than it does in the default settings. The performance of this slightly different variant of the standard protocol is shown in the figures as "BEmin=3". We can see that the performance is about the same when N is small ($N < 10$). However, the performance gain becomes obvious when N is large. The network throughput is almost doubled for $N = 30$ and it is ten-folded for $N = 60$. Meanwhile, the average frame service time is always shorter than that in the default setting, and the gap between them increases with N, e.g., ζ for $N = 60$ decreases to just 1/3 of that with the default settings.

For larger BE_{min}'s (4 and 5), the performance is also shown in Figure 4.5 as "BEmin=4" and "BEmin=5", respectively. It is interesting to observe that the saturation network throughput first increases with N when N is small (less than 15 for "BEmin=4" and 25 for "BEmin=5"), then start to decrease with N, but much slower



(a)



(b)

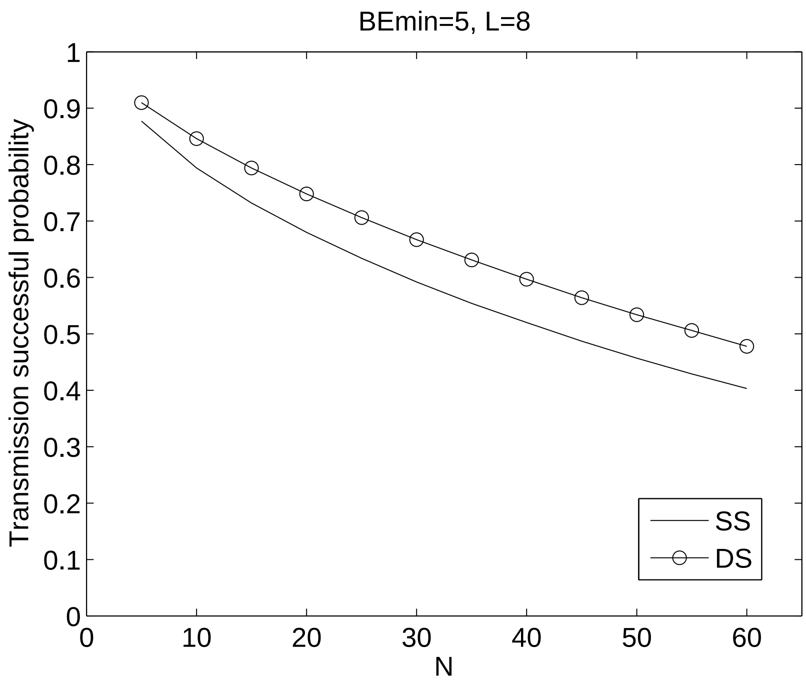
Figure 4.5: Performance of CAP-MAC with saturated stations

than in the "BEmin=3" and the default settings cases. This is because when N is small, stations can access the channel to transmit frames relatively easily with relatively small collision probability. For a small N, a larger BE_{min} means the stations spend more time in backoff for each frame transmission, resulting in a larger portion of channel idle time and lower network throughput. As N increases, more stations contribute to the increase of network throughput by more successful frame transmissions and more overlapped backoff time until this is offset by the increasing collision probability, upon which the maximum network throughput is reached. After that optimal point, further increasing N will cause a busier channel with less opportunity for stations to transmit and, even worse, higher collision probability for transmissions, leading to decreased network throughput. A larger BE_{min} gives a larger range for the selection of the number of backoff slots, which mitigates the above two adverse effects and makes the degradation of network throughput slower. For the same reason, ζ for larger BE_{min} cases is slightly longer when N is small, but becomes much shorter with large N, as shown in Figure. 4.5(b).

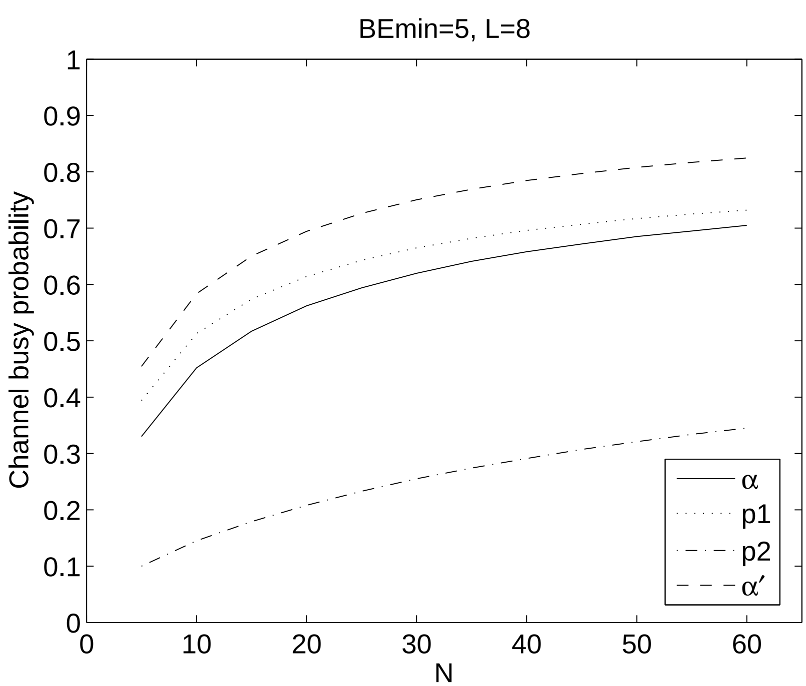
Single Sensing vs. Double Sensing

In developing the analytical model in this section, we have considered both the single sensing and double sensing mechanisms. Two expressions with the same form, (4.25) and (4.41), have been obtained for the channel sensing failure probabilities α and $\alpha^{(d)}$ as a function of the sensing probability τ and $\tau^{(d)}$, respectively. However, the difference in channel sensing requirements leads to the two different expressions for the relationship between the two probabilities, as shown in (4.19) and (4.34). In the following, we study the effect of this difference on the performance of the two mechanisms.

The probabilities of success for a frame transmission (P_{suc}) in the SS and DS cases



(a) Transmission successful probabilities



(b) Channel busy probabilities

Figure 4.6: Comparison between the SS and DS cases

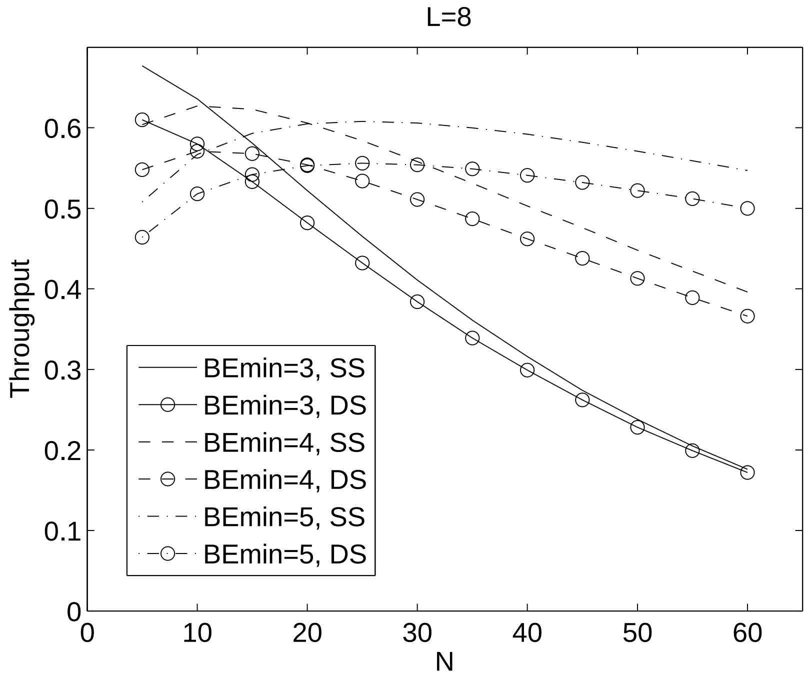


Figure 4.7: Saturation throughput comparison between SS and DS modes

are compared in Figure 4.6(a). With the same parameter (e.g., N, L and BE_{min}) values, P_{suc} of the DS is higher than that of the SS, which may suggest that the DS mechanism is preferable over the SS. However, as shown in Figure 4.6(b), the probability p_1 of sensing a busy channel in the first CCA slot in the DS case alone is always larger than that in the SS, which means a station gets less chance to transmit in the DS than in the SS during the same given period of time. Therefore, the DS mechanism is in an obvious disadvantage position, considering further the potential adverse effect of the probability p_2 of sensing a busy channel in the second CCA slot. The net effect of the above two contradicting factors is a lower network throughput of DS, which is clearly shown in Figure 4.7. It can be seen that with the same parameters (L=8), network throughput of the SS mode is always about 10% higher than that of

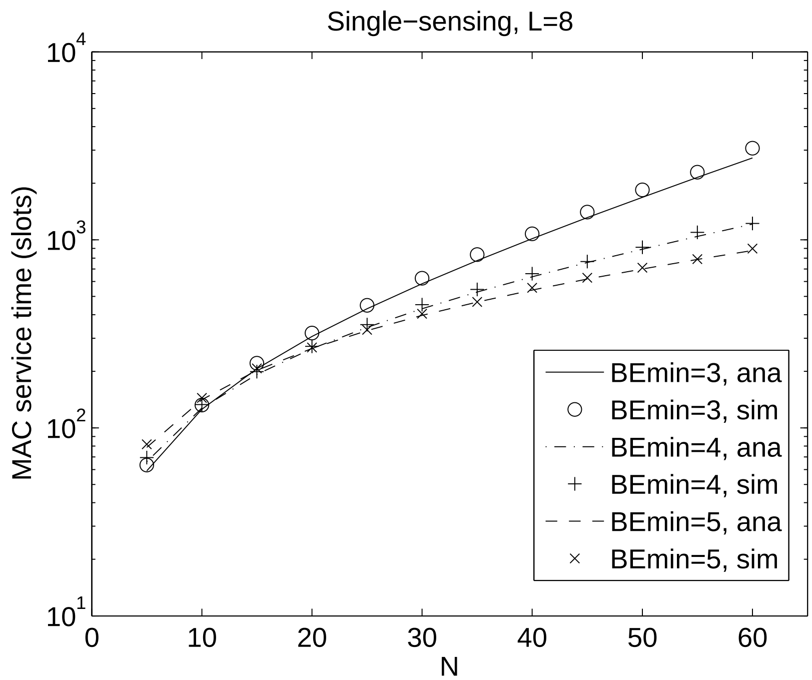


Figure 4.8: Average frame service time in the SS case

the DS mode, which conforms with the simulation results presented in [78, 89]. In addition, the performance gain of larger BE_{min} still exists in the SS case due to the similar reasons given in Section 4.2.5.

Figure 4.8 shows the average frame service time for the SS case. The relationships among the results for different parameter settings are similar to those in Figure 4.5(b). It should be mentioned that according to the general relationship between network throughput and average frame service time of the SS case is always shorter than that of the DS case with the same protocol parameters.

Unsaturated Stations

To demonstrate the effectiveness of the model for the unsaturated case, Figure 4.9 shows the average frame service time versus the frame arrival rate for $N = 20$. Poisson traffic is used in the simulation to compare with the analytical results. T_s increases quite slowly with low to medium load, and it soars when the load becomes high until it reaches a saturation level which depends only on N when the other parameters are given. It can be seen that the analytical results approximate the simulation ones very well.

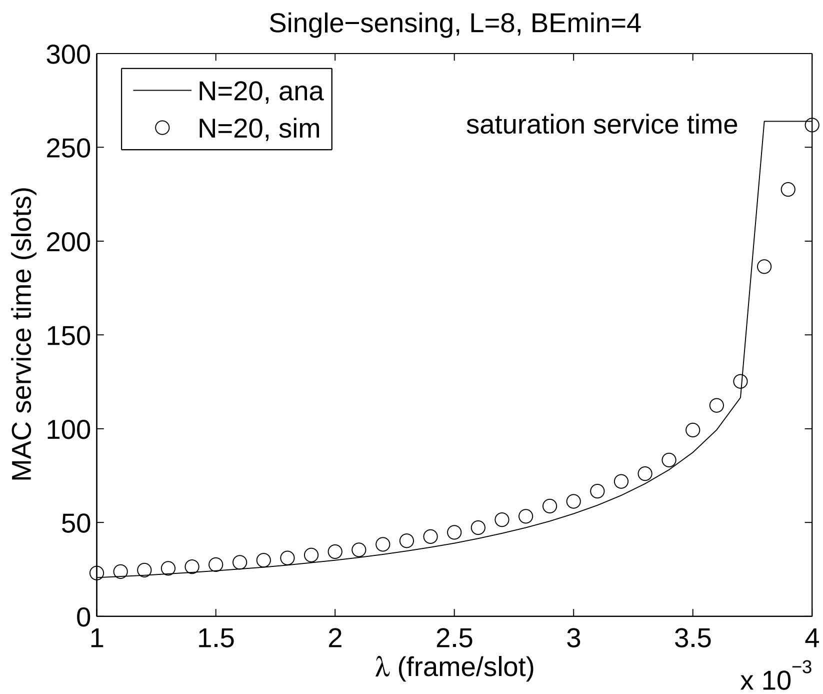


Figure 4.9: Average frame service time in unsaturated case

4.3 The IEEE 802.11 DCF

4.3.1 Analysis of Saturated Stations

According to the protocol described in Section 2.2.3, there are two salient attributes of the DCF as listed below:

- The backoff procedure freezes when the channel is busy, which is similar to the p-persistent CSMA/CA protocol but different from the CAP-MAC;
- The backoff parameter changes after each collision involving the tagged station, which is different from the p-persistent CSMA/CA protocol but similar to the behavior of the CAP-MAC when it encounters channel sensing failure.

Therefore, although a level-1 cycle for DCF is still the period between two consecutive transmissions from the tagged station as in the basic model, the level-2 cycles are actually *semi-renewal* due to the changing backoff parameters caused by the binary exponential backoff activity at this level. However, the renewal points for level-3 cycles remain to be the time instants when a new frame starts to be served. Note that they are equivalent to the instants when the CW is reset to CW_0, which are the same as the renewal points for level-1 cycles in the model for the CAP-MAC. This resemblance inspires us to analyze DCF directly at level-3, using an approach similar to the one used for analyzing the level-1 cycles in CAP-MAC, as outlined below.

The assumption that each transmission results in a collision with a constant independent probability β regardless of the backoff and transmission history of the frame [6] is adopted in this analysis. With a given collision probability, the number of *transmission trials* H is thus a random variable with geometric distribution. For each new frame, H can also be deemed as a reward associated to the level-3 renewal cycle. Therefore, by the renewal reward theorem, the probability of a station to transmit (or equivalently, access the channel) at the beginning of a randomly chosen generic slot, γ, is given by the ratio of the average number of transmission trials to the total number of generic slots in the level-3 cycle. On the other hand, the collision probability β can also be obtained as a simple function of the transmitting probability γ, due to the fact that a collision occurs only when any other station transmits simultaneously with the tagged station. These two equations can be jointly solved to obtain the above two probabilities.

More specifically, a collision occurs if at least one of the other $N-1$ stations transmit in the same slot. Thus, we have

$$\beta = 1 - (1-\gamma)^{N-1}. \tag{4.50}$$

Denote M the retry limit specified in the protocol, and $E[\omega]$ the average number of total backoff slots the tagged station has to wait during the level-3 cycle. It is clear that there are $E[H]$ transmissions during $E[\omega] + E[H]$ slots. Hence, the transmitting probability is given by

$$\gamma = \frac{E[H]}{E[\omega] + E[H]}. \tag{4.51}$$

In fact, the probability of successfully delivering a frame with one transmission is $(1-\beta)$, with two transmissions is $\beta(1-\beta)$, and so on. Moreover, the frame will be removed from the MAC sublayer buffer after the Mth trial regardless of the transmission result. Therefore, similar to the $E[R]$ in (4.17), H follows a truncated geometric distribution with parameters β and M, and the average number of transmissions for a frame is given by

$$\begin{aligned} E[H] &= \sum_{i=1}^{M-1} i\beta^{i-1}(1-\beta) + M\beta^{M-1} \\ &= \sum_{i=0}^{M-1} \beta^{i}. \end{aligned} \tag{4.52}$$

Let b_r denote the average number of backoff slots in backoff stage $r, r = 0, 1, \ldots, M$, where $r = 0$ refers to the initial backoff stage with the minimum contention window $W = CW_0$. It is clear that the average number of backoff slots for a frame is the weighted summation of the b_r's as given by

$$\begin{aligned} E[\omega] &= \sum_{i=0}^{M-1} \left(\beta^i (1-\beta) \sum_{r=0}^{i} b_r \right) + \beta^M \sum_{i=0}^{M-1} b_i \\ &= \sum_{i=0}^{M-1} (\beta^i b_i). \end{aligned} \tag{4.53}$$

Finally, we have

$$\gamma = \frac{\sum_{i=0}^{M-1} \beta^i}{\sum_{i=0}^{M-1} \beta^i (b_i + 1)}. \tag{4.54}$$

Given a specific backoff policy, *i.e.*, the backoff parameters such as W and M, the equation set (4.50) and (4.54) can be solved numerically to obtain a pair of β and γ.

Note that different from the fixed length slot used in the previous two protocols, a generic slot in the above analysis may refer to an idle time slot, a successful transmission or a collision with corresponding probabilities, as in [6]. According to the above argument, a level-3 cycle can be deemed as a sequence of generic slots in which the tagged station either does not transmit or it transmits but encounters a collision, followed by an ending generic slot containing the successful transmission from the tagged station. In other words, in each generic slot, the tagged station conducts a Bernoulli experiment with its successful transmission defined as the event success. Consequently, the average length of the level-3 cycle in units of generic slots has a geometric distribution with parameter $\gamma(1-\beta)$. Thus, $E[Z]$ can be obtained as

$$E[Z] = \frac{1}{\gamma(1-\beta)} E[GS], \tag{4.55}$$

where $E[GS]$ is the average length of a generic slot, as given by

$$\begin{aligned} E[GS] &= \Pr\{\text{channel is idle}\} \cdot 1 + \Pr\{\text{channel is busy}\} \cdot L \\ &= (1-\gamma)^N \cdot 1 + (1-(1-\gamma)^N) \cdot L \\ &= (1-\gamma)^N + L - L(1-\gamma)^N. \end{aligned} \tag{4.56}$$

The network throughput can be obtained following the approach given in the basic model, *i.e.*,

$$\eta = \frac{NL}{E[Z]}. \tag{4.57}$$

Alternatively, it can be obtained as the portion of the average time used for successful transmissions in a generic slot [6]. The former item is given by $N\gamma(1-\gamma)^{N-1}L$, while the latter is given in (4.56). Combining the two expressions, we have

$$\eta = \frac{N\gamma(1-\gamma)^{N-1}L}{(1-\gamma)^N + L - L(1-\gamma)^N}. \tag{4.58}$$

Noticing from (4.50) that $1-\beta = (1-\gamma)^{N-1}$, it is easy to verify that the two expressions for the network throughput (4.57) and (4.58) are equivalent.

4.3.2 Analysis of Unsaturated Stations

We have successfully applied the proposed model to analyze the network with unsaturated stations for the previous two protocols. Similar analysis for the DCF can be carried out straightforwardly. Following the same key idea that a station will compete for channel access only when it has a frame for service, we can obtain the following equation set for DCF:

$$\beta' = 1 - (1 - \rho\gamma')^{N-1} \tag{4.59}$$

$$\gamma' = \frac{\sum_{i=0}^{M-1} (\beta')^i}{\sum_{i=0}^{M-1} (\beta')^i (b_i + 1)} \tag{4.60}$$

$$E[GS'] = (1 - \gamma')(1 - \gamma'\rho)^{N-1} + L\left(1 - (1 - \gamma')(1 - \gamma'\rho)^{N-1}\right) \tag{4.61}$$

$$E[Z'] = \frac{E[GS']}{\gamma'(1 - \beta')} \tag{4.62}$$

$$\rho = \lceil \lambda E[Z'] \rceil^1, \tag{4.63}$$

where λ is the average frame arrival rate on an individual station. The above equation set can be solved numerically when N, L and λ are given to obtain $E[Z']$, which is the main desired MAC performance metric for unsaturated stations.

4.3.3 With Default Parameters in DCF

Contention Window

In the DCF specification, the initial value of the backoff counter in backoff stage r is uniformly chosen over $[0, CW_r)$, where $CW_r = 2^r \cdot W = 2^r \cdot 32$ is the corresponding contention window. Therefore, the average backoff time in stage r is $b_r = \frac{CW_r}{2}$ slots. The maximum number of allowed retransmission is $M = 7$. In addition, the contention window is bounded by 1024, so $m' = \log_2(1024/32) = 5$ is the number of backoff stages that have different contention window size. That is, when the backoff stage $r \geq m'$, the contention window will be the same (1024). Substituting these parameters into (4.53), we obtain the average number of backoff time slots of a station as

$$
\begin{aligned}
E[\omega] &= \frac{W-1}{2}(1-\beta) + \cdots + \frac{\sum_{i=0}^{m'}(2^i W - 1)}{2}\beta^{m'}(1-\beta) \\
&\quad + \cdots + \frac{\sum_{i=0}^{m'}(2^i W - 1) + (M-m')2^{m'}W}{2}\beta^M \\
&= \frac{A-B}{2(1-\beta)(1-2\beta)}, \qquad (4.64) \\
A &= W(1-\beta)(1-(2\beta)^{m'+1}) + W\beta(1-2\beta)(2\beta)^{m'}(1-\beta^{M-m'}), \\
B &= (1-2\beta)(1-\beta^{M+1}).
\end{aligned}
$$

The final expression for $E[\omega]$ in (4.64) is valid only when $\beta \neq 0.5$, but $E[\omega]$ can be evaluated directly at the first step of (4.64) for $\beta = 0.5$.

Combining (4.54) and (4.64), the transmission probability of the station is thus obtained as

$$
\tau = \frac{2(1-\beta^m)(1-2\beta)}{A+B}, \qquad (4.65)
$$

where A and B are given in (4.64). This result is consistent with that derived in [110] using the much more complicated two-dimension Markov chain approach.

Successful Frame Transmission Time and Collision Time Calculation

Denote T_s the time duration spent by the tagged station on a successful transmission, and T_c the time duration for a collision. In the basic access mode,

$$
T_s = T_{(data)} + SIFS + T_{(ACK)} + DIFS, \qquad (4.66)
$$

$$
T_c = T_{(data)} + ACK\_Timeout + DIFS. \qquad (4.67)
$$

In the above, $T_{(x)}$ represents the transmission time of the corresponding frame type x. In fact, $T_s \approx T_c$ because $ACK\_Timeout \approx SIFS + T_{(ACK)}$ as specified in the standard. Note that T_s also represents the time duration that the channel is sensed busy by the tagged station due to a successful transmission of another station. For the time period of busy channel due to a collision among other stations, it is $T_{\text{data}} + EIFS$ for the basic access mode, which can be safely approximated by T_c in (4.67) according to the standard. Once a transmission starts, the channel will be deemed busy for the whole period of either T_s or T_c due to two reasons:

1. In the case of a successful transmission, the duration of $SIFS$ is shorter than a slot time given by the standard, which assures that no new transmission will start before the transmission of the ACK frame from the receiver;

2. In the case of a collision, the $EIFS$ period helps to prevent new transmissions to start before the end of T_c.

Therefore, we can use T_s (or T_c) normalized by the slot time as L in the analysis for the basic mode of DCF.

In the RTS/CTS mode, for the tagged station we have

$$T_s^{(RTS)} = T_{(RTS)} + T_{(CTS)} + T_{(data)} + T_{(ACK)} + 3SIFS + DIFS, \tag{4.68}$$

$$T_c^{(RTS)} = T_{(RTS)} + CTS\_Timeout + DIFS. \tag{4.69}$$

Similar to the basic mode, $T_s^{(RTS)}$ is for the channel busy period caused by a successful transmission from either the tagged station or others. Thus, we may still set L equal to the normalized $T_s^{(RTS)}$. On the other hand, the channel busy period caused by collisions from other stations is $T_{(RTS)} + EIFS$, which can also be approximated by $T_c^{(RTS)}$ in (4.69). However, since $T_s^{(RTS)} \neq T_c^{(RTS)}$ in this mode, the calculation of

$E[GS]$ need to be changed to

$$\begin{aligned}E[GS]^{(RTS)} =& \Pr\{\text{channel is idle}\} \cdot 1 + \\ & \Pr\{\text{channel is busy due to a successful transmission}\} \cdot T_s^{(RTS)} + \\ & \Pr\{\text{channel is busy due to a collsion}\} \cdot T_c^{(RTS)} \\ =& (1-\gamma)^N + N\gamma(1-\gamma)^{N-1}T_s^{(RTS)} + \\ & (1-(1-\gamma)^N - N\gamma(1-\gamma)^{N-1})T_c^{(RTS)}.\end{aligned} \tag{4.70}$$

The remaining part of the analytical model can be applied to the RTS/CTS mode without further modification.

We have used L to represent the time for successful frame transmission in the analysis and directly used it in the calculation of network throughput. If a more accurate expression for throughput is desired, the L in the numerator of (4.58) should be replaced by the normalized T_{data}. Similar replacement is also applicable to the other two protocols when necessary.

Usually $T_c^{(RTS)} << T_c$ (or T_s) $< T_s^{(RTS)}$, so $E[GS]^{(RTS)}$ is usually much smaller than $E[GS]$ in the basic mode and thus a higher network throughput can be achieved in the RTS/CTS mode compared with the basic mode, when all the other parameters (e.g., W and M) are the same. Therefore, the RTS/CTS mode is "recommended for the majority of the practical cases" in [6]. With the advance of physical layer technologies, the data rate of WLAN has increased dramatically, *e.g.*, the emerging standard IEEE 802.11n [114] can provide raw data rate of 216Mbps.

The high data rate makes $T_{(data)}$ much smaller, and it is possible that the extra cost of $(T_{(RTS)} + T_{(CTS)} + 2SIFS)$ in $T_s^{(RTS)}$ occupies so large a portion that the benefit from the reduction of $T_c^{(RTS)}$ is offset[6]. Therefore, the RTS/CTS mode is not always recommended for networks with high data rate.

4.3.4 Numerical Results

As for the previous two protocols, simulations have also been run to verify the analysis accuracy for the DCF. As an illustration of converting the normalized units to the practical ones, the throughput is in units of Mbps and the average frame service time is in units of mili-second.

Table 4.1: Some DCF Parameters Used in the Analysis and Simulations

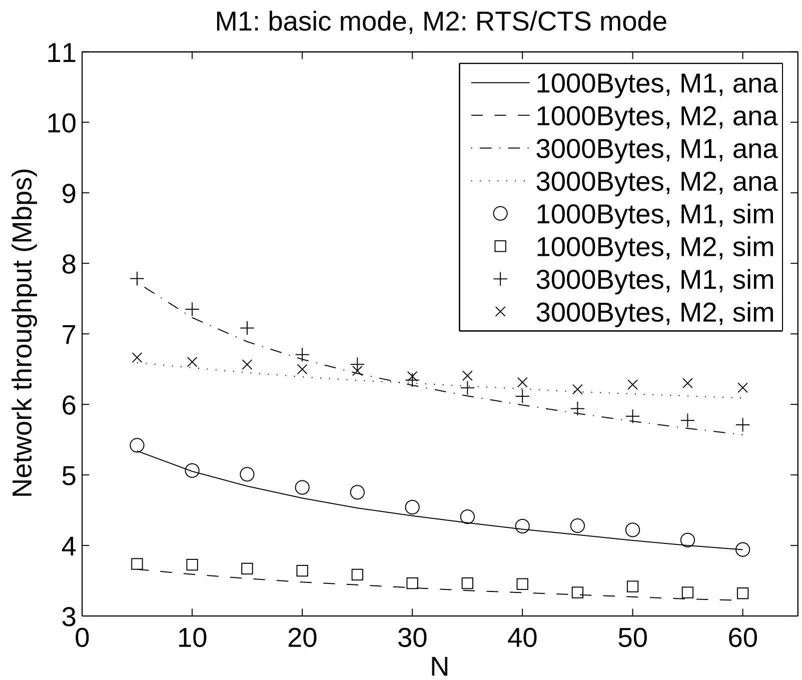
minimum CW (W)	32	retransmit limit (M)	7
m'	5	MAC frame data rate	11 Mbps
slot time	20 μs	SIFS	10 μs
DIFS	50 μs	DSSS PHY header	192 μs
RTS frame size	28 Bytes	CTS frame size	14 Bytes
ACK frame size	14 Bytes	control frame data rate	1Mbps

We have tested the performance of DCF in both the basic mode and the RTS/CTS mode for a given range of N, with two different MAC frame payload values, 1000 Bytes (Payload-1) and 3000 Bytes (Payload-2), respectively. The parameters used in the

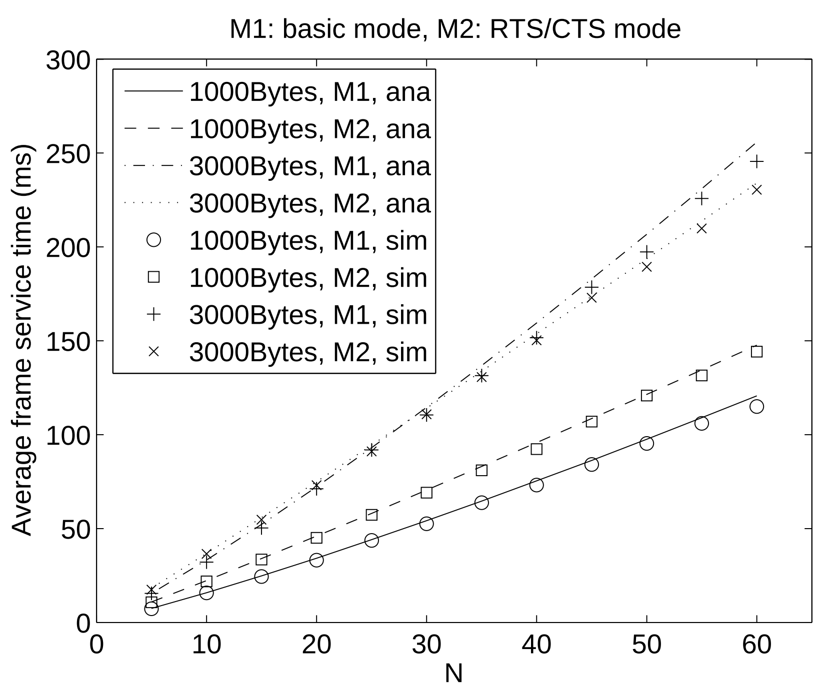
[6]Every frame is associated with the same amount of physical layer overhead, regardless of the payload (the whole frame from the MAC layer). It is such fixed and relatively large physical layer overhead that makes the effect described here possible to occur in high data rate systems.

analysis and simulations are for the IEEE 802.11b as given in Table 4.1. With this setting, the time for the RTS/CTS exchange sequence is $2 * 192 + 10 + 28 * 8 + 14 * 8 = 730\mu$s, which is quite large, especially compared with the transmission time of Payload-1 ($2 * 192 + 10 + 1000 * 8/11 + 14 * 8 \approx 1233\mu$s). The disadvantage of using RTS/CTS mode when the channel data rate is just relatively high (still much lower than the 216Mbps in IEEE 802.11n) is clearly shown in Figure 4.10. It is observed that with Payload-1, the RTS/CTS mode always gives a lower throughput (Figure 4.10(a)) and longer average frame service time (Figure 4.10(b)) than those given by the basic mode, due to the large overhead of the RTS/CTS control frame exchange. With Payload-2, the RTS/CTS mode outperforms the basic mode only after $N > 30$, where the collision probability becomes relatively high. This is because only in this case does the time saved by short collision time of the RTS frames (in comparison with the longer collision time of the date frame) become larger than the extra time cost of the RTS and CTS frames in the final successful transmission. Therefore, the RTS/CTS mode should be used with caution when the overhead of the control frames is large.

To illustrate the application of the analysis model for the unsaturated stations, we show in Figure 4.11 the maximum supportable N for a given range of traffic arrive rates with two different payload values. The maximum supportable N refers to the maximum number of stations that can remain in the unsaturated situation with the given payload size and average traffic arrival rate. Due to the fixed overhead of physical layer headers and the associated ACK frame, double valued payload size does not decrease the maximum supportable N by half. From the figure we can also observe that the maximum supportable N decreases non-linearly with the increasing λ, because there are more overlapped backoff and collisions slots shared by the stations when the traffic load is high.



(a)



(b)

Figure 4.10: Saturation throughput and average frame service time of DCF in basic and RTS/CTS modes

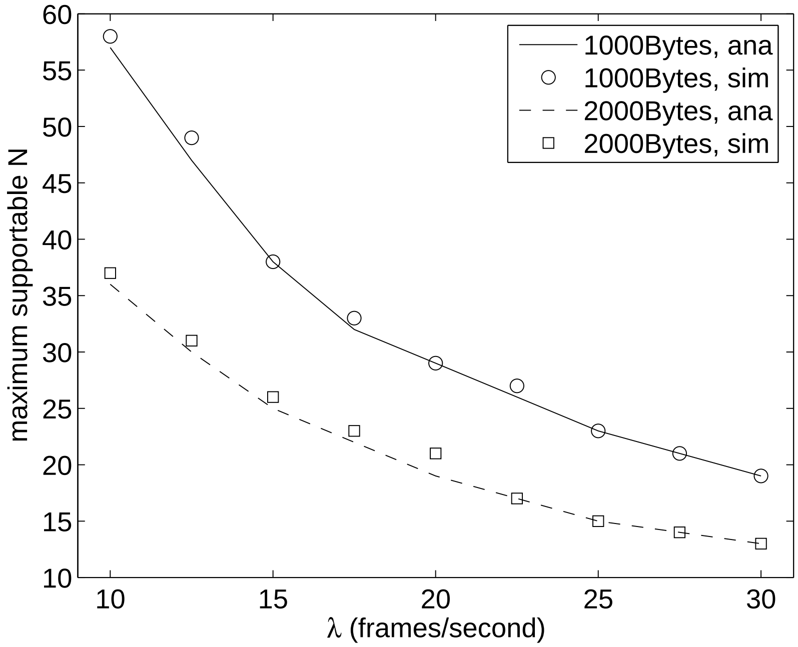


Figure 4.11: Capacity of DCF in the basic mode

4.4 Discussion on the Proper Selection of Fixed Point

From the above application instances, we can see that it is important to properly determine the *fixed point*, which is the key to the quantitative analysis in the proposed analytical framework. To model the MAC protocol, the criterion for selecting the fixed point is that the MAC behavior of each node can be independently modeled around the parameter associated with the fixed point; the equations describing different nodes are coupled by the fixed point. For the p-persistent CSMA/CA protocol, it is obvious that the transmitting probability p is the fixed point because this is the only parameter that determines the channel access behavior of the stations. In analyzing the CAP-MAC, the probability to start sensing the channel is selected as the fixed point; in contrast, the channel access probability serves as the fixed point in the analysis of IEEE 802.11 DCF. It is difficult, if not impossible, to present a theoretical proof that these two probabilities strictly meet the fixed point selection criterion in their respective context, but it can be intuitively justified. In the CAP-MAC protocol, each node observes the shared common channel, and independently determines its backoff behavior according to the protocol specification. The channel sensing probability associated with a certain node is exclusively determined by the node's backoff procedure; therefore, the channel sensing probabilities associated with different nodes are independent from each other due to the independent backoff procedures. In the homogeneous network, all the nodes are configured with the same backoff parameters, and therefore they have the same channel sensing probability. Similar arguments hold for the channel access probability for the DCF case. It is noteworthy that if an improper fixed point without the independency property is selected, the analytical model will lead to inaccurate performance results.

4.5 Maximum Saturation Throughput of the Three Protocols

In this section, we compare the maximum network throughput that can be achieved with the three protocols studied in this chapter. Meanwhile, we will derive the optimal key parameter(s) that lead to the maximum network throughput for each protocol. In the following, for a fair comparison, the network under study has N stations; the channel busy period due to a frame transmission and the associated overhead (e.g., ACK/NACK, inter-frame spaces) is L slots; and the slot length is normalized to unit for all the three protocols.

4.5.1 p-Persistent CSMA/CA

In the p-persistent CSMA/CA protocol, the only parameter that can be adjusted is the backoff probability p. The expression for network throughput in (4.8) is complex and it is difficult to do an exact optimization. However, when $p << 1$ and it is acceptable to approximate $(1-p)^N$ by $(1-Np)$, we can get a much simpler expression for the network throughput as

$$\begin{aligned} \eta_{pp} &= \frac{NLp(1-p)^{N-1}}{L-(L-1)(1-p)^N} \\ &\approx \frac{NLp[1-(N-1)p]}{L-(L-1)(1-Np)} \\ &= \frac{NLp[1-(N-1)p]}{1+N(L-1)p}. \end{aligned} \tag{4.71}$$

Taking the derivative of the above η_{pp} with respect to p and letting it equal to zero, we have the second degree equation

$$N(N-1)(L-1)\cdot p^2 + 2(N-1)\cdot p - 1 = 0. \tag{4.72}$$

The optimal p^* rendering the maximum network throughput is the solution of the above equation, as given by

$$\begin{aligned} p^* &= \frac{-2(N-1)+\sqrt{(2(N-1))^2-4N(N-1)(L-1)\cdot(-1)}}{2N(N-1)(L-1)} \\ &= \frac{\sqrt{\frac{N}{N-1}(L-1)+1}-1}{N(L-1)}. \end{aligned} \tag{4.73}$$

Substituting p^* back into (4.71), we can obtain a complex expression for the maximum network throughput η_{pp}^*.

When L and N are large so that 1 can be neglected as compared with L, $\sqrt{L}$ and N, we can further simplify (4.73) as

$$p^* \approx \frac{1}{N\sqrt{L}}. \tag{4.74}$$

Substituting the above p^* into (4.71), the maximum achievable network throughput is approximated by a simple expression as

$$\eta_{pp}^* \approx \frac{\sqrt{L}-1}{\sqrt{L}+1}. \tag{4.75}$$

It is noteworthy that $\eta_{pp}^* \to 1$ when $L \to \infty$.

4.5.2 CAP-MAC

To obtain the maximum network throughput of the CAP-MAC, we re-write (4.30) as

$$\begin{aligned} \eta_{CAP} &= NL\tau(1-\tau)^{N-1}(1-\alpha) \\ &= \frac{NL\tau(1-\tau)^{N-1}}{1+L(1-(1-\tau)^N)}. \end{aligned} \tag{4.76}$$

When τ is very small, we may again use the approximation $(1-N\tau)$ to replace $(1-\tau)^N$ so that

$$\begin{aligned} \eta_{CAP} &\approx \frac{NL\tau[1-(N-1)\tau]}{L+1-L(1-N\tau)} \\ &= \frac{NL\tau[1-(N-1)\tau]}{1+NL\tau}. \end{aligned} \tag{4.77}$$

Comparing the above expression for η_{CAP} to (4.71), we notice that, if τ is replaced by p, they are in fact very similar except for a slight difference in the denominator: an item of $NL\tau$ in (4.77) corresponds to an item of $N(L-1)p$ in (4.71). Hence, intuitively, for the same value of p and τ, η_{CAP} will be smaller than η_{pp}. We compare them with the same value of p and τ in Figure 4.12. It can be seen that when L is small ($L = 10$ in the figure), the throughput gap is obvious; when L is large ($L = 100$ in the figure) so that $L-1 \approx L$, the throughput gap is almost negligible. In both cases, N does not affect the gap.

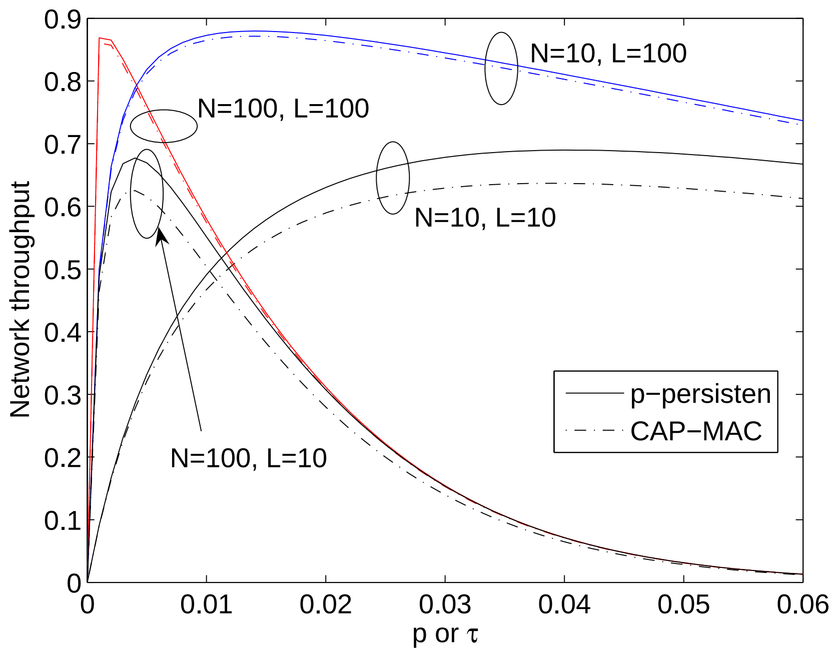


Figure 4.12: Saturation throughput comparison between p-persistent CSMA/CA and CAP-MAC

A procedure similar to the previous one can be used to find the optimal τ^* as given by

$$\tau^* = \frac{\sqrt{\frac{N}{N-1}L + 1} - 1}{NL}, \tag{4.78}$$

and another complex expression for the maximum network throughput for CAP-MAC. The τ^* in (4.78) is very close to p^* in (4.73), especially when N and/or L are large compared to 1. The key parameter p can be directly adjusted in the p-persistent CSMA/CA protocol. However, it is not straightforward to adjust the τ to its optimal value. In the CAP-MAC protocol, τ is not directly adjustable; instead, the corresponding parameters are: the minimum backoff exponent BE_0, the maximum backoff exponent BE_{max}, and the maximum allowed retry limit M. The optimal τ

can only be approached by adjusting these three parameters. Next we discuss a viable way of achieving this target.

As discussed in Section 4.2.5, we may select a large BE_{max} such that $BE_{max} \geq BE_0 + M$, which effectively removes the upper limit of the backoff window so that the protocol can work well in a network with large station population. Then, we can select a parameter pair of (BE_0, M) for the CAP-MAC to achieve the τ^*. Given the optimal τ^*, the corresponding α^* can be obtained from (4.25).

With Binary Exponential Backoff

Noticing that for the binary exponential backoff procedure adopted in the CAP-MAC, we have

$$b_m = 2^{BE_m - 1} = 2^m \cdot 2^{BE_0 - 1}, m = 0, 1, \ldots, M,$$

in (4.18) and (4.19). Given τ and α, equation (4.19) determines the relationship between BE_0 and M. Since

$$\sum_{m=0}^{M-1} \alpha^m = \frac{1 - \alpha^M}{1 - \alpha},$$

we may rewrite (4.19) as

$$\begin{aligned} \tau &= \frac{\sum_{m=0}^{M-1} \alpha^m}{\sum_{m=0}^{M-1} \alpha^m (2^m 2^{BE_0 - 1} + 1) + (1 - \alpha^M) L} \\ &= \frac{(1 - \alpha^M)/(1 - \alpha)}{2^{BE_0 - 1}(1 - (2\alpha)^M)/(1 - 2\alpha) + (1 - \alpha^M)/(1 - \alpha) + (1 - \alpha^M) L} \\ &= \left[2^{BE_0 - 1} \frac{(1 - (2\alpha)^M)(1 - \alpha)}{(1 - 2\alpha)(1 - \alpha^M)} + 1 + L(1 - \alpha) \right]^{-1}. \end{aligned} \tag{4.79}$$

Thus, we have

$$\begin{aligned} 2^{BE_0 - 1} &= \frac{(1 - 2\alpha)(1 - \alpha^M)}{(1 - (2\alpha)^M)(1 - \alpha)} \left[\frac{1}{\tau} - 1 - L(1 - \alpha) \right] \\ \Rightarrow BE_0 &= 1 + \log_2 \left[\frac{(1 - 2\alpha)(1 - \alpha^M)}{(1 - (2\alpha)^M)(1 - \alpha)} \left(\frac{1}{\tau} - 1 - L(1 - \alpha) \right) \right] \end{aligned} \tag{4.80}$$

Given a BE_0 we may get the corresponding M, and vice versa.

However, there are other constraints: $BE_0 > 1$, $M > 0$, and both have to be integers in the CAP-MAC. Therefore, with the optimal τ^* and α^* given previously, we may not always be able to choose an appropriate pair of integer BE_0^* and M^* with the current version of CAP-MAC. This problem can be solved if we let $W = 2b_0$ and remove the constraint that $\log_2 W$ has to be an integer. Instead of adjusting BE_0, we change W according to a given M. In this way, we may achieve a network throughput closer to the maximum one than by adjusting BE_0.

With Fixed Backoff Window

If a fixed backoff window $\hat{W}$ is adopted, we have

$$b_m = \frac{\hat{W}}{2}, m = 0, 1, \ldots, M. \tag{4.81}$$

Equation (4.19) can thus be re-written as

$$\begin{aligned} \tau &= \frac{(1-\alpha^M)/(1-\alpha)}{(1+W/2)(1-\alpha^M)/(1-\alpha) + L(1-\alpha^M)} \\ &= \frac{1}{(1+\hat{W}/2) + L(1-\alpha)}, \end{aligned} \tag{4.82}$$

which yields

$$\hat{W} = 2\left(\frac{1}{\tau} - L(1-\alpha) - 1\right). \tag{4.83}$$

The optimal fixed backoff window size $\hat{W}^*$ is obtained by the above expression with the given optimal values τ^* and α^*. Note that M, the maximum number of allowed re-transmissions for a frame, does not appear in the above expression, which is expected because the backoff window is fixed.

SS versus DS

Some numerical results given in Section 4.2.5 show that *for the same network configuration* (*i.e.*, N, L, BE_{min}, BE_{max} and M), the throughput of the DS mode is always less than that of the SS mode. However, the resemblance between (4.30) and (4.44) implies that the DS mode can give the same maximum network throughput as the SS mode if $\tau^{(d)}$ can be set to the optimal τ^*. Indeed, by adjusting the backoff related parameters, we may also achieve the target τ^* in the DS mode. Taking the fixed backoff window as an example, similar to the SS mode, we just need to set

$$\hat{W^{(d)}} = 2\left(\frac{1}{\tau^*} - L(1-\alpha^{(d)*}) - 1 - c^*\right), \tag{4.84}$$

where $\alpha^{(d)*}$ and c^* can be obtained from (the corresponding version of) (4.41) and (4.32), respectively, with the given τ^*.

4.5.3 DCF

A careful examination of the expression (4.58) will reveal that they are in fact the same expressions if γ is replaced by p. Then, we obtain immediately the same expression for the optimal γ^* as

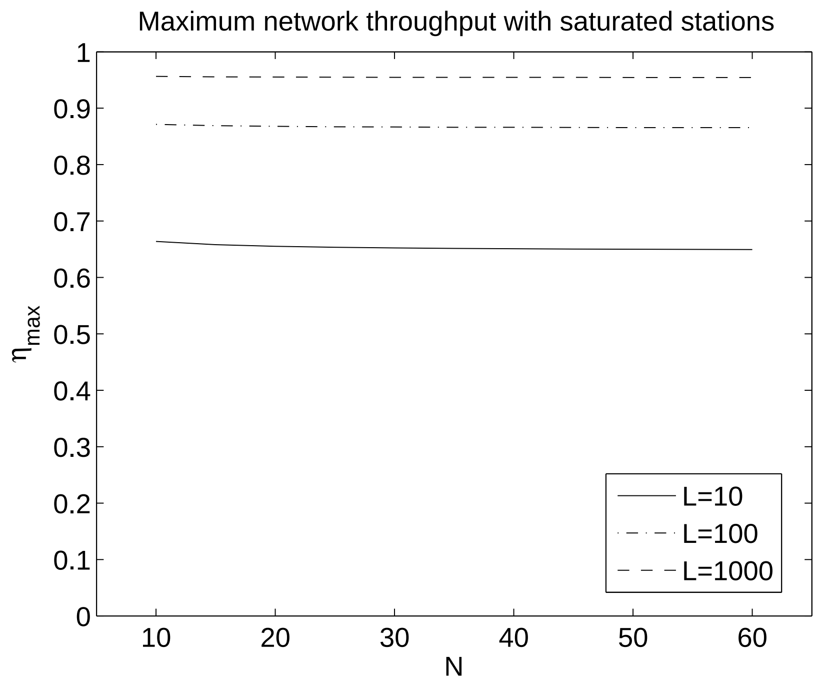
$$\gamma^* = \frac{\sqrt{\frac{N}{N-1}(L-1)+1} - 1}{N(L-1)}. \tag{4.85}$$

In addition, since the binary exponential backoff policy is also adopted in DCF as in CAP-MAC, we can follow a procedure similar to the one in Section 4.5.2 to approach the optimal γ^* by adjusting the minimum contention window W and the maximum allowed retransmissions M.

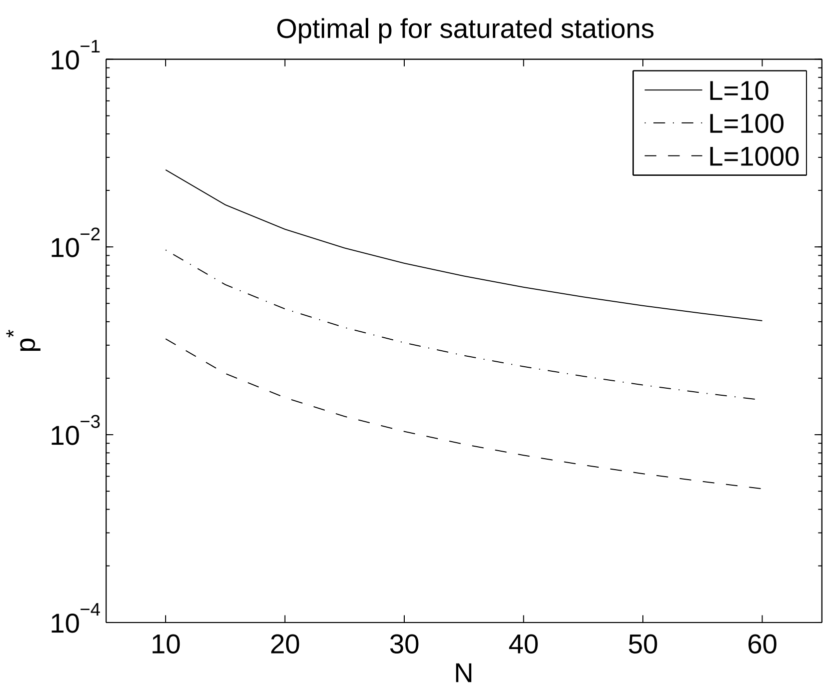
4.5.4 Numerical Results

Figure 4.13 shows the maximum network throughput η_{max} and the corresponding optimal transmission probability p^* for the p-persistent CSMA/CA protocol with saturated stations, for three cases $L = 10, 100$ and 1000, respectively. It can be seen that with the optimal p^* selected according to the number of saturated stations N in the network, the maximum network throughput is basically determined by the parameter L and independent of N, as indicated in (4.75).

As pointed out in the previous section, the theoretical maximum network throughput of the IEEE 802.11 DCF is the same as that of the p-persistent CSMA/CA protocol when all the protocol overheads are the same. However, the specific binary exponential backoff policy adopted by the IEEE 802.11 standards brings difficulty in approaching the theoretical maximum network throughput as discussed earlier. Similar difficulty exists for the CAP-MAC to achieve its theoretical maximum network throughput. In Figure 4.14(a), the symbol η^* refers to the theoretical maximum network throughput, and η_* refers to the one achieved by the BEB backoff policy adopted by the CAP-MAC (without the BE_{max} limit). It is observed that due to the limited ability of adjusting the τ to approach the optimal value in the BEB policy, η_* is always lower than η^*. The corresponding initial contention window (by symbol 2^{BE_0}) is given in Figure 4.14(b). In contrast, if the fixed contention window policy is adopted and the limitation of $W^* = 2^n$ (n integer) is removed, the protocol does achieve the theoretical maximum network throughput with the corresponding optimal backoff window W^* shown in Figure 4.14(b).

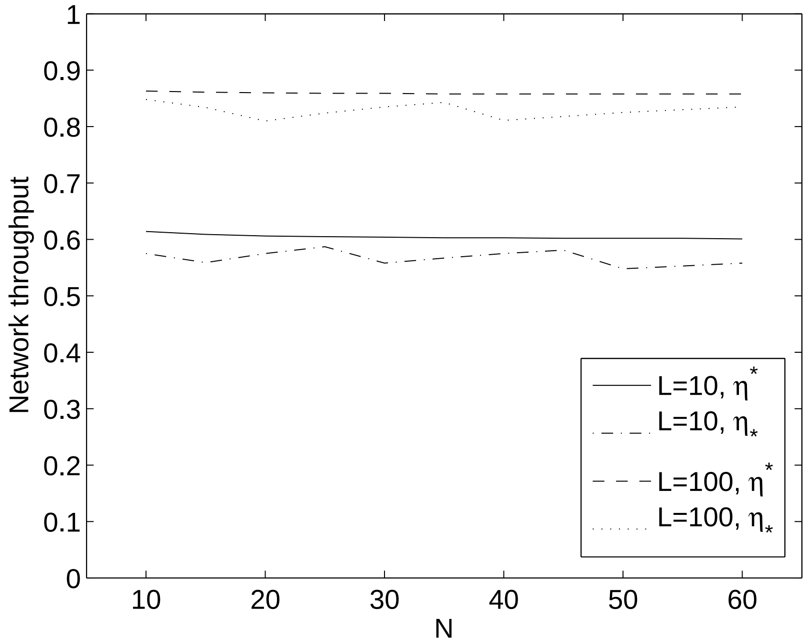


(a)

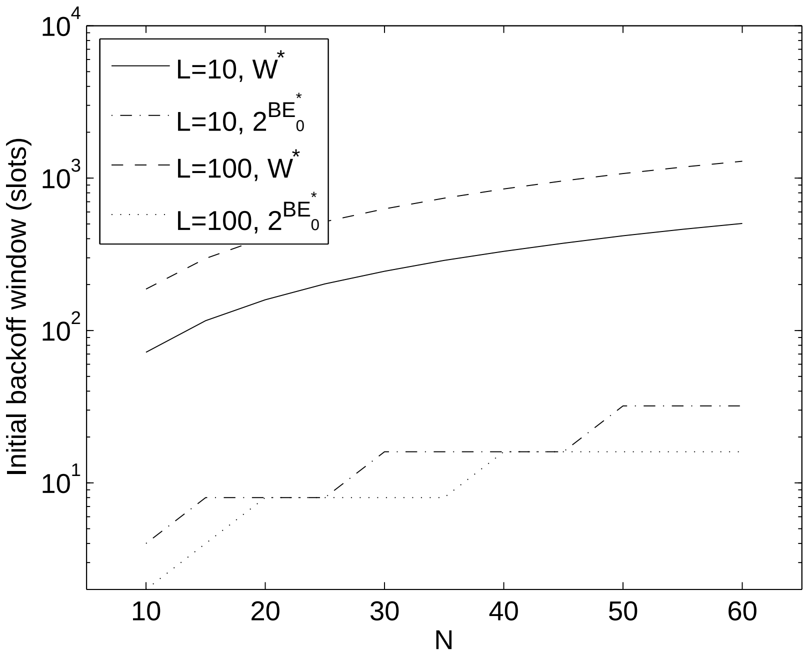


(b)

Figure 4.13: Maximum network throughput and optimal p of p-persistent CSMA/CA protocol with saturated stations



(a)



(b)

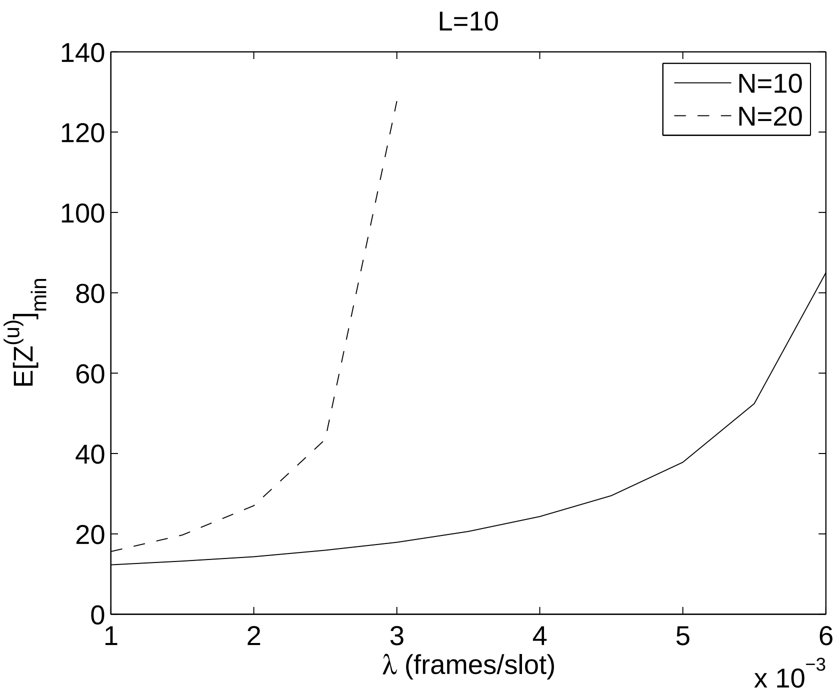
Figure 4.14: Optimal initial backoff window and maximum network throughput of CAP-MAC SS protocol with saturated stations

4.5.5 Discussion on the Optimization for Unsaturated Stations

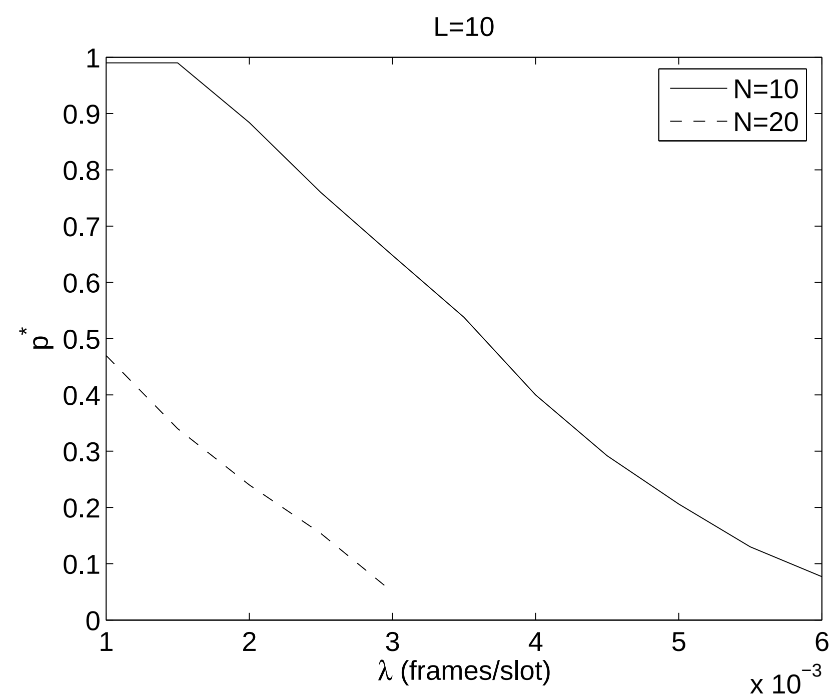
The objective of the optimization in the previous subsection is to maximize the network throughput for saturated stations. For a network with unsaturated stations, the network throughput is always the given aggregate incoming traffic. Therefore, the objective of optimization for such a case is naturally switched to minimize the average frame service time ζ', or equivalently, $E[Z']$.

Without loss of generality, we take the p-persistent CSMA/CA protocol as an example to discuss the possible parameter optimization with a given per station traffic load λ. In this protocol, the adjustable parameter is p and the relationship between $E[Z']$ and p are given by equations (4.9) and (4.14). Nevertheless, it is very difficult, if not impossible, to give a closed-form solution to these two non-linear equations, which makes the task of finding the expression for the optimal p that minimizes $E[Z']$ even more challenging. Notice that p is limited over (0, 1), however, we propose to use the global search algorithm to find the optimal p. For a given λ, the p increases from a small value close to zero (e.g., 0.001) to a value close to and strictly less than one (e.g., 0.999) with a small incremental step $\Delta p = 0.001$. In each step, the corresponding $E[Z']$ is calculated by solving numerically the aforementioned two equations and compared with the recorded $E[Z']_{min}$, which is updated when necessary. With this global search algorithm, the final $E[Z']_{min}$ and its corresponding p^* can be found for a given λ. It is possible that some values of p may make the stations saturate. However, this renders no adverse effect to the algorithm because in such cases the resulting $E[Z]$ is larger than the final $E[Z']_{min}$.

As an example, Figure 4.15 shows the $E[Z']_{min}$ and the corresponding p^* versus λ for the case of $L = 10$ with two different N values (10 and 20). The results show



(a)



(b)

Figure 4.15: Minimum average frame service time and optimal p for p-persistent CSMA/CA protocol with unsaturated stations

that when the traffic load is light, the optimal transmission probability should be set relatively high; with the increase of the traffic load, p^* decreases almost linearly. When the traffic load increases close to the sustainable rate, the service time increases very fast as in Figure 4.3(a) even though the optimal p^* is used.

Note that the above approach is effectively applicable to both the CAP-MAC and the DCF protocols with appropriate mapping between the optimal p and the adjustable parameters such as BE_{min} and W following the discussion in Section 4.5.2. Also, the weakness of unable to give a transmission probability equal to the theoretical optimal still exists in the BEB policies; thus the minimum $E[Z']$ achieved by BEB is slightly larger than the theoretical one.

4.6 Related Work

Being a simple and elegant random access protocol, the p-persistent CSMA/CA protocol is first analyzed by Kleinrock and Tobagi with the "S-G" technique to obtain the throughput-delay characteristics for infinite stations in [55]. Its performance in a network with finite number of stations is studied by the same authors in [97], using the technique of embedded Markov chain, the computational complexity of which becomes inhibitive for systems with large station population. After these two classic papers, there is a long time in which the analysis of this protocol is of very limited interest to researchers, until it is studied again much later by Cali *et al.* when they use p-persistent CSMA/CA as an alternative version of the IEEE 802.11 DCF MAC protocol in [12] and [13].

In contrast, the wide deployment of IEEE 802.11 DCF based wireless LANs (Wi-Fi networks) has attracted great interests from researchers. There are numerous work on the performance study of DCF in terms of throughput and average frame service time, especially for the saturation case. A well-known one on this topic is first reported in [5] and further detailed in [6] by Bianchi. The BEB procedure is modeled as a discrete time two-dimensional Markov chain. The assumption of constant conditional collision probability of frames regardless of the transmission history is first adopted in these papers and later justified theoretically by Sharma *et al.* in [86] by relating it to the mean-field models in statistical physics. A direct extension of the Markov model in [6] is proposed by Wu *et al.* in [110] and Chatzimisios *et al.* in [18] to take into consideration the retransmission limit for each frame as specified in the standard. Along this line, many papers modify the basic Markov model proposed in [6] to consider some other details of the DCF [15, 104, 19, 31, 7], or adapt the Markov model to other backoff variants [74, 102, 111]. Cali *et al.* analyze the p-persistent version of IEEE 802.11 DCF in [12] and [13], using the concept of virtual transmission time of a frame. Based on simulation results, they conclude that the maximum throughput is achieved when the average channel idle time is equal to the average time for collisions, which is further justified analytically in [10]. Tay and Chua analyze the protocol behavior from the long term average point of view in [92]. By computing the average rates of transmission, collision and successful transmission, and utilizing the condition that all these rates sum up to one, the saturation throughput is obtained. Based on the analysis, some insights on how to achieve the optimal performance by adjusting the protocol parameters according to the number of stations are also given in the paper. Following this direction, Kumar *et al.* represent the average transmission attempt rate as the ratio of average transmission times over the average backoff slots, and calculate it using the fixed point technique [57]. It is also pointed out in this paper that by using the fixed point equations, the analysis of the Markov chain in [6] is in fact not necessary. Medepalli and Tobagi extend further this approach to compute the average cycle time of a frame and the saturation throughput in [66].

The only paper adopts the equilibrium point analysis is [106] by Wang *et al.*, which requires a computational effort comparable to that of the Markov chain based models.

Another thread of work is to obtain higher moments of the frame service time. Carvalho and Garcia-Luna-Aceves compute the first two moments of the service time in [15]. In [123], Zanella and Pellegrini study the statistical characteristics of the frame service time by means of probability generating function (PGF), considering directly the distributions of the time of successful transmission, collisions and backoff slots. In another paper [125], Zhai *et al.* give the PGF of frame service time using generalized state transition diagram [81] based on the Markov chain developed in [6]. Vu and Sakurai present a more accurate service time PGF compared with that in [125] by taking into consideration of the dependence between the number of backoff slots and the number of transmissions and collisions of the stations [103]. Using a two-dimensional absorbing discrete time Markov chain, Issariyakul *et al.* model the channel access time in DCF as a phase-type distribution in [49], which is numerically solved by the matrix geometric technique [71].

Recently there are also some papers on the performance of DCF with unsaturated stations. Among them, Zhai *et al.* combine the results in [125] with M/G/1 analysis to calculate the throughput, delay, jitter and packet loss rate for Poisson arrival traffic [124]. Zaki and EI-Hadidi[122] modified the basic Markov model proposed in [6] to have a constant state transition time equal to the slot time. Cantieni *et al.* [14] proposed another modified Markov model by adding some extra states for the so-called "post-backoff" procedure. In both papers, M/G/1 queueing analysis is used to obtain the channel throughput, which may not be directly applicable to some practical applications such as VoIP over WLAN. The post-backoff states are also incorporated in the Markov chain developed by Duffy *et al.* in [25], where the stations are assumed to buffer one frame only. Similar Markov chain based analytical models for finite load situation (e.g., [85] ,[130]) have also been proposed, all assuming specific traffic sources such as Poisson or Bernoulli arrivals. Tikoo and Sikdar [93, 94] extended the work in [92] to the unsaturation case by considering the MAC sublayer queue status. It also models each station as a discrete time G/G/1 queue to obtain the frame delays. Along this thread, Ling *et al.* propose a more accurate model in calculating the average frame service time in [135] and use it to obtain the voice capacity of a DCF based ad hoc mode WLAN.

For the IEEE 802.15.4 MAC protocol considered in this paper, there are several recent analytical works appeared in the literature. A Markov chain based analytical model is proposed in [68, 67] to analyze the access delay of uplink transmissions in an IEEE 802.15.4 beacon enabled PAN of nodes with finite size buffer. Many details of the protocol are taken into consideration in the model. With the assumption of Poisson arrivals to each node and the use of M/G/1/K queueing model, the probability generating functions (PGF) of the access delay and packet queue size at the nodes are derived. In addition, up to date these are the only papers that analyze comprehensively the performance of 802.15.4 MAC protocol with the complete superframe structure. With the assumption that each station's probability to start sensing the channel is independent, the Markov model proposed in [76] gives satisfactory throughput accuracy in the saturated case, where all the nodes always have frames in their MAC buffers waiting for transmission. A more complicated three-dimensional Markov chain is proposed in [89], also for the saturated case only. Another Markov chain based model is presented in [78], and both throughput and power efficiency are studied. It replaces the uniform distribution with a geometric distribution in the selection of a random number of slots in each backoff stage, primarily for analytical tractability. Also, the model limits itself only to a Bernoulli frame arrival process for the unsaturated case. Both [89] and [78] advocate changing the initialization of CW to one, *i.e.*, using single sensing instead of double sensing for the collision avoidance purpose.

Simulation-based studies of the IEEE 802.15.4 protocol have also been reported in the literature for the studies of delay performance [127], energy efficiency in a dense wireless mircosensor network [9], a small size star-topology network [65], scalability issues and the impact of interference from co-existing WLANs in medical environment (e.g, hospitals) [36]. The only performance evaluation that is based on real hardware experiments is reported in [58].

4.7 Summary

We have applied the analytical framework proposed in Chapter 3 to analyze three representative CSMA/CA based MAC protocols: p-persistent CSMA/CA, IEEE 802.15.4 CAP-MAC and IEEE 802.11 DCF. In each application instance of the framework, a pair of fixed point equations is obtained by properly deriving the parameters to capture the features of the specific backoff procedure and channel access policy in the protocol studied. After the fixed point equations are solved, the MAC throughput and the average frame service time for an individual station are obtained. The applications have demonstrated that the proposed framework is a versatile one. It can be used for networks with saturated or unsaturated stations, and for diverse backoff policies. The accuracy of the analysis has been verified by extensive simulation results.

In addition to the analysis of protocols with default parameters given in the standards, we have also analyzed the the theoretical and practical maximum throughput for networks with saturated stations. We found that the theoretical maximum network throughputs of the three protocols are very close especially with large L, despite that the backoff policies are completely different. Besides, in the course of deriving the optimal values of the adjustable parameters in the three protocols, the limitation of binary exponential backoff is discussed in detail. A backoff scheme with fixed backoff window for all the backoff stages is found to be more flexible than the BEB, and is able to approach the theoretical maximum network throughput.

For performance optimization in networks with unsaturated stations, we have studied the minimum average frame service time and the corresponding optimal transmission probability, taking p-persistent CSMA/CA as an example. The approach used is easily extensible to the other two protocols, considering the direct mapping relationship between p and the backoff parameters.

Chapter 5

Networks with Service Differentiation

In the previous chapter, we have studied the performance of several representative distributed MAC protocols in networks with homogeneous service. With the increasing popularity of multimedia applications, wireless networks nowadays are more likely to provide multi-service to users. Accordingly, QoS-aware MAC protocols that can provision differentiated service to different stations have emerged. For instance, in order to enhance the QoS provisioning demanded by multimedia services in WLANs, the recently released IEEE 802.11e [48] defines three service differentiation mechanism: contention window (CW), transmission opportunity (TXOP) and arbitrary interframe space (AIFS). Similar approaches have also been adopted by the Multi-band OFDM Alliance (MBOA) in its contention based medium access protocol called prioritized channel access (PCA) [26] for emerging ultra-wideband wireless personal area networks (WPANs).

Performance evaluation of these mechanisms by means of simulations and theoretical modeling approaches have shown that they are effective in service differentiation provisioning. However, the scenarios studied are quite limited, mostly for networks with saturated stations. To better understand and quantify the effects of these mechanisms in a broader range of network situations, in this chapter, we extend the analytical framework for DCF in Chapter 4 to evaluate their performance in networks with both saturated and unsaturated stations.

The remainder of this chapter is organized as follows. The three mechanisms are analyzed using the proposed framework one by one in the following three sections. Related work on the performance study of these mechanisms is discussed in Section 5.4. The salient features discussed in this chapter are summerized in Section 5.5.

5.1 Service Differentiation with CWs

In this section, the channel busy time caused by frame transmissions from all the stations are assumed to have the same fixed length of L physical slots, regardless of the transmission result as a success or collision. The case of different frame lengths are analyzed in the next section. We derive two key probabilities first, then proceed to the MAC performance metrics.

5.1.1 Analysis of Saturated Stations

Let γ_k and β_k denote the transmitting probability and the frame collision probability of a station of class k, respectively[1]. A frame transmitted by a class k station will experience a collision only when one or more stations of any class transmit in the

[1]In this chapter, the terms "class" and "*AC*" are used interchangeably.

same slot. Therefore, we have the frame collision probability for a class k station as

$$\begin{aligned}\beta_k &= 1 - (1-\gamma_k)^{N_k - 1} \prod_{i=1, i\neq k}^{K} (1-\gamma_i)^{N_i} \\ &= 1 - \frac{\prod_{i=1}^{K}(1-\gamma_i)^{N_i}}{1-\gamma_k}, \quad k = 1, \ldots, K.\end{aligned} \tag{5.1}$$

Since each station performs its backoff procedure only depending on the transmission result of its frame, it enters the next backoff stage only when its frame experiences a collision, which occurs with probability β_k. Therefore, similar to the derivation of γ in (4.54) in Chapter 4, we have the transmitting probability of a class k station given by

$$\gamma_k = \frac{\sum_{i=0}^{M_k-1}(\beta_k)^i}{\sum_{i=0}^{M_k-1}(\beta_k)^i(b_{i,k}+1)}, \quad k = 1, \ldots, K, \tag{5.2}$$

where $b_{i,k} = CW_{i,k}/2$ is the average number of backoff slots in backoff stage i, $i = 0, \ldots, M_k$, and M_k is the retry limit of class k stations. Note that the class-dependent CW parameters have been included in the analysis.

Equations (5.1) and (5.2) can be solved numerically to obtain the transmitting probability γ_k and frame collision probability β_k for all the classes.

In the network with K classes of stations, the channel is idle when none of the stations transmit, which occurs with probability

$$P_{\text{idle}} = \prod_{k=1}^{K}(1-\gamma_k)^{N_k}. \tag{5.3}$$

Therefore, the average length of generic slots in this network is

$$\begin{aligned}E[GS] &= P_{\text{idle}} \cdot 1 + (1-P_{\text{idle}}) \cdot L \\ &= L - (L-1)\prod_{k=1}^{K}(1-\gamma_k)^{N_k}.\end{aligned} \tag{5.4}$$

Following the reasoning in Section 4.3.1, from the viewpoint of a tagged class k station, it conducts a Bernoulli experiment in each generic slot with its successful transmission defined as the success event. Thus, the average frame service time for the tagged class k station is

$$\zeta_k = \frac{1}{\gamma_k(1-\beta_k)} E[GS], \quad k = 1, \ldots, K, \tag{5.5}$$

where $E[GS]$ is given by (5.4). The per station throughput of class k is[2]

$$\eta_k = \frac{L}{\zeta_k}, \quad k = 1, \ldots, K, \tag{5.6}$$

and the network throughput is

$$\eta = \sum_{k=1}^{K} N_k \eta_k. \tag{5.7}$$

5.1.2 Analysis of Unsaturated Stations

For the analysis of unsaturated stations in a network with the three service differentiation mechanisms adopted, the approach given in Section 3.3.1 is still applicable. Similar to the cases in Chapter 4, the key to the analysis in this scenario is that an unsaturated station of class k contends only with probability of $\gamma'_k \rho_k$, where

$$\rho_k = \lceil \lambda_k \zeta_k \rceil^1, \quad k = 1, \ldots, K, \tag{5.8}$$

and λ_k is the average incoming frame rate of a class k station. Therefore, we have the frame collision probability for the tagged station of class k as

$$\beta'_k = 1 - \frac{\prod_{i=1}^{K}(1-\gamma'_i \rho_i)^{N_i}}{1-\gamma'_k \rho_k}, \quad k = 1, \ldots, K. \tag{5.9}$$

Since the proposed model is developed from the viewpoint of a tagged station of each class when it is contending for channel access, we have the transmitting probability as

$$\gamma'_k = \frac{\sum_{i=0}^{M_k-1}(\beta'_k)^i}{\sum_{i=0}^{M_k-1}(\beta'_k)^i(b_{i,k}+1)}, \quad k = 1, \ldots, K. \tag{5.10}$$

[2]As discussed in Chapter 4, L can be replaced by the transmission time of the MAC frame payload for a more accurate throughput calculation, if desired.

In addition, the tagged station of class k contends only with the busy stations from both its own class and the other classes. Therefore, the channel seen by a class k busy station is different from that seen by a busy station of another class. Consequently, the channel idle probability is class-dependent as

$$P'_{\text{idle},s} = (1 - \gamma'_k)(1 - \gamma'_k \rho_k)^{N_k - 1} \prod_{i=1, i \neq s}^{K} (1 - \gamma'_i \rho_i)^{N_i}, \quad k = 1, \ldots, K. \tag{5.11}$$

We further have the class-dependent average length of generic slots as

$$E[GS'_k] = P'_{\text{idle},s} \cdot 1 + (1 - P'_{\text{idle},k}) \cdot L, \quad k = 1, \ldots, K, \tag{5.12}$$

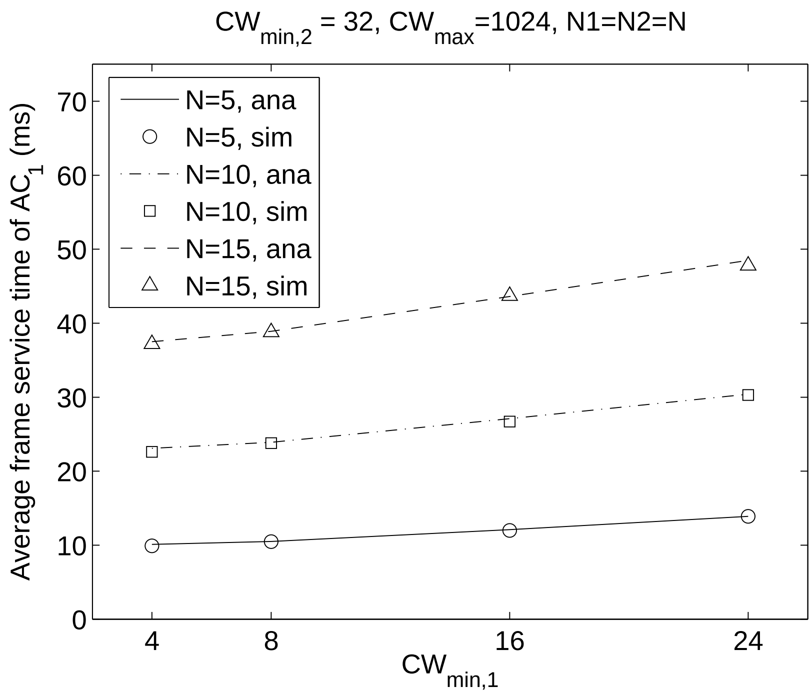
and the average frame service time for the tagged class k station as

$$\zeta'_k = \frac{1}{\gamma'_k(1 - \beta'_k)} E[GS'_k], \quad k = 1, \ldots, K. \tag{5.13}$$

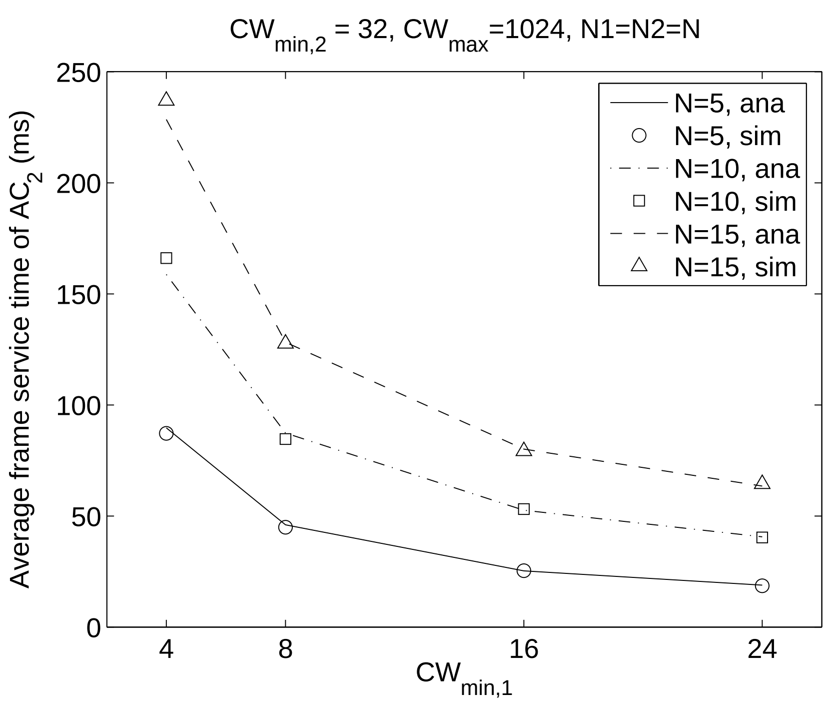
5.1.3 Numerical Results

The differentiation effects of class-dependent CW parameters have been examined by both analysis and simulations. We take the basic access mode of the IEEE 802.11e as the example protocol and consider two classes of stations with different CW parameters. In the following numerical examples, the frame payload is set to 1,000 bytes. Other parameters are set as given in Table 4.1 unless explicitly stated.

For saturated stations of both classes, Figure 5.1 shows the average frame service times for both classes versus the minimum CW ($CW_{min,1}$) of class 1 stations while keeping $CW_{min,2} = 32$ and the maximum CW for both classes as 1024. It can be seen from Figure 5.1(a) that the average frame service time of class 1 stations (ζ_1) does not change much with $CW_{min,1}$, especially when the number of stations in each class N is small. In contrast, as shown in Figure 5.1(b), the average frame service time of class 2 stations (ζ_2) is obviously affected by $CW_{min,1}$, even for a small N. When



(a)



(b)

Figure 5.1: Effect of $CW_{min,1}$ on the average frame service times for saturated stations

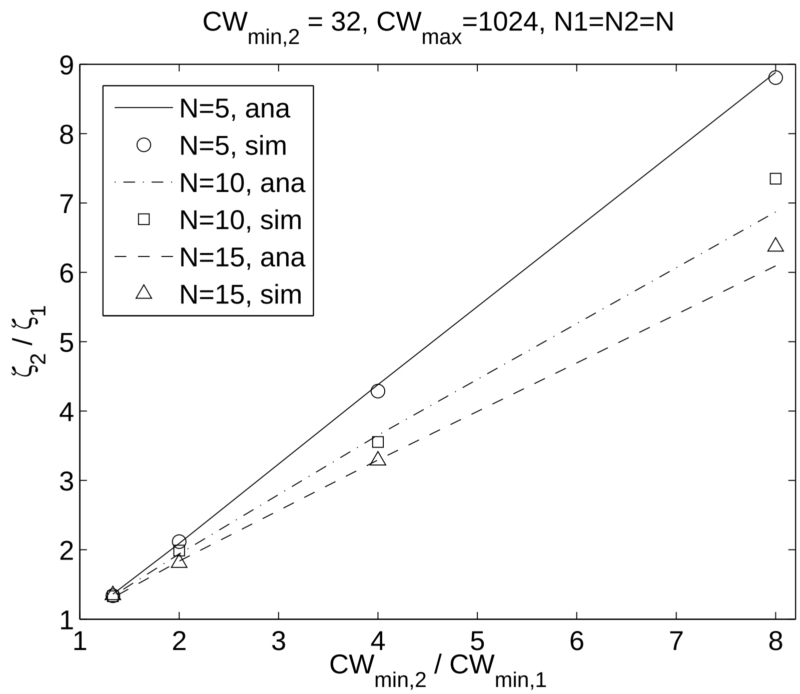
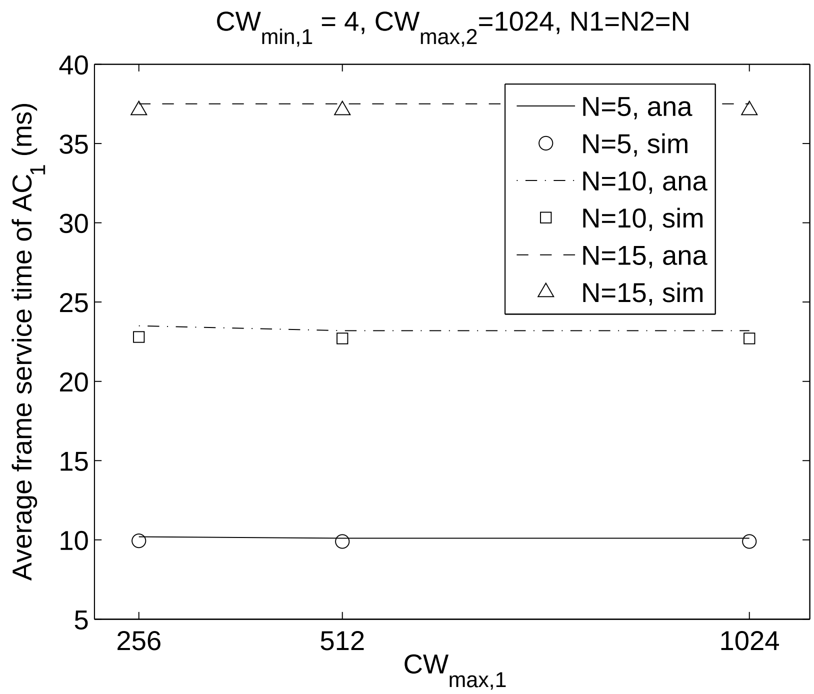


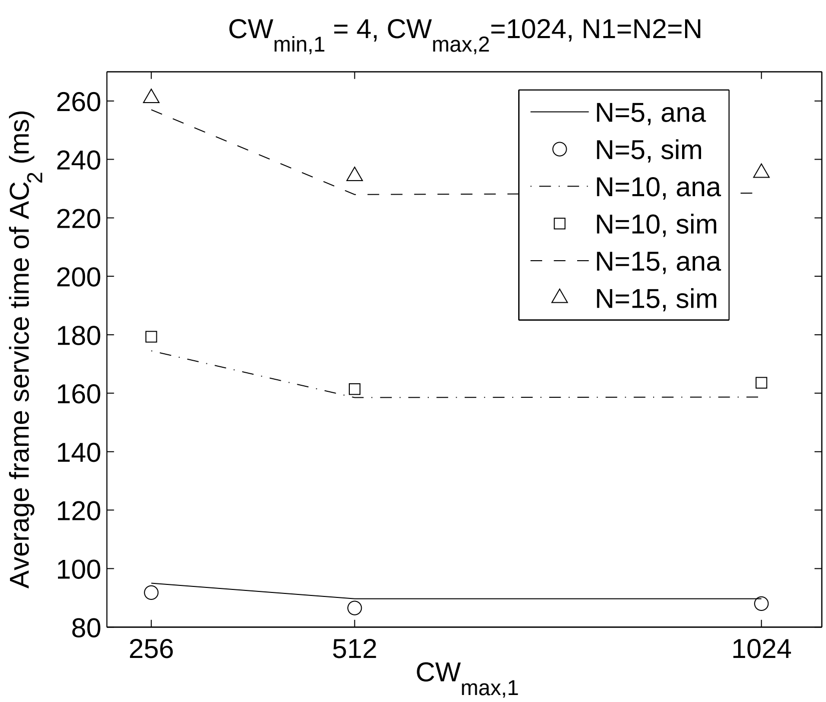
Figure 5.2: ζ_2/ζ_1 vs. $CW_{min,2}/CW_{min,1}$

$CW_{min,1}$ increases from 4 to 16, ζ_2 is shortened dramatically; and the larger the N, the larger the decrease. When $CW_{min,1}$ is further increased to 24, the decrease of ζ_2 is just marginal. The ratio of ζ_2 over ζ_1 versus the ratio of $CW_{min,2}$ over $CW_{min,1}$ is given in Figure 5.2. It shows that the relationship between these two ratios is almost linear, with the slope determined mostly by N if other parameters (such as CW_{max} and $CW_{min,2}$) are kept the same. All these results demonstrate that the class with small minimum CW have higher priority in access the channel. In addition, the smaller the minimum CW, the larger the performance gap between the two classes.

The effect of the maximum CW of the high priority class is shown in Figure 5.3. With the fixed $CW_{min,1} = 4, CW_{min,2} = 32$ and $CW_{max,2} = 1024$, $CW_{max,1}$ changes from 256 to 1024. We can see from Figure 5.3(a) that ζ_1 is almost constant. Fig-



(a)



(b)

Figure 5.3: Effect of $CW_{max,1}$ on the average frame service times for saturated stations

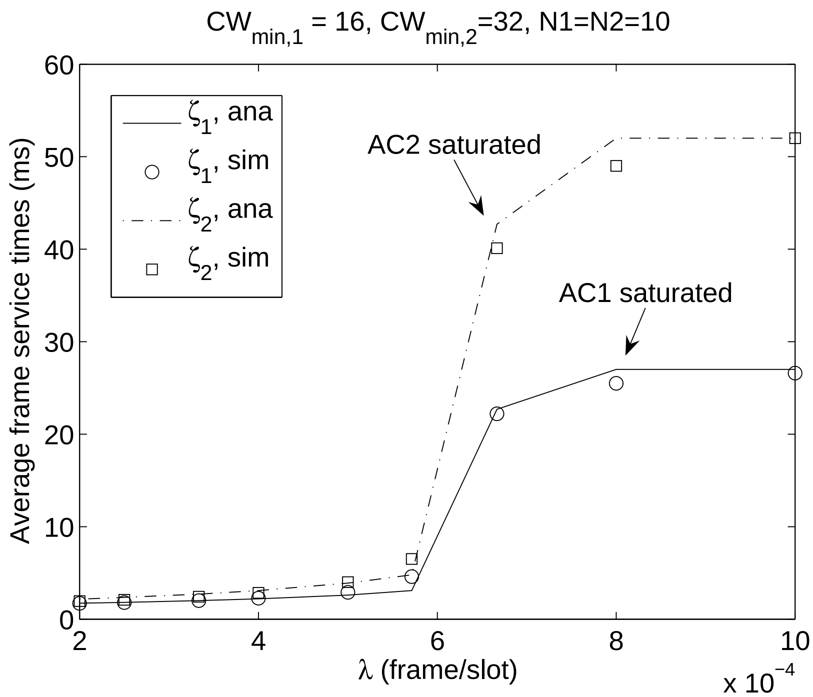


Figure 5.4: Average frame service times with changing traffic load

ure 5.3(b) shows that ζ_2 also changes just marginally, except when $CW_{min,1}$ changes from the relatively small value of 256 to 512 for $N = 15$. Combining the results in Figures 5.1 and 5.3, we may conclude that the minimum CW of the high priority class is the main determining factor of the performance of the two classes, while the maximum CW of it has a much weaker effect.

Figure 5.4 shows the average frame service times of the two classes for changing traffic load (with average frame arrival rate λ frames per slot) to each station, with $CW_{min,1}$ is half of $CW_{min,2}$. It can be observed that when $\lambda < 6 \times 10^{-4}$, the average frame service times of the two classes are both small and increase very slowly. In other words, the CW differentiation effect is not obvious when traffic load is in the range of low to intermediate. When λ is increased to about 6.7×10^{-4}, ζ_2 shows a sharp increase because class 2 stations become saturated with this load. This phenomenon is similar to those in Figures 4.3 and 4.9, and the reason is also similar. Interestingly, ζ_1 also experience a remarkable increase, which is due to the severer contention from class 2 stations resulting from the largely increased ζ_2. More interestingly, despite that class 2 stations have already been saturated, ζ_2 further increases with λ until class 1 stations also become saturated when λ reaches about 8×10^{-4}. The reason of this further increase is that ζ_1 keeps increasing before class 1 stations become saturated finally, which corresponds to deteriorating contention and longer ζ_2; and it stops only after class 1 stations also become saturated.

From the above, we can see that the service differentiation effect of class-dependent CW is only obvious when the stations are about to enter the saturation situation, and it is enforced when the number of high priority class stations becomes larger.

5.2 Service Differentiation with TXOP

With the TXOP service differentiation mechanism, the stations of different classes may be allowed to transmit different number of frames after one successful channel access. In effect, this mechanism also includes the cases of allowing stations to transmit frames of different lengths with the same data rate, or to transmit the same length of frames with different data rates, or both. The effect of allowing different TXOPs on the analysis lies in the calculation of the duration of channel busy periods, which depends on the stations involved in the transmission. Therefore, equations (5.1) and (5.2) are applicable to the analysis of saturated stations and equations (5.9) and (5.10) are applicable to the analysis of unsaturated stations.

5.2.1 Analysis of Saturated Stations

For notation simplicity, let L_k denote the TXOP assigned to class k stations and also the duration of channel busy time caused by a transmission from a class k station. Without loss of generality, assume that $L_1 \geq L_2 \geq \cdots \geq L_K$. Since the stations start to transmit at the beginning of a generic slot independently, it is not difficult to obtain the probability of having at least one class k station transmitting in a slot as

$$\phi_k = 1 - (1 - \gamma_k)^{N_k}, \quad k = 1, \ldots, K. \tag{5.14}$$

In the basic access mode, the duration of a channel busy period is determined by the longest L_k, no matter whether the busy period is caused by a successful transmission or a collision. Then, the average duration of a randomly chosen channel busy period can be calculated as

$$E[L] = \sum_{k=1}^{K} \big(L_k \cdot \phi_k \prod_{i=1}^{k-1} (1 - \phi_i) \big). \tag{5.15}$$

Accordingly, the average length of a generic slot is[3]

$$E[GS] = P_{\text{idle}} \cdot 1 + E[L], \tag{5.16}$$

where P_{idle} is given in (5.3).

In the RTS/CTS access mode, the duration of channel busy time caused by a collision is constant (denoted as L_{col}) while that caused by a successful transmission will depend on the transmitting station. In addition, the transmission time of the RTS/CTS exchange has to be included in the channel busy time $L_k^{(RTS)}$ for each successful transmission from class k stations. Hence, to calculate the average length of a generic slot, we need the probabilities of having a collision (P_{col}) or a successful

[3]Note that all the probabilities in (5.15) sum up to (1-P_{idle}).

transmission from a class k station ($P_{\text{suc},k}$) in a slot, which can be obtained as

$$P_{\text{suc},k} = N_k \gamma_k (1-\gamma_k)^{N_k - 1} \prod_{i=1, i\neq s}^{K} (1-\gamma_i)^{N_i}, \quad k = 1, \ldots, K, \tag{5.17}$$

$$P_{\text{col}} = 1 - P_{\text{idle}} - \sum_{k=1}^{K} P_{\text{suc},k}. \tag{5.18}$$

With the above results, the average length of generic slots in the RTS/CTS mode is calculated as

$$E[GS^{(RTS)}] = P_{\text{idle}} \cdot 1 + P_{\text{col}} \cdot L_{\text{col}} + \sum_{k=1}^{K} P_{\text{suc},k} L_k^{(RTS)}. \tag{5.19}$$

Equations (5.16) and (5.19) can be substituted into (5.6) to obtain the per station throughput of class k in the basic and the RTS/CTS access mode, respectively. After that, (5.7) can be used to obtain the corresponding network throughput.

5.2.2 Analysis of Unsaturated Stations

We consider the basic access mode in this subsection to explain the main point of the analysis. As explained in Section 5.1.2, the channel seen by the tagged busy stations is class-dependent in a network with unsaturated stations. Thus, from the viewpoint of a tagged busy station of class k, it sees a slot containing transmission from at least one class i station with probability

$$\phi'_{i,k} = \begin{cases} 1 - (1-\gamma'_i \rho_i)^{N_i - 1}(1-\gamma'_i), & k = i \\ 1 - (1-\gamma'_i \rho_i)^{N_i}, & k \neq i \end{cases} \quad k = 1, \ldots, K, i = 1, \ldots, K. \tag{5.20}$$

Accordingly, we have the class-dependent $E[L'_k]$ and the $E[GS'_k]$ for a tagged busy station of class k as follows

$$E[L'_k] = \sum_{i=1}^{K} \big(L_i \cdot \phi'_{i,k} \prod_{j=1}^{i-1} (1 - \phi'_{j,k})\big), \tag{5.21}$$

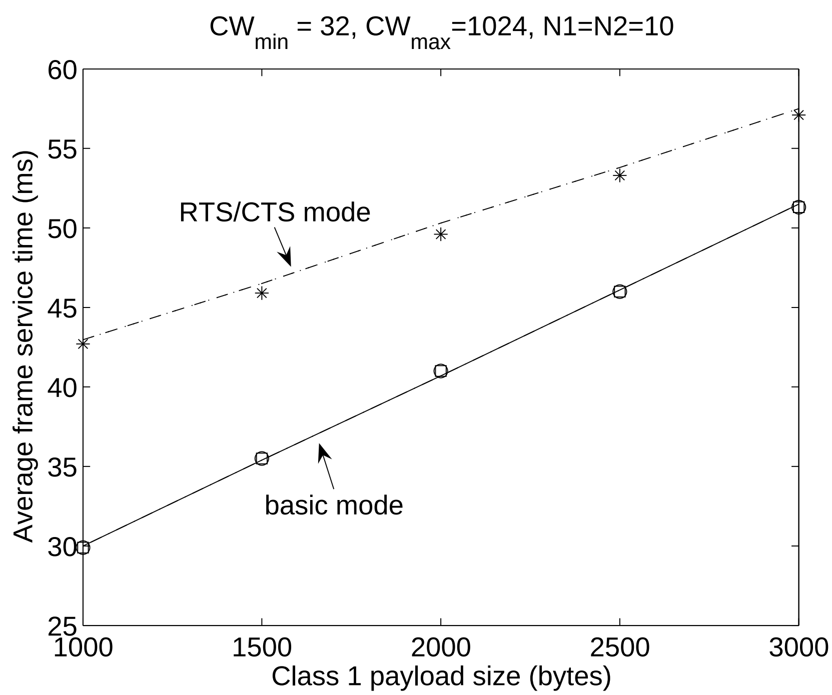
$$E[GS'_k] = P'_{\text{idle, k}} \cdot 1 + E[L'_k], \tag{5.22}$$

where $P'_{\text{idle, k}}$ is given in (5.11). Then, the average frame service time for the tagged class k station can be obtained according to (5.13).

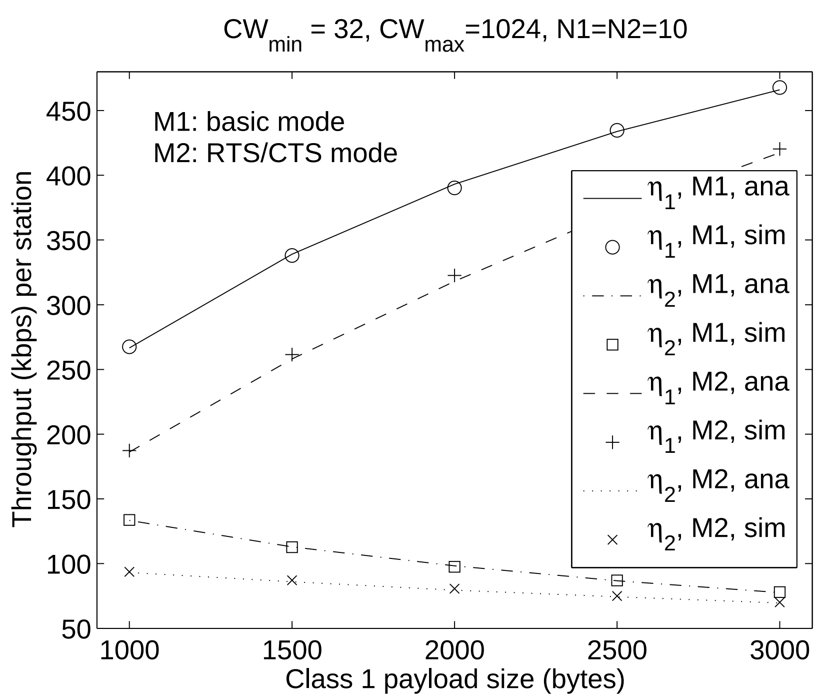
5.2.3 Numerical Results

To show the net effect of TXOP to saturated stations, the CW parameters for the two classes of stations are set to the same. In the following numerical results, the payload size of class 2 stations is 500 bytes, and that of class 1 stations ranges from 1000 to 3000 bytes.

As shown in Figure 5.5(a), the average frame service times (ζ) are almost the same for the two classes. This is because for saturated stations, the contention behavior is completely determined by the CW parameters. With the same CW parameters, all the stations get the same chance in accessing the channel to transmit their frames in the long run [41]. On the contrary, the per station throughputs (η) of the two classes are different due to the different payloads they carry. When ζ increases with the class 1 payload size, η_1 increases proportionally while η_2 decreases slightly. Note that with the given payload parameters, the average frame service time in the RTS/CTS mode is always longer than that in the basic mode, due to the large overhead of RTS/CTS exchange, especially for the class 2 stations with small payload size (see Section 4.3.4). Correspondingly, the throughput in the RTS/CTS mode is lower than that in the basic mode.



(a)



(b)

Figure 5.5: Effect of class 1 payload size for saturated stations

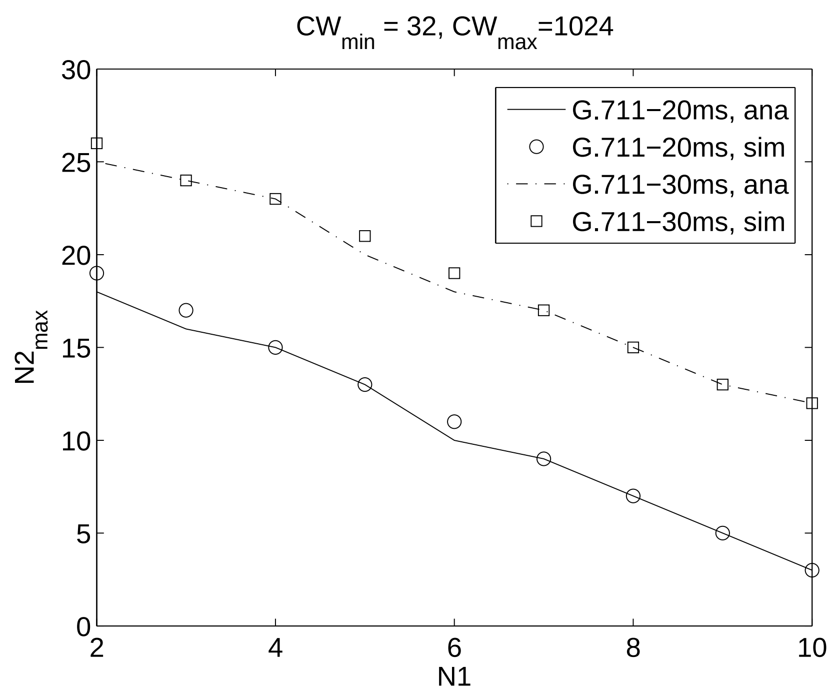


Figure 5.6: Voice capacity with background data traffic

To demonstrate the efficacy of the analytical model for the TXOP, we show the maximum number of supportable voice sessions $N2_{max}$ (also called voice capacity [11]) in a network with background data traffic from saturated class 1 stations with frame payload of 1000 bytes. Each class 2 station carries a 64kbps voice session using the ITU-T G.711 codec [8], the parameters of which is given in Table 5.1. Figure 5.6 shows that the model predicts the voice capacity of the network accurately as verified

Table 5.1: Parameters for the 64kbps ITU-T G.711 Voice Codec

Sample Period (ms)	Arrival Rate (frames/sec)	Payload (bytes)
20	50	160
30	33.33	240

by simulations.

5.3 Service Differentiation with AIFS

With the AIFS mechanism, stations are classified according to their assigned AIFS. In order to focus on the analysis of this mechanism, the following assumptions are adopted in this section: 1) stations belonging to the same class have the same CW; 2) all the stations have the same TXOP; and 3) the basic access mode is used by all the stations, and L denotes the time duration of a channel busy period.

5.3.1 Analysis of Saturated Stations

Due to the different AIFS values assigned, stations of different classes are eligible to contend for channel access in different zones, as shown in Figure 2.3. More specifically, a station of class k is eligible to decrease its backoff counter and transmit, if its backoff counter has been decremented to zero, in zones Z_k to Z_K, for $k = 1, \ldots, K$. As a result, stations face different contention situations and experience different frame collision probabilities in different zones. On the other hand, each station performs its backoff procedure only depending on the transmission results of its frames transmitted in the eligible zones, *i.e.,* it enters the next backoff stage only when its frame experiences a collision, which occurs with probability of β_k, the mean collision probability of frames transmitted in any of the eligible zones. Therefore, (5.2) still holds for stations following the AIFS mechanism, with the above new interpretation of β_k. Then, with the assumption that a station of class k transmits independently with probability γ_k in any slot *in its eligible zones*, we have the following analysis for the collision probabilities.

Frame Collision Probabilities

For a class k station, the collision probability of its transmitted frames in Zone z is given by

$$\beta_{z,k} = 1 - \frac{\prod_{i=1}^{z}(1-\gamma_i)^{N_i}}{1-\gamma_k}, \quad k = 1,\ldots,K, z = k,\ldots,K, \tag{5.23}$$

where the eligibility for transmission in the zones of the station classes has been taken into consideration. The probability $\beta_{z,k}$'s where $z = 1,\ldots,k-1$ are undefined because there is no frame transmission from any class k stations in these zones .

In Zone z, a slot is idle when none of the eligible stations transmit. Hence, the probability that a Zone z slot is idle is

$$a_z = \prod_{i=1}^{z}(1-\gamma_i)^{N_i}, \quad z = 1,\ldots,K. \tag{5.24}$$

For a randomly chosen transmission in the network, it starts in Zone z with probability

$$\begin{aligned} \pi_z &= (1-(a_z)^{\Delta_z})\prod_{i=1}^{z-1}(a_i)^{\Delta_i}, \quad z = 1,\ldots,K-1, \\ \pi_K &= \prod_{i=1}^{K-1}(a_i)^{\Delta_i}. \end{aligned} \tag{5.25}$$

Since a class k station transmits with independent constant probability in its eligible zones, the average collision probability of its transmitted frames can be obtained as

$$\beta_k = \sum_{z=k}^{K}\Big(\frac{\pi_z}{\sum_{z=k}^{K}\pi_z}\beta_{z,k}\Big), \quad k = 1,\ldots,K, z = k,\ldots,K. \tag{5.26}$$

Equations (5.2) and (5.23)–(5.26) can be solved numerically to obtain γ_k and β_k for $k = 1,\ldots,K$. With these probabilities given, we can proceed to obtain the average frame service time for each station class using either of the two methods introduced below.

Average Frame Service Time (Method 1)

The contention zones caused by the AIFS mechanism raise new challenges to the analysis of average frame service time for each station class. In this subsection, we derive the average frame service time based on the analysis of a randomly chosen transmission in the network and its effects on the backoff counter decrement procedure and the associated delay of different stations, as Method 1. The other method that follows the approach in Section 4.3.1 is presented in the next subsection.

Define $\Delta_z = AIFSN_{z+1} - AIFSN_z, z = 1, \ldots, K-1$ as the length of Zone z in units of slots in Figure 2.3, which is also the number of idle slots for which a class $z+1$ station has to wait more than a class z station does before it is eligible to decrement the backoff counter or transmit. Given a transmission starts in any of the Δ_z slots of Zone z, $z = 1, \ldots, K-1$, the transmission may start at the first slot with probability $1 - a_z$, at the second slot with probability $a_z(1 - a_z)$, and so on. Therefore, for such a transmission, the average number of generic slots spent in Zone z is

$$\begin{aligned} E[O_z] &= \frac{(1-a_z)\cdot 1 + a_z(1-a_z)\cdot 2 + \cdots + a_z^{\Delta_z-1}(1-a_z)\cdot \Delta_z}{1-(a_z)^{\Delta_z}} \\ &= \frac{\sum_{i=0}^{\Delta_z-1}(a_z)^i - \Delta_z(a_z)^{\Delta_z}}{1-(a_z)^{\Delta_z}}, \quad z = 1, \ldots, K-1. \end{aligned} \tag{5.27}$$

Thus, the corresponding time spent in Zone z can be obtained as

$$\begin{aligned} E[D_z] &= \frac{(1-a_z)\cdot(0+L) + a_z(1-a_z)\cdot(1+L)}{1-(a_z)^{\Delta_z}} + \cdots \\ &\quad \frac{+(a_z)^{\Delta_z-1}(1-a_z)\cdot\big((\Delta_z-1)+L\big)}{1-(a_z)^{\Delta_z}} \\ &= \frac{(1-a_z)\sum_{i=1}^{\Delta_z-1} i(a_z)^i + (1-(a_z)^{\Delta_z})L}{1-(a_z)^{\Delta_z}}, \quad z = 1, \ldots, K-1. \end{aligned} \tag{5.28}$$

For Zone K (i.e., the last zone), the number of slots spent in it is simply given by

$$E[O_K] = \frac{1}{1-a_K}, \tag{5.29}$$

because it follows the geometric distribution with parameter a_K and the transmission must occur in Zone K if the previous zones have been passed idly. Accordingly, the time spent in Zone K is

$$E[D_K] = (\frac{1}{1-a_K} - 1) + L. \tag{5.30}$$

Note that if a transmission occurs in Zone z, the (possibly existing) preceding zones are all idle[4]. Hence, a station of class k can deduct the average value of

$$E[\widehat{O_{z,k}}] = \begin{cases} \sum_{i=k}^{z-1} \Delta_i + E[O_z], & z = 1, \ldots, K,\ k = 1, \ldots, z \\ 0, & z = 1, \ldots, K, k > z \end{cases}. \tag{5.31}$$

from its backoff counter for a transmission occurring in Zone z. In contrast, the corresponding average time cost associated to this transmission is the same for stations of all the classes, as given by

$$E[\widehat{D_{z,k}}] = E[\widehat{D_z}] = \sum_{i=1}^{z-1} \Delta_i \cdot 1 + E[D_z], \quad z = 1, \ldots, K, k = 1, \ldots, K. \tag{5.32}$$

Therefore, for a randomly chosen transmission in the network, a class k station may deduct its backoff counter by the average value of

$$E[\widetilde{O_k}] = \sum_{z=1}^{K} \pi_z \cdot E[\widehat{O_{z,k}}], \quad k = 1, \ldots, K, \tag{5.33}$$

and spends a time period with average duration of

$$E[\widetilde{D_k}] = \sum_{z=1}^{K} \pi_z \cdot E[\widehat{D_z}], \quad k = 1, \ldots, K. \tag{5.34}$$

Define such a randomly chosen transmission in the network as a *virtual backoff event* for all the stations. A class k station spends an average of $E[Z_k] = \sum_{i=0}^{M_k-1} \beta_k^i (b_{i,k}+1)$

[4]This is not applicable to $z = 1$ because the channel idle time in AIFS1 is included in the calculation of L for each channel busy period.

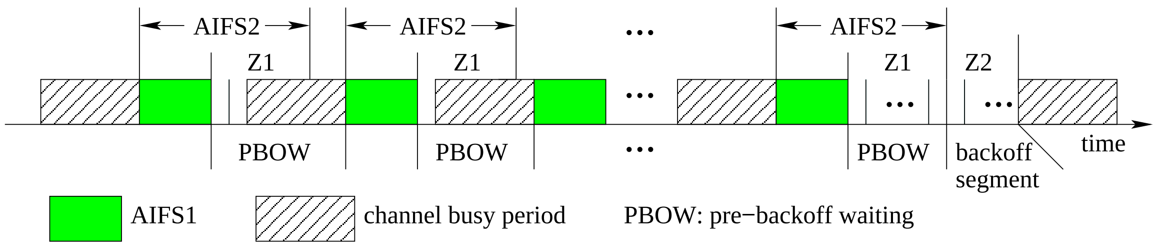


Figure 5.7: Illustration of the backoff segments and pre-backoff waiting periods for a class 2 station

backoff slots for one frame[5], as given in (5.2). According to the above, for a class k station, it takes $(E[Z_k]/E[\widetilde{O_k}])$ virtual backoff events for it to finish the the $E[Z]$ backoff slots, on average. In each such virtual backoff event, the station spends a time period with duration of $E[\widetilde{D_k}]$. Therefore, the average frame service time of a class k station is given by

$$\zeta_k = \frac{\sum_{i=0}^{M_k-1}(\beta_k)^i(b_{i,k}+1)}{E[\widetilde{O_k}]}E[\widetilde{D_k}], \quad k = 1, \ldots, K. \tag{5.35}$$

The above ζ_k can be substituted into (5.6) to obtain the per station throughput of class k, and further into (5.7) for the corresponding network throughput.

Average Frame Service Time (Method 2)

In this method, the average frame service time of a class k station is decomposed into two parts: the pre-backoff waiting time and the backoff time. Define one *backoff segment* of a class k station as the period from it begins to decrement the backoff counter in the first eligible zone to the end of this decrement procedure caused by a transmission from any station, as illustrated in Figure 5.7. For each backoff segment, there may be zero or more pre-backoff waiting periods preceding it, the number of

[5]Note that the generic slots used for transmitting the frame are included in $E[Z_k]$.

which is a random variable. Based on the above main understanding, we take a network with two classes of stations as an example to present the essence of this method as below.

As the high priority class station, the tagged class 1 station involves the contention in both Zone 1 and Zone 2. Therefore, it experiences no pre-backoff waiting periods. Among the average $E[Z_1]$ generic slots it spends for one frame, approximately $E[Z_1]\pi_1$ are in Zone 1 and $E[Z_1]\pi_2$ are in Zone 2. The average length of a generic slot in Zone z can be computed as

$$E[GS_z] = a_z \cdot 1 + (1 - a_z) \cdot L, \quad z = 1, 2, \tag{5.36}$$

where a_z is the probabilities of the channel being idle in Zone z, as given by (5.24). Then, the average frame service time for AC_1 is given by

$$\zeta_1 = E[Z_1]\big(\pi_1 E[GS_1] + \pi_2 E[GS_2]\big) \tag{5.37}$$

The frame service time of the tagged class 2 station contains two parts, as explained earlier. The backoff time that it spends in Zone 2 is given by

$$\xi = E[Z_2]E[GS_2]. \tag{5.38}$$

The pre-backoff waiting time can derived as follows. As shown in Fig. 5.7, when the tagged class 2 station is backing off in Zone 2, the backoff procedure is interrupted when any station transmits, which occurs with probability $1 - a_2$. Therefore, the backoff procedure of total $E[Z_2]$ slots is divided into $E[Z_2](1 - a_2)$ segments. In each segment, only when there are M consecutive idle slots (i.e., an idle Zone 1) after the end of a channel busy period can the class 2 stations start their backoff counter decrementing procedure. This occurs with probability equal to π_2. With probability π_1, one or more class 1 stations may transmit in any of the slot in Zone 1 and the current uncompleted Zone 1 is ended immediately by this transmission. Therefore, for the tagged class 2 station, there are $1/\pi_2$ such pre-backoff waiting periods preceding each of its backoff segment, on average. The mean length of the pre-backoff waiting periods is $E[D_1]$ given by (5.28). Thus, the total time spent in such pre-backoff waiting periods by the tagged class 2 station is given by

$$\omega = E[Z_2](1 - a_2)\frac{E[D_1]}{\pi_2}. \tag{5.39}$$

Summing up the two parts given in (5.38) and (5.39), we obtain the average frame service time for the tagged class 2 station as

$$\zeta_2 = \xi + \omega. \tag{5.40}$$

In the above example, only two contention zones are involved so the time of backoff segments for class 1 stations and that of pre-backoff waiting periods for class 2 are relatively simple to calculate. In a network with more than two classes, for a station of class k with $k > 2$, the pre-backoff waiting periods are of $k-1$ types, each of which covers different number of contention zones. In addition, for a station of class k with $k > 1$, each backoff segment may cover more than one contention zones. These factors make the analysis with Method 2 much more complicated as compared to Method 1. Therefore, Method 1 is recommended in obtaining the average frame service time for the stations.

5.3.2 Analysis of Unsaturated Stations

Following the approach used for the analysis of the previous two mechanisms, we have the following equations for unsaturated stations

$$\beta'_{z,k} = 1 - \frac{\prod_{i=1}^{z}(1-\gamma'_i\rho_i)^{N_i}}{1-\gamma'_k\rho_k}, \quad k = 1,\ldots,K, z = k,\ldots,K, \tag{5.41}$$

$$\beta'_k = \sum_{z=k}^{K}\Big(\frac{\pi'_{z,k}}{\sum_{z=k}^{K}\pi'_{z,k}}\beta'_{z,k}\Big), \quad k = 1,\ldots,K, z = k,\ldots,K, \tag{5.42}$$

$$\gamma'_k = \frac{\sum_{i=0}^{M_k-1}(\beta'_k)^i}{\sum_{i=0}^{M-1}(\beta'_k)^i(b_{i,k}+1)}, \quad k = 1,\ldots,K \tag{5.43}$$

$$a'_{z,k} = \begin{cases} (1-\gamma'_k)(1-\gamma'_k\rho_k)^{N_k-1}\prod_{i=1,i\neq s}^{z}(1-\gamma'_i\rho_i)^{N_i}, z = 1,\ldots,K, k = 1,\ldots,z, \\ \prod_{i=1}^{z}(1-\gamma'_i\rho_i)^{N_i}, \quad z = 1,\ldots,K, k = \min(z+1,K-1),\ldots,K-1, \end{cases} \tag{5.44}$$

$$\pi'_{z,k} = (1-(a'_{z,k})^{\Delta_z})\prod_{i=1}^{z-1}(a'_{i,k})^{\Delta_i}, \quad z = 1,\ldots,K-1, k = 1,\ldots,K, \tag{5.45}$$

$$\pi'_{K,k} = \prod_{i=1}^{K-1}(a'_{i,k})^{\Delta_i}, \quad k = 1,\ldots,K. \tag{5.46}$$

With the above results of $a'_{z,k}$ and $\pi_{z,k}$, each tagged busy station of class k can obtain a set of class-dependent equations as the counterparts of (5.33)–(5.35) in Method 1. All these equations can then be solved jointly to obtain the average frame service time for each station class.

5.3.3 Numerical Results

The net effect of class-dependent AIFS on service differentiation is examined in this subsection. For all the station classes, $CW_{min} = 32$, $CW_{max} = 1024$ and the MAC frame payload size is 1000 bytes.

First, a network with three station classes and 5 saturated stations in each class is considered. The difference between the AIFS of the first two classes is fixed as $\Delta_1 = 1$. Figure 5.8 shows the average frame service time (ζ's) and the throughput (η's) versus Δ_2, the difference between the AIFS of class 2 and class 3. When Δ_2 increases from 1 to 6, ζ_3 increases almost exponentially while ζ_1 almost keeps constant and ζ_2 decreases slightly[6]. Correspondingly, η_3 decreases exponentially while ζ_1 almost keeps constant and ζ_2 have a slight increase. This shows that Δ_2 affects mainly the class 3 stations, because it determines the length of Zone 2 which delays the backoff counter decrement procedure and the channel access of class 3 stations only. A large Δ_2 gives class 3 stations little chance to start the backoff counter decrement procedure. On the contrary, a longer Zone 2 gives class 1 and class 2 stations more chance to contend just between these two classes, which renders a better successful transmission probability than that in Zone 3 where class 3 stations join the contention. Compared with class 2 stations, however, class 1 stations can further backoff and access the channel in Zone 1, which is even less crowded than Zone 2. Hence, the length of Zone 2 (Δ_2) has much smaller effect on the class 1 stations than on the class 2 ones.

With $\Delta_1 = \Delta_2 = 2$, Figure 5.9 shows the effect of N, the number of saturated stations in each class, on the perceived performance of each class. As N increases, the performance of all the stations degrades (i.e., longer average frame service time and lower throughput), due to the severer contention in channel access. Moreover, the performance gaps among the classes increases with N. This is because a larger N means more higher priority stations contend and succeed in accessing the channel in the zone(s) where the lower priority stations are ineligible to contend, which causes longer pre-backoff waiting time to lower priority stations. In addition, class 3 stations, having the lowest priority in channel access, are more sensitive to N than stations in

[6]Note the log-scale of the y-axis in the figure.

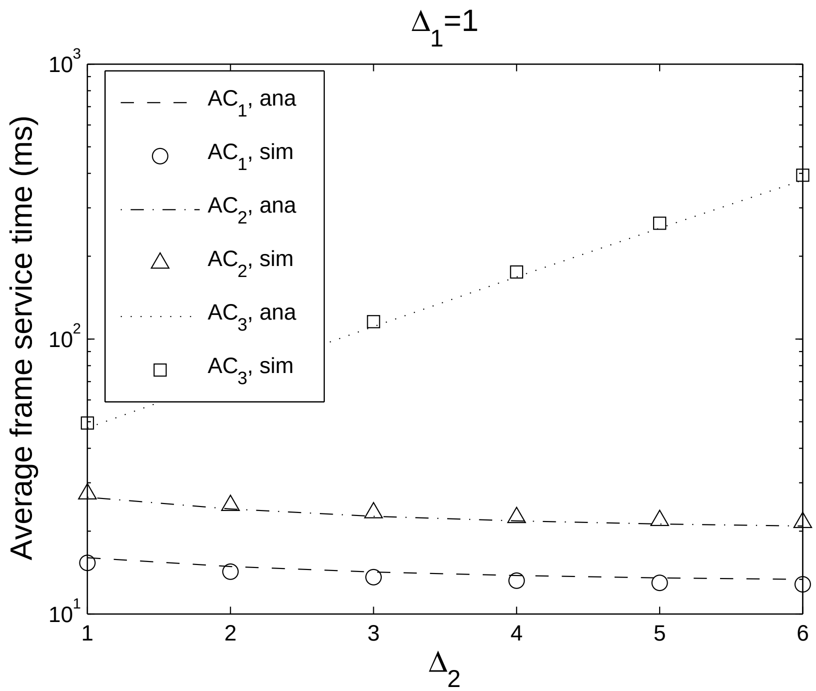
the other two classes.

The effect of AIFS for unsaturated stations is also studied. Two classes with the difference between their AIFS as $\Delta = 1$ are considered, and there are 10 stations in each class. Figure 5.10 shows the average frame service time (ζ) of the two classes changing with the incoming traffic on each station (λ frames per slot). When λ is smaller than about 6.2×10^{-4}, both classes are unsaturated; and the smaller the λ, the smaller the performance gap between the two classes. After the class 2 stations become saturated at $\lambda = 6.3 \times 10^{-4}$, ζ_1 has a slow but steady increase with λ until class 1 stations also become saturated when λ reaches around 7.6×10^{-4}. Therefore, ζ_2 still increases accordingly because the service time for low priority stations is still affected by the increasing ζ_1 in this area. Comparing Figures 5.4 and 5.10, we observe that the service differentiation effect of $\Delta = 1$ is roughly the same as having the CW_{min} halved. As $\Delta = 1$ is the minimum possible difference between AIFS while the ratios of CW_{min} among the classes can be fine-tuned, one may conclude that the service differentiation effect of AIFS mechanism is coarser than that of the CW mechanism.

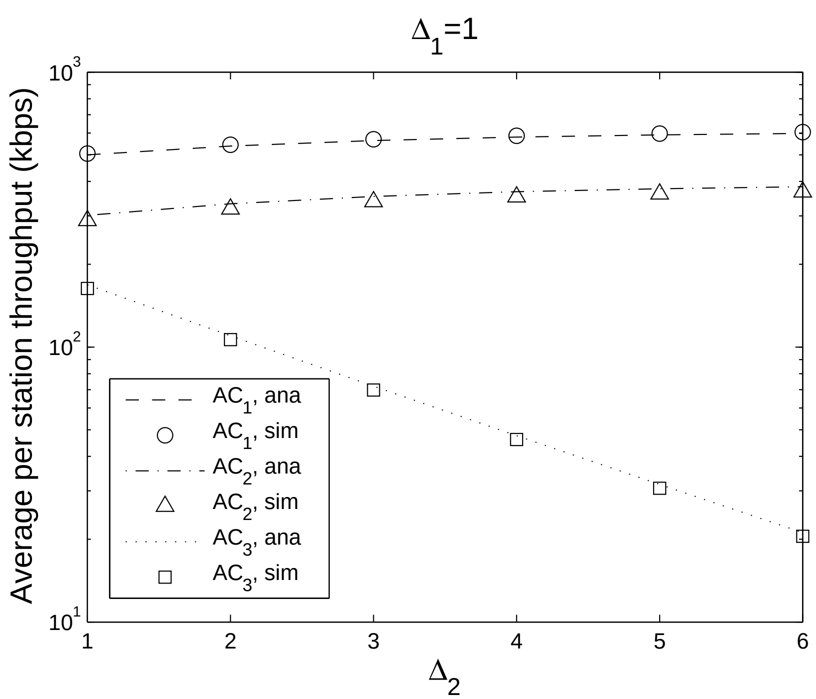
5.4 Related Work

The three main service differentiation mechanisms discussed above were proposed and evaluated by means of simulation in [1]. Performance studies of one or more of the three mechanisms by simulations have also been reported in [38, 39, 63, 22, 116, 73]. Test-bed based experimental evaluation of the IEEE 802.11e protocol is reported in [72]. All these studies demonstrate the diverse effectiveness of service differentiation provided by the three mechanisms.

In the literature, two main techniques have been used to analyze the performance

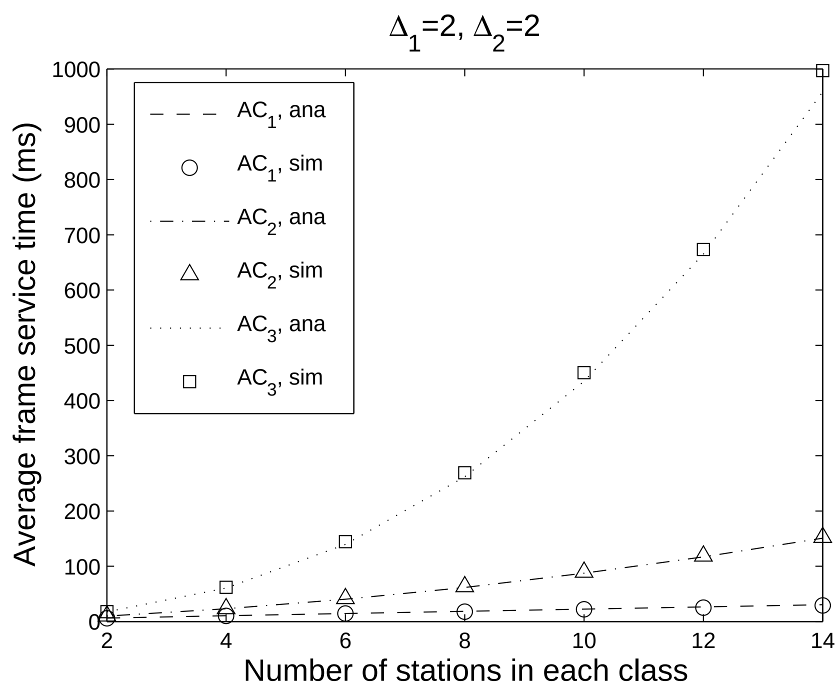


(a)

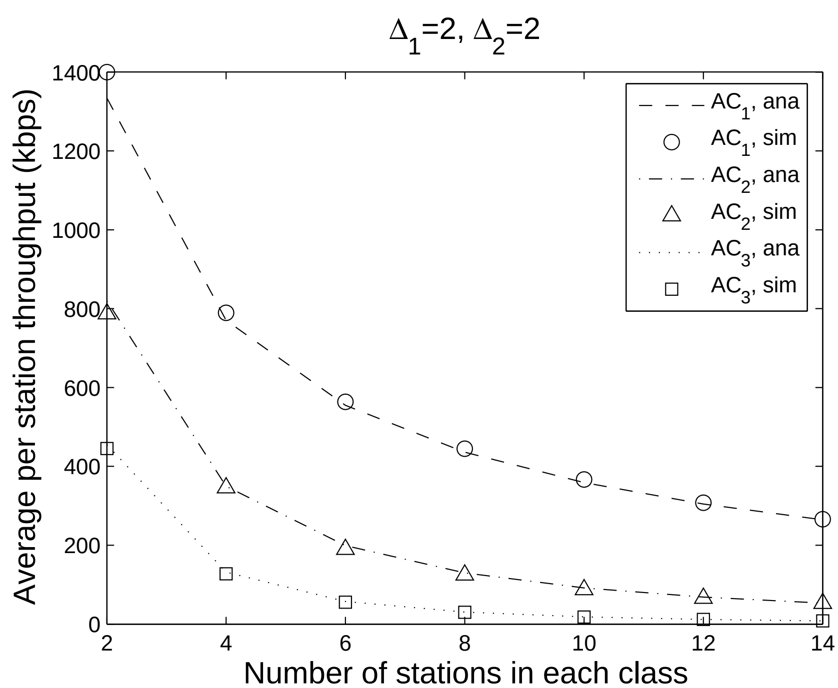


(b)

Figure 5.8: Effects of AIFS for saturated stations



(a)



(b)

Figure 5.9: Effects of N for saturated stations

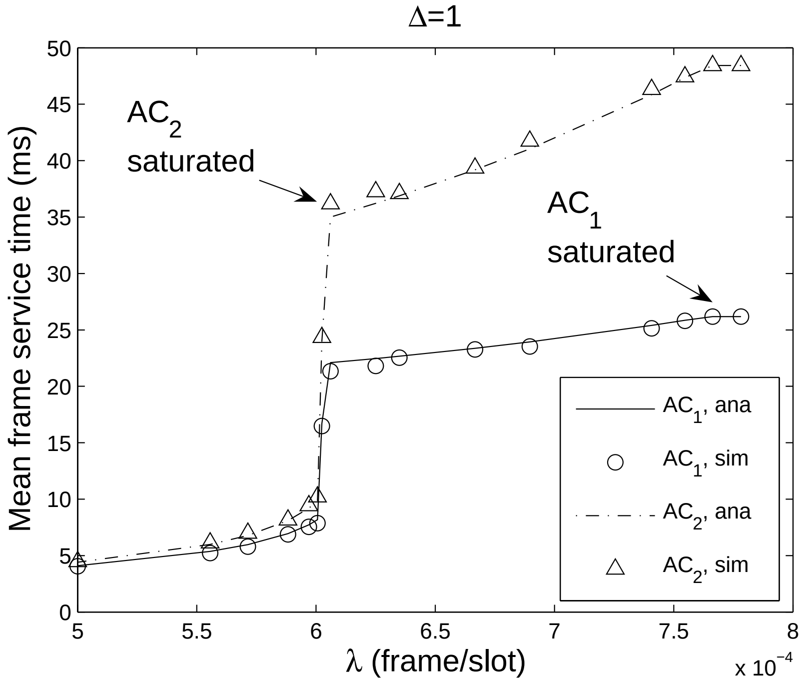


Figure 5.10: Average frame service time with changing traffic load

of these service differentiation mechanisms. The *discrete time Markov chain* widely used in modeling the DCF has been extended to study the performance of EDCA and PCA. Setting up a two-dimension (2-D) Markov chain for stations of each class, the differentiation effect of CW is studied in [77]. Similar 2-D Markov models also appear in [40, 43] for the same topic. A three-dimensional Markov chain is used in [113, 112, 117, 115], where the third dimension represents the station classes. Effects of three backoff related parameters (initial window size, retry limit and the backoff increasing factor) on saturation throughput and delay are studied. The same 3-D Markov model is used in [129] to study the effects of TXOP. The effects of AIFS, however, are not investigated in all the above papers. The contention in different zones delimitated by AIFS is analyzed and the network throughput is given in [82], again with a 2-

D Markov chain for each station class. A three-dimensional Markov chain different from the one in [113] is developed in [126] to obtain the saturation throughput, where the third dimension represents the remaining idle slots before the backoff counter decrements as required by the AIFS of a station. A similar model is used in [61] to analyze a network with only two classes of stations. In [56], another three-dimension Markov chain is developed to describe the protocol behavior and a recursive method is proposed to compute the mean access delay. In [118], a multi-dimensional Markov chain model is proposed for throughput and delay analysis. As the dimension equals the number of stations in the network and each dimension represents the backoff counter value of a station, the state space of the multi-dimensional Markov chain is huge even for a moderate number of stations, and the computational complexity to solve the model is prohibitively high.

Another technique is to approximate the system dynamics by *mean value analysis*, which is applied in [62] to derive the network saturation throughput. Due to the specific approach of handling the extra delay to low priority stations caused by longer AIFS, the model in [62] is applicable only to the case of small difference in $AIFS$' of the station classes. In [44], the station transmission probabilities are obtained from both mean value analysis and multiple two-dimension Markov chain analysis; then the network throughput and frame service time are derived. In [42], the PCA is analyzed using the similar approach introduced in [44], and only throughput is given.

All of the above papers study the saturated situation case only. The common procedure in these models is that the network saturation throughput is obtained first, usually from the analysis of a typical transmission in the network. Then the per station saturation throughput is derived according to the proportional sharing of network throughput among the stations. Finally, the average frame service time is given as the reciprocal of the per station throughput. However, the last step cannot be applied to unsaturated stations, as have been explained in Section 4.1.2. Therefore, even if the per station throughput were known (same as the given incoming traffic load), the frame service time would be very difficult, if not impossible, to obtain with those models. This is the main obstacle in extending those previously reported models to the unsaturated station case.

Recently, the analysis of EDCA with unsaturated stations has been reported in [27] and its follow-up series [28, 29], which extend the three-dimensional Markov model [117] for saturated stations by adding a set of states with no frame to transmit. The frame service time for low priority stations is underestimated due to the overly simplified calculation of blocking delay in the AIFS periods caused by higher priority stations. Moreover, only "extreme non-saturation condition" is considered in the service time analysis for unsaturated stations, which leads to a seriously flawed estimation of the key parameter (queue utilization factor) of the model and further undermines its accuracy.

5.5 Summary

In this chapter, we have proposed a novel analytical model for EDCA-like service differentiation MAC protocols unified for both saturated and unsaturated stations. We model the backoff and channel access behavior of a tagged station in each class, and obtain their respective average frame service time. Based on this result, saturation throughput of individual station is derived. The wide applicability of the model enables us to understand the different effects of the same prioritizing mechanisms in saturated and unsaturated conditions. In addition, the analysis of all the three main service differentiation mechanisms are naturally integrated into this model.

The numerical results show that the service differentiation effects of the three mechanisms are effective especially in a network with saturated stations. Their effects are not so obvious when the traffic load in the network is light and most of the stations are far from saturated. Basically, in the CW mechanism, the minimum CW of each class has a larger effect than the maximum CW when the latter is sufficiently large. Also, the CW mechanism may achieve fine-tuning in service differentiation due to the small granularity of the CW parameter. The TXOP mechanism, if used alone, does not provide differentiation in the chance of channel access, but it does yields different throughput for different classes. The AIFS parameters in the AIFS mechanism has a very strong effect of service differentiation, especially for the lower priority classes. Due to the nature of the AIFS parameter, the smallest possible change of it is one slot. However, an increase of just one slot in the AIFS of a low priority class will cause significant performance degradation to this class and the lower priority ones, but has much smaller effect on the higher priority classes. Compared to the CW mechanism, the AIFS mechanism usually has a much larger granularity in service differentiation among the classes. In general, the three mechanisms may be combined together to achieve the desired level of service differentiation effectively and efficiently.

Chapter 6

Conclusions and Future Work

In this chapter, we summarize the major research contributions of this thesis, and propose future work.

6.1 Major Research Contributions

In this thesis, we have proposed a simple but accurate generic performance analysis framework for a family of CSMA/CA based distributed MAC protocols and applied it to analyze the performance of several popular MAC protocols in wireless networks with homogeneous service and with service differentiation. Any CSMA/CA based distributed MAC protocols can be analyzed with the proposed framework, as long as the backoff and channel access policies are the same for each MAC frame. More specifically, the main contributions of this thesis are

- *A generic performance analysis framework for CSMA/CA based distributed MAC protocols*: Developed from the perspective of a tagged station (of each class), the generic performance framework focuses on modeling the backoff procedure and the channel access behavior and setting up a set of fixed point equations for the key element in the analysis of CSMA/CA based protocols, the probability of channel accessing of an individual station. Based on this key variable, two important MAC performance metrics, average frame service time and the per station throughput are derived from a novel three-level renewal process. The proposed generic framework is applicable to a family of CSMA/CA based distributed MAC protocols regardless of the details of the backoff procedure, the channel access policy and the arrival traffic. First, the backoff procedure may be memoryless (as the geometric backoff in the p-persistent CSMA/CA protocol), and the counting down of the backoff counter may depend on the channel status (as in the IEEE 802.11 DCF), or not (as in the IEEE 802.15.4 CAP-MAC). Secondly, the station may access the channel immediately or one time slot after one successful channel sensing, or after two successful channel sensing events, or even more. Finally, for unsaturated stations, traffic arrival distribution can be general, instead of being limited to Bernoulli or Poisson arrivals as assumed in most previous works.

- *A unified performance modeling approach for both saturated and unsaturated stations*: Most previously reported performance analysis models follow the path of setting up a model to derive the system throughput, obtaining the per station throughput based on the proportional sharing of resource among the stations, and then the average frame service time for each station. Such a path is viable for networks with saturated stations. However, it is not applicable to networks with unsaturated stations or with mixed saturated and unsaturated stations because it is impossible to derive the average frame service time from the throughput of an unsaturated station. The modeling approach in this thesis takes the opposite way by focusing on obtaining the average frame service time, which is the key performance metric for networks with both unsaturated and saturated stations. With this result, the per station throughput and system throughput for networks with saturated stations are straightforwardly derived. Therefore, the modeling approach is unified for networks with saturated and/or unsaturated stations. This unification of modeling helps in studying, within one framework, the protocol performance under a broad range of traffic load, especially in the transition stage where stations change from unsaturation to saturation. Using this unified approach, the *capacity region* of a network with regard to given applications can be obtained, which is the most important information needed by the call admission control scheme to guarantee satisfactory QoS provisioning to end users.

- *Insights into three representative distributed MAC protocols*: The performance of three popular distributed MAC protocols — p-persistent CSMA/CA, the IEEE 802.15.4 CAP-MAC and the IEEE 802.11 DCF — in a network with homogeneous service have been analyzed and compared with the proposed framework. By studying the saturation throughput, we show the mutual-convertible relationship between the p-persistent CSMA/CA protocol and the IEEE 802.11 DCF. We found that the saturation throughput of the three protocols are very close to each other when N and L are large. In addition, we pointed out that, for the CAP-MAC, the double-sensing mechanism can achieve the same *maximum* saturation throughput as the single-sensing mechanism does, although the former gives a lower saturation throughput with a variety of protocol parameters, especially the default parameters given in the standard. The limitation of the widely used binary exponential backoff has also been discussed in detail.

- *Simple and elegant performance analysis of prevalent service differentiation mechanisms*: Assigning class dependent minimum contention window (CW) size, transmission opportunity (TXOP) and arbitration inter-frame space (AIFS) to stations of different classes are the three main service differentiation mechanisms used in current WLANs and WPANs. The proposed analytical framework is naturally extended to study the effects of CW and TXOP, because of the station-centric modeling approach used. Two novel concepts, *virtual backoff events* and *pre-backoff waiting periods*, have been introduced in the more challenging analysis of the effects of AIFS. These two concepts directly reflect the essential service differentiation effect of AIFS (delay the channel access of lower priority class stations) from two different aspects, which make the analysis much simpler and easier to follow than those in other models. The analysis of the three mechanisms show that although all of them can provide service differentiation to stations of different classes, the AIFS mechanism gives a coarser differentiation effect than the CW mechanism, and the TXOP alone just gives throughput differentiation. It is favorable to jointly use the three mechanisms to achieve an effective and efficient service differentiation effect in a network.

An immediate application of the above extended framework is to analyze a network with heterogeneous traffic among the stations even though a non-differentiation MAC protocol is used, e.g., a WLAN with an access point (AP) serving as a gateway to the outside networks and many mobile nodes (MNs) carrying different applications within the WLAN.

6.2 Future Work

The research work in this thesis focuses on the performance analysis of distributed MAC protocols in single-hop wireless networks. The following relevant research topics are of importance and deserve further investigation:

- *Closed-form solution to the proposed analytical model*: In the current work, the two important MAC performance metrics — average frame service time and per station throughput — are obtained from the proposed analytical model by numerical methods. It is desirable to find a closed-form solution to a (probably) simplified analytical model, so that optimization of the parameters can be performed with methods other than the exhaustive search used in this work. In addition, a sensitivity analysis of each parameter may be conducted. Such results will be helpful in the design of a relatively simple, implementable, dynamic/adaptive tuning scheme of the MAC parameters according to the required QoS level of various services coming from upper layers.

- *Cross-layer design for QoS Provisioning*: Most modern wireless networks, including WLANs and WPANs, are required to support multimedia applications with diverse QoS requirements. One typical QoS requirements is the *effective bandwidth* [53] of a bursty traffic with variable data rate [84]. The QoS analysis and flow (or call) level capacity planning in wireless networks is in fact a cross-layer problem, in which the effective bandwidth required by the network layer of QoS guarantee needs to be provisioned by the MAC layer with the help of call admission control (CAC) [21, 100]. Our proposed analytical model unified for both saturated and unsaturated stations is an indispensable element in the cross-layer analytical framework. The MAC service time statistics obtained from the proposed model can be used by the queueing analysis at the network layer to predict the performance of both the existing and the newly arrived flows, and the proper admission control decision can be made to guarantee the QoS requirements of all the admitted flows. Such a cross-layer design framework is an interesting and challenging topic.

- *Performance model for multi-hop wireless networks*: The wireless networks considered in this thesis are single-hop networks in which all the stations are within the transmission ranges of one another and the carrier sensing result is the same for all the stations at a given time. The situation is different in multi-hop wireless networks such as the emerging wireless mesh networks [30, 59] and vehicular networks [99, 121], where the carrier sensing results are location dependent. The resulting *hidden-terminal* problem [96] degrades significantly the performance of CSMA/CA based MAC protocols in multi-hop wireless networks. Since the DCF and EDCA have been naturally used in multi-hop wireless networks [105, 3, 20] due to their success in WLANs, it is important to analyze their performance taking into consideration the hidden-terminal problem and other issues such as the effects of routing schemes on the traffic load on stations along a path [33]. How to extend the proposed model to analyze the performance of such protocols in multi-hop networks needs more investigation.

Abbreviations and Symbols

Abbreviations

AC	access category
ACK	acknowledgement
AIFS	arbitration interframe space
AP	access point
BO	backoff
BE	backoff exponent
CAC	call admission control
CAP	contention access period
CCA	channel clear assessment
CDMA	code division multiple access
CFP	contention free period
CSMA	carrier sense multiple access
CSMA/CA	carrier sense multiple access with collision avoidance
CTS	clear to send
CW	contention window

DCF	distributed coordination function
DIFS	DCF interframe space
DS	double sensing
EPA	equilibrium point analysis
EDCA	enhanced distributed channel access
GS	generic slot
GTS	guaranteed time slot
MAC	medium access control
MIMO	multiple in put multiple output
NACK	negative acknowledgement
NAV	network allocation vector
OFDM	orthogonal frequency division multiplex
OFDMA	orthogonal frequency division multiple access
PCF	point coordination function
PCS	physical carrier sense
PSI	possible station idle period
QoS	quality of service
RTS	request to send
SIFS	short interframe space
SS	single sensing
TXOP	transmission opportunity
VCS	virtual carrier sense
WiMAX	worldwide interoperability for microwave access
WLAN	wireless local area network

WMAN	wireless metropolitan area network
WPAN	wireless personal area network

Main Symbols

D_z	the time spent in zone z of a randomly chosen transmission
H	the number of transmission trials for a frame
K	the number of station classes in a network with service differentiation
L	the channel busy period in units of slots caused by a frame, the associated ACK/NACK transmission and the interframe spaces
M	the frame transmission retry limit in CAP-MAC and DCF
M_k	the frame transmission retry limit for class k stations
N	the number of stations in a network with homogeneous service
N_k	the number of stations in class k in a network with K station classes
O_z	the number of generic slots spent in zone z of a randomly chosen transmission
p	transmitting probability in the p-persistent CSMA/CA protocol
P_b	the probability that the channel is busy
P_{col}	the probability of a collision in the channel
P_i	the probability that a channel is idle
P_{idle}	the probability that a generic slot is idle
P_{suc}	the probability of a Y cycle is of type Y_2
$P_{suc,k}$	the probability of a successful transmission from a class k station
P_{tx}	the probability of a X cycle is of type X_2

R	the random number of transmission trials for a frame
$W(CW_0)$	the minimum contention window
$\hat{W}$	the fixed contention window size
X	level-one renewal cycle
X_1	level-one cycle with transmission from other stations
X_2	level-two cycle with transmission from the tagged station
Y	level-two renewal cycle
Y_1	level-two cycle with a collision involving the tagged station
Y_2	level-two cycle with a successful transmission from the tagged station
Z	level-three renewal cycle
b_m	the average number of backoff slots in backoff stage m
Δ_z	the length of zone z in units of slots
α	the channel sensing failure probability in CAP-MAC
β	the conditional frame collision probability in DCF
η_s	the throughput of an individual station
η	the network throughput
γ	the transmission probability of a tagged station in DCF
λ	the frame arrival rate in units of frame per slot
ω	the number of total backoff slots for a frame in DCF
π_z	the probability of a randomly chosen transmission starting in zone z
ϕ_k	the probability that a class k station transmits
ρ	the probability of having an empty MAC buffer of a station
τ	the transmitting probability of a frame in CAP-MAC
ζ	average frame service time

$^{(d)}$	the superscript indicating variables for the DS case in CAP-MAC
*	the superscript indicating the optimal value of a variable
$'$	the superscript indicating variables for unsaturated stations

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