REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	3.Nov.99	DISSERTATION

4. TITLE AND SUBTITLE
IMPROVING THE REAL-TIME PERFORMANCE OF A WIRELESS LOCAL AREA NETWORK

5. FUNDING NUMBERS

6. AUTHOR(S)
CAPT BALDWIN RUSTY O

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
VIRGINIA POLYTECHNICAL INSTITUTE

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
FY99-386

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

19991117 086

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

14. SUBJECT TERMS	15. NUMBER OF PAGES
	334
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

DTIC QUALITY INSPECTED 4

Improving the Real-Time Performance of a Wireless Local Area Network

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Electrical Engineering

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June 23, 1999
Blacksburg, Virginia

Keywords: Wireless LAN, Real time systems, Access protocols, Integrated voice-data communication, Queueing models

Improving the Real-Time Performance of a Wireless Local Area Network

Rusty O. Baldwin

(ABSTRACT)

This research considers the transmission of real-time data within a wireless local area network (WLAN).

Exact and approximate analytic network evaluation techniques are examined. The suitability of using a given technique in a particular situation is discussed.

Simulation models are developed to study the performance of our protocol RT-MAC (real-time medium access control). RT-MAC is a novel, simple, and elegant MAC protocol for use in transmitting real-time data in point to point *ad hoc* WLAN. Our enhancement of IEEE 802.11, RT-MAC, achieves dramatic reductions in mean delay, missed deadlines, and packet collisions by selectively discarding packets and sharing station state information. For example, in a 50 station network with a normalized offered load of 0.7, mean delay is reduced from more than 14 seconds to less than 45 ms, late packets are reduced from 76% to less than 1%, and packet collisions are reduced from 36% to less than 1%. Stations using RT-MAC are interoperable with stations using IEEE 802.11. In networks with both RT-MAC and IEEE 802.11 stations, significant performance improvements were seen even when more than half of the stations in the network were not RT-MAC stations.

The effect of the wireless channel and its impact on the ability of a WLAN to meet packet deadlines is evaluated. It is found that, in some cases, other factors such as the number of stations in the network and the offered load are more significant than the condition of the wireless channel.

Regression models are developed from simulation data to predict network behavior in terms of throughput, mean delay, missed deadline ratio, and collision ratio. Telemetry, avionics, and packetized voice traffic models are considered.

The applicability of this research is not limited to real-time wireless networks. Indeed, the collision reduction algorithm of RT-MAC is independent of the data being transported. Furthermore, RT-MAC would perform equally well in wired networks. Incorporating the results of this research into existing protocols will result in immediate and dramatic improvements in network performance.

Dedication

To my beloved wife Heather and our children Ian, Nathan, Ryan, Carrie, Noel, and Bethany.

Acknowledgments

During the course of this research, I have received the assistance of many people for which I am very grateful. Chief among these is my advisor, Dr. Davis. During the inevitable crises that occur during a course of research, his expertise, experience, and reassurance were much needed and appreciated. I would also like to thank Dr. Midkiff for his thorough and honest critiques that kept me focused. Dr. Kobza was especially helpful when dealing with the mathematical intricacies of queueing systems. Thanks also go to Dr. Bostian and Dr. Gray for their helpful comments on the drafts of this dissertation. I would also like to thank the faculty and staff of the Center for Wireless Telecommunications; especially, Mr. Woody Farley and Ms. Angie Rutledge. For the use of computing facilities, I am indebted to the Virginia Tech Information Systems Center. For help on statistical matters, I relied heavily on Mr. Robert Noble from the Statistical Consulting Center. Any statistical errors or misstatements that are contained herein are due to my not asking for (or not heeding) the wise advice of Mr. Noble.

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Chapter 1

Introduction

1.1 Background

One would have to be isolated indeed not to have noticed the proliferation of ways in which technology can be used to communicate in modern society. From the dissemination of information by broadcast radio and television, to the exchange of information via two-way radios, telephones, cellular phones and pagers, to the global internet, communications pervades every part of our lives. Technology has had an enormous impact on the industrial and manufacturing industries as well. Production lines and industrial control systems rely more and more on computers, often several, to control manufacturing processes and robotic assembly systems. These computer systems in turn require a variety of communication networks to coordinate their actions. Coordinated action is also vital to the success of military operations. Not only do military commanders require timely information from all of the units under their control, but modern warfare requires extensive communication between the military services (e.g., the Army, Air Force, Navy, etc.) as well as between units in those services. Moreover, military personnel in the field need to communicate with their weapon systems which are often controlled remotely.

In the commercial sector, the desire for mobility while communicating has spurred the development of wireless communication. The cellular phone industry alone has seen a growth rate of more than 50% since 1994 [Rap96]. Since the cellular phone industry has effectively provided access to telephone services from almost anywhere, it follows that there has been a parallel demand for "anywhere, anytime" access to local computer networks and to the global internet as well. Wireless computer networks have been and are being developed to meet this demand. For example, in areas without existing wire-based communications infrastructure, wireless computer networks are a means to provide an "instant" infrastructure without the sometimes prohibitive capital cost associated with wired alternatives. Also attractive is the ability of wireless computer networks to simultaneously carry any kind of data, often more efficiently than traditional wired analog systems. Examples of data that can be transmitted include text, computer programs, electronic mail (e-mail), digitized voice, video, and control data.

Control and voice data are examples of data that have not typically been transported over general-purpose wired (not to mention wireless) packet switched computer networks. When control data (such as that which sends commands to an automated vehicle guidance system) is transmitted, the vehicle must receive and perform the requested action within a certain amount of time—that is, the data has a hard delivery deadline associated with it. A system that has this type of data to deliver is known as a *hard real-time system.* If a deadline is missed in a hard real-time system, a catastrophic failure may occur. This requirement for a time-constrained response is especially pronounced in a vehicle that is traveling at high speeds like an automobile or airplane. General-purpose networks do not provide this type of hard deadline guarantee; more often they provide a best effort service which does not guarantee delivery. Voice data, on the other hand, is more tolerant of variations in delivery time; but it too has a point after which the data is no longer useful. Systems which can tolerate some delay beyond a scheduled delivery time are known as *soft real-time systems.* Digital voice, video, and interactive multi-media systems are examples of this type of real-time system.

Most real-time systems (hard or soft) are specialized; designed and built to satisfy a unique requirement. As such, these systems are typically expensive and not easily transferred to other application areas. Given the increasing demand for real-time systems, especially in the areas of voice and video data, and coupled with the desire for mobility, a low-cost solution to real-time communications is highly desirable. IEEE 802.11 is a recent (1997) standard developed for wireless local area networks (LANs). It has capabilities which can be exploited to provide real-time service. A standards-based solution offers the potential for a low-cost (if not high performance) implementation of an effective real-time system. The motivation for this type of solution is obvious. When first introduced, a typical ethernet network interface card (IEEE 802.3) could cost $1500 or more. Today they can be purchased for less than $40. If, by using industry standards, this same dramatic drop in price can be realized in wireless network interface cards, then sending real-time data via wireless networks may become as commonplace as sending e-mail is on the internet today.

Another challenge real-time systems face is the difficulty of analyzing such systems; especially the analysis of a system's ability to meet deadlines. Assumptions made in order to make the analysis tractable can impose such restrictions on the system model (e.g., Poisson arrivals or constant periodic arrivals) that the model no longer even approximately represents the system that will ultimately be built, thus greatly limiting the usefulness of the analysis. On the other hand, an accurate model that cannot be solved is useless. Thus, there is a tension between analysis that provides a useful approximation and one that accurately models system behavior.

1.2 Research Goals

The goals of this research are two-fold. The first is to extend the body of knowledge with respect to real-time wireless LANs. To that end, this research will develop a real-time wireless LAN protocol that delivers hard real-time data, under a range of operating conditions, using the IEEE 802.11 wireless LAN standard as a point of departure. The IEEE 802.11 contention period (CP) will be used to deliver hard real-time data. This implies medium access will be via a probabilistic distributed algorithm. The primary objective of the protocol will be to ensure (insofar as possible) the delivery of the real-time data prior to deadline expiration. The protocol will accomplish this objective by not transmitting packets that have exceeded their deadline and by transmitting addition information along with a data packet that permits stations in the network to dramatically reduce packet collisions. In addition, a simulation model of the network will be developed to validate the protocol.

The second goal of this research is to develop regression models of the real-time wireless LAN which will accurately predict the deadline performance of stations participating in the network. The techniques used to develop the regression model can, of course, be applied to any network protocol. IEEE 802.11 was chosen because it is a new protocol that has been implemented on real systems and shows promise as becoming a viable standard for wireless LANs. As alluded to above, a model for real-time systems is especially useful so performance can be predicted, and therefore inadequate solutions eliminated, prior to simulation or implementation. While this is desirable in any system, it is especially desirable (but seldom realized) in real-time systems since the theory for real-time systems has not developed to the same degree as other types of systems. In this research, simulation data will be statistically analyzed and used to construct regression models to predict system performance based on the stochastic behavior of packet arrivals, service requirements, deadlines, and wireless channel effects.

To date, investigations of hard real-time data over a wireless link have been limited. Especially difficult to find is any research that incorporates a dynamically varying bit error rate (BER). Further, no research was found that developed regression models to predict real-time performance of such a system.

This research shows that the regression model developed will predict deadline performance of the wireless LAN using probabilistic descriptions of packet arrival, service requirements, and wireless medium characteristics. Additionally, it shows that while IEEE 802.11 may not achieve the throughput efficiency of a protocol specifically designed to handle real-time traffic, it does provide a reliable, effective, low-cost method of delivering hard real-time data across a wireless medium. Simulation of the protocol is discussed as well as results of that simulation. The manner in which various system parameters affect performance is discussed and used to optimize the system.

1.3 Document Overview

This chapter is a brief introduction to real-time wireless LANs. Motivation for the use of industry standards in the design of real-time wireless LANs is presented as well as some of the limitations of analysis techniques when applied to real-time systems.

Chapter 2 presents an overview of wireless LANs. The Open Systems Interconnection (OSI) seven layer network model is briefly presented and the position of IEEE 802.11 within the OSI model is highlighted. Wireless Medium Access Control (MAC) protocols are discussed, especially ALOHA, Carrier Sense Multiple Access (CSMA) techniques, and IEEE 802.11 itself. Several source traffic models and channel error models are reviewed. Finally, relevant research in real-time wireless networks is presented.

Chapter 3 contains a survey of analytic methods used to analyze networks. Concepts and terminology used by these methods is defined. Their suitability for analyzing real-time systems is discussed.

Chapter 4 presents the methodology being employed to meet the research objectives. Goals and assumptions and how they affect performance are discussed.

Chapter 5 describes the protocol developed (called RT-MAC) in detail. The transmission control and collision avoidance modifications are presented.

Chapter 6 contains the simulation results. Charts comparing IEEE 802.11 and RT-MAC for each performance metric is presented and the results are discussed.

Regression models are presented in Chapter 7. Using the simulation data, regression models are developed. The quality of the models and their predictive power is discussed.

Chapter 8 presents the research conclusions and recommendations for further research.

Appendix A contains a detailed description of the IEEE 802.11 simulation model. It includes discussion of the architecture, state diagrams, and detailed behavior. Also discussed are the simulation parameters and factors. The appendix concludes with a presentation of the model validation.

Appendix B contains the simulation data in tabular form, including confidence intervals.

Appendix C contains the SAS [SAS] output obtained during the development of the regression models.

Chapter 2

Background and Literature Survey

Real-time wireless local area networks (LANs), as a subset of wireless LANs, have unique challenges associated with their implementation. This chapter examines some of these issues. Section 2.1 presents an overview of the Open Systems Interconnection (OSI) model, its purpose, and in what areas within the model this research focuses. Noteworthy wireless medium access control (MAC) protocols are presented in Section 2.2 including ALOHA (Section 2.2.1) and carrier sense multiple access (CSMA) (Section 2.2.2). Their similarities and differences are discussed and compared; throughput performance of each scheme is addressed. Section 2.2.3 is dedicated to IEEE 802.11. The operation of the protocol is explained and its performance is highlighted. Section 2.2.4 covers previous proposed or actual real-time MAC protocols. Section 2.3 surveys some traffic and channel models commonly used in simulations. An overview of related research efforts is given in Section 2.4.

2.1 OSI Network Model

The OSI network model serves as a frame of reference for discussing various network architectures. The model separates the functions (or services) that are performed in a computer

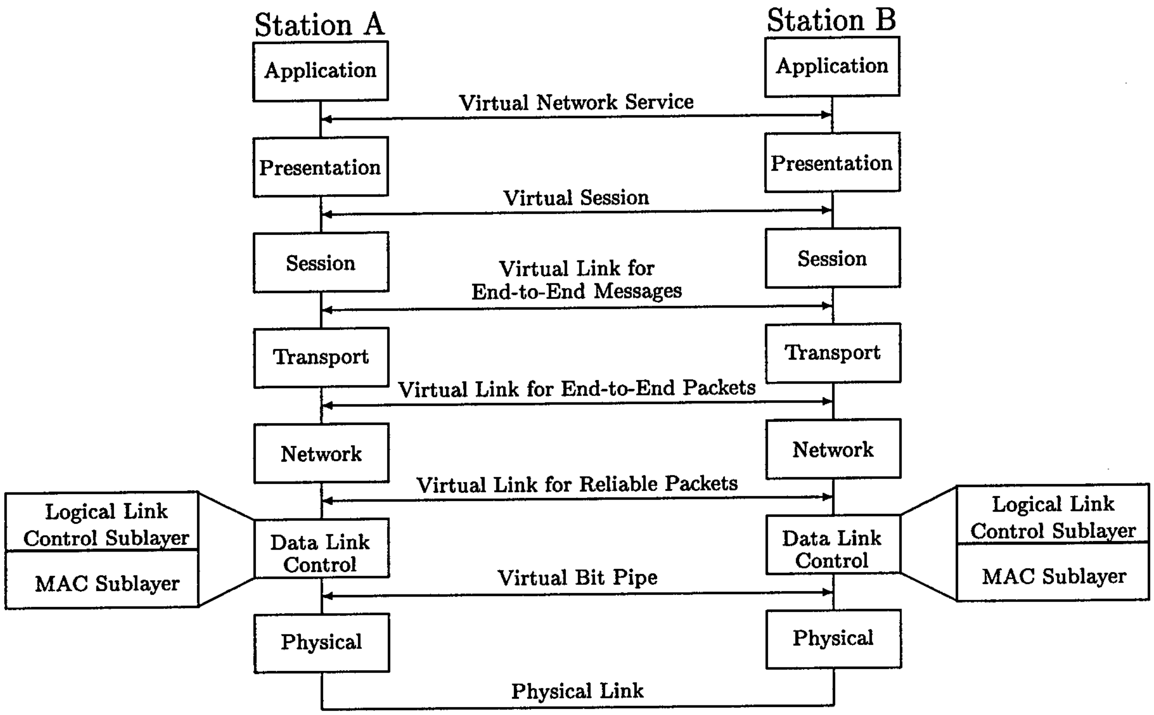


Figure 2.1: OSI Network Model

network into a layered hierarchy. Each station (or computer) in the network can be thought of as having each of the layers in the OSI network model implemented in a separate black box. Each box provides all of the services performed by that layer. A given layer will only communicate with the same layer on a different station or, within the station where the layer resides, the layer immediately above it and below it. Each layer provides services to the layer above it and receives services from layer below it. In Figure 2.1 (adapted from [BG92]) a graphic presentation of that concept is presented. This figure depicts two stations in a LAN. Note how each of the seven layers only communicates with the layer above, below, or the same layer on a different station by a virtual link.

The physical link (shown at the bottom of the Figure 2.1) is what is actually used to transfer information between stations. Once specified, it is the one item in the network model which cannot be directly manipulated; it is simply used. If the physical link is highly reliable, as in fiber-optics and wires, it may be assumed to be error-free. If, however, the link is a radio, it is likely that there will be errors introduced into the information transferred between the stations. It is the job of each of the layers in the model to correct or mask these errors so that the next higher layer receives "error-free" service.

2.1.1 The Physical Layer

The physical layer deals directly with the actual medium, the physical link, connecting the stations. On the transmitting station, the primary service the physical layer provides is to accept bits from the data link control layer (DLC) and to transform those bits into the appropriate signals that will transfer the information through the physical link. On the receiving station, the physical layer converts those signals back into bits and presents them to the DLC on the receiving station. This service is sometimes referred to as a *virtual bit pipe.*

2.1.2 Data Link Control Layer

The data link control layer transforms the unreliable virtual bit pipe provided by the physical layer into an error-free reliable link between stations (i.e., a virtual link for reliable packets). On a transmitting station, this layer may break a long sequence of bits to be transmitted into smaller pieces or fragments. To these smaller pieces it may append other bits to be used on the receiving station for error correction or detection. Upon reception, the receiving station uses these extra bits to correct any errors or, if required, it may request retransmission. The station may simply discard the corrupt data depending on the protocol being used. Once the DLC layer has error-free bits (however obtained) it will then, if required, reassemble the fragments of bits into a format suitable for the next higher layer.

If the medium used to connect the stations is not a point-to-point link (that is, the medium is being shared by multiple stations), then a sublayer within the DLC known as the Medium Access Control (MAC) sublayer coordinates access to the medium between all the stations. The IEEE 802.11 standard, for example, defines this sublayer for wireless LANs.

2.1.3 The Network Layer

Routing and flow control are the primary services the network layer provides. This layer is responsible for routing data from one station to another in the network. In a network where all stations can hear the transmissions of all other stations (such as a LAN), this function is trivial. In a wide area network (WAN), this layer determines the intermediate stations that the data must traverse in order to arrive at its ultimate destination. Flow control is used in a WAN to avoid network congestion. In a LAN, this function is handled in the DLC layer.

2.1.4 The Transport Layer

The transport layer is responsible for providing reliable end-to-end transport of data between processes. In contrast to lower layers which handle communication between individual stations in the network, this layer handles communication between processes on those stations. This layer performs several functions which may or may not be needed depending on a given network. It may break up large amounts of data into packets suitable for lower layers or reassemble and reorder packets destined for higher layers. It may also, for efficiency, multiplex data from several processes destined for the same station into one packet. This, of course, will need to be de-multiplexed by the transport layer on the receiving station.

2.1.5 The Session Layer

The session layer acts as a network service broker of sorts. It locates network services and then establishes, maintains, and terminates connections between processes. Prior to establishing a connection it may check the access rights of a process to use a particular network service.

2.1.6 The Presentation Layer

The major services of this layer are encryption/decryption, compression/de-compression, and code conversion. Encryption and compression are self-explanatory. Code conversion may need to be done when transferring data between machines with incompatible representations of data. For instance, text characters are represented, primarily, by two codes; Extended Binary Code - Decimal Interchange Code (EBCDIC) and American Standard Code for Information Interchange (ASCII). These might have to be converted from one to another between stations using different codes.

2.1.7 The Application Layer

All applications access network services at the application layer. The protocols used at this layer are necessarily user dependent. Whereas network layers below this layer handle services common to all applications requiring network access, this layer handles tasks specific to a given application.

The OSI network model is, undoubtedly, a convenient frame of reference for network models; however, it is seldom (if ever) strictly followed in an actual implementation. Therefore, in order to ensure compatibility between stations at the physical and the data link layers, the IEEE defined the 802 family of standards of which the IEEE 802.11 (the wireless LAN standard) is a part. IEEE 802.11 is presented in Section 2.4.1.

2.2 Wireless Medium Access Control (MAC) Protocols

From the earliest wireless LANs such as ALOHA [Abr70], research into wireless LANs has continued uninterrupted. Early research identified fundamental principles and analysis techniques [KT75], [Kle75], [Kle76], [Abr77], [Kle78], [FST76], [TK78], [KS80] which are still applicable, as well as fundamental problems that are still encountered [TK75], [TK77]. As briefly discussed above, MAC protocols are part of the DLC layer in the OSI model. A MAC protocol is used whenever multiple stations require access to the same medium to transfer data. The number of MAC protocols that have been developed is vast. In this section, the focus will be on several fundamental MAC protocols used in wireless networks.

2.2.1 ALOHA

It is appropriate to begin this presentation by considering one of the first wireless multiple access protocols—ALOHA. ALOHA is a contention-based protocol; that is, stations must compete with each other for access to the medium. ALOHA uses a truly random access approach to medium access; stations transmit as soon as they have data. Since transmission is immediate, ALOHA is also asynchronous. When two stations access the medium at the same time, the resulting collision is resolved by retransmission of both messages after random delays. The throughput equation of pure ALOHA, $S = Ge^{-2G}$, is well known [Abr77]. S is the normalized throughput in packets and G is the normalized channel traffic in packets. The equation reaches its maximum at $G = 0.5$ where $S = 0.184$. While a utilization of 0.184 is poor, the advantage pure ALOHA has over other protocols is its utter simplicity. There are but two rules: (1) transmit when data is ready, and (2) retransmit if the packet is not acknowledged.

An improvement on pure ALOHA, in terms of utilization, is slotted ALOHA. In slotted

ALOHA, transmissions can only occur at the beginning of fixed time slots. Slotted ALOHA's throughput equation is $S = Ge^{-G}$ and has its maximum of $S = 0.368$ at $G = 1$ [Abr77]. While slotted ALOHA is not as simple as pure ALOHA, the added complexity of fixed slots is minimal and the performance gain is substantial.

Another variation on the ALOHA protocol is Reservation-ALOHA (R-ALOHA). The primary difference in R-ALOHA is that it is not a contention-based protocol. The performance of R-ALOHA is given in [CN95]. Using the reservation strategy, requests are sent on the same channel as the data during idle periods (and are themselves subject to collisions). A successful reservation request results in the reservation of the channel for a normalized period of v^{-1} where v is the ratio of reservation request duration to packet length duration. For the case of $v = 0.05$ and $G = 20$, a maximum throughput of $S = 0.88$ was determined by analysis and simulation in [CN95]. R-ALOHA clearly outperforms the other protocols but, again, at the cost of added complexity. Another interesting result is described in [CN95]; the performance of R-ALOHA is identical to the performance of slotted non-persistent carrier sense multiple access/collision detection (CSMA/CD) when the reservation time and propagation delay are equal.

As a final example of ALOHA-based protocols, Generalized Multi-copy ALOHA is considered [Leu95]. In multi-copy schemes, multiple packets are transmitted in hopes of avoiding collisions in one of the packets. An individual attempt in a multi-copy scheme is called a trial. Obviously, the time between trials is randomized, otherwise collisions would occur again and again. In generalized multi-copy, capture is also employed. Capture is a technique whereby the receiving station may recover one signal from many that were transmitted given sufficient signal strength and additional signal processing. When a station transmits a packet, it transmits with power $J (J > 1)$ watts with probability B. Maximum throughput is determined as a function of K trials, the probability of transmitting at high power B, and normalized channel traffic A. The performance of generalized multi-copy ALOHA has a constant maximum throughput of $S = 0.5$ for a normalized arrival rate of $\lambda > 2$. In order to relate λ to the offered load, G, recall that $G = \lambda T$ where T is the packet length. Using the

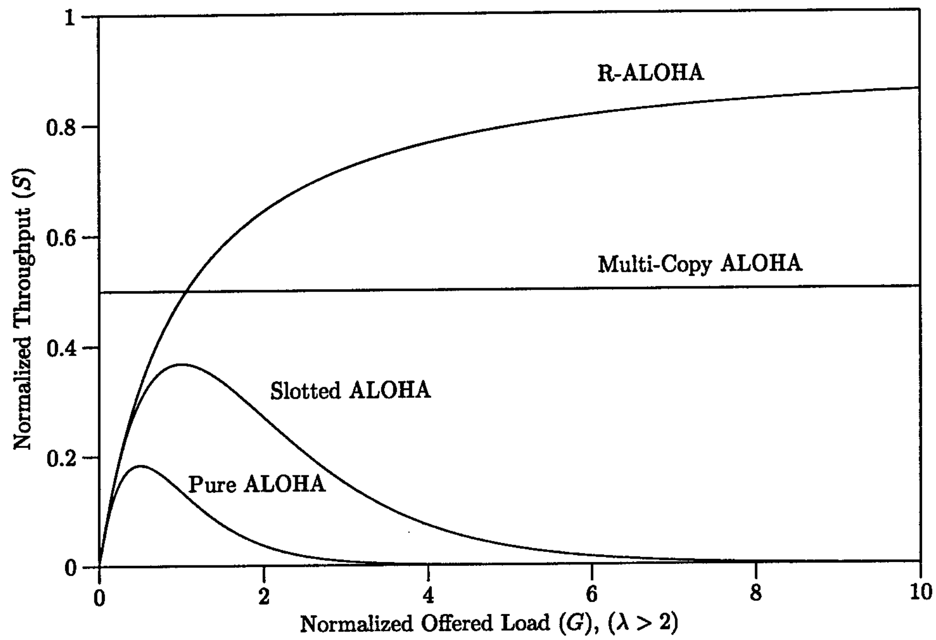


Figure 2.2: Performance of ALOHA Protocols

assumption that $G > 2T$, the performance of the different variations of ALOHA (Figure 2.2) can be compared.

Generalized multi-copy ALOHA appears to be a very effective alternative for normalized packet lengths $T < 0.5$ when compared to R-ALOHA; it outperforms slotted ALOHA and pure ALOHA in all cases (assuming a minimum normalized arrival rate $\lambda > 2$).

2.2.2 Carrier Sense Multiple Access (CSMA)

Arguably the definitive performance analysis of CSMA techniques is [KT75]. Extensive descriptions and analysis of variants on the basic CSMA technique such as non-persistent CSMA, 1-persistent CSMA, p-persistent CSMA, and slotted CSMA and the like are presented. The interested reader is encouraged refer to it for a detailed treatment of CSMA. In that work the authors define CSMA as a technique used in multiple access systems where stations, prior to transmitting, first listen to the medium to determine whether or not it is idle. If it is not idle, transmission is deferred. Recall that in the ALOHA MAC protocols, idle medium detection was not performed.

Several variants of CSMA have been devised. In non-persistent CSMA, if the medium is determined to be busy, the packet is rescheduled for later transmission. In p-persistent CSMA, if the medium is busy, a packet will be transmitted (upon the medium becoming idle) with probability p. Finally, in 1-persistent CSMA, a packet will be transmitted with certainty upon the medium becoming idle.

Propagation and detection delay are important factors affecting the performance of CSMA. Consider the following equation [BG92],

$$\beta = \frac{\tau C}{L} \tag{2.1}$$

where β is equal to the total delay (propagation and detection) in packets, τ is the total delay in seconds, C is the raw channel bit rate, and L is the number of bits in a packet. It is obvious that as β increases, then the performance of CSMA decreases because stations must wait longer prior to accessing the medium. The raw channel bit rate, C, and the number of bits per packet, L, then, are key parameters in CSMA performance.

The throughput equation for non-persistent CSMA is

$$S = \frac{Ge^{-\beta G}}{G(1+2\beta)+e^{-\beta G}} \tag{2.2}$$

where S is the normalized throughput in packets, G is the normalized channel traffic in packets, and β is the delay [KT75]. Figure 2.3 shows CSMA throughput for various values of β. As indicated above, smaller values of β can achieve a higher maximum throughput.

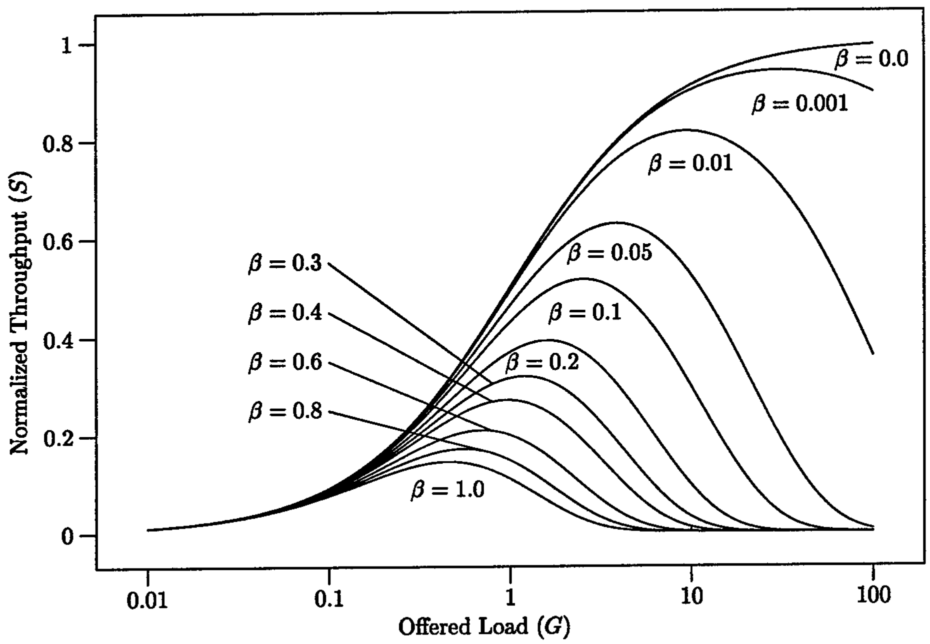


Figure 2.3: Throughput in Non-Persistent CSMA

2.2.3 IEEE 802.11

IEEE 802.11 [Edi97], the last wireless MAC to be considered, uses non-persistent CSMA for medium access. Three different physical layer specifications are currently defined: frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS), and infrared (IR). Both FHSS and DSSS use the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. For reference, the ISM frequency bands are shown in Table 2.1 [Dix94]. The IR specification uses near-visible light in the 850 nm to 950 nm range. Two mandatory data rates are currently supported: 1 Mbps and 2 Mbps. Data rates upto 30 Mbit/s have been proposed [Bra98], but all stations must use the 1 Mbps rate for sending and receiving control frames to ensure compatibility among stations transmitting at different data rates.

At the MAC sublayer, IEEE 802.11 supports both contention-free access to the medium, the Point Coordination Function (PCF) which is under the control of a single point coordinator (PC); and contention-based access to the medium, the Distributed Coordination Function (DCF). As can be seen in Figure 2.4 [Edi97], the PCF ultimately uses the contention-based

Table 2.1: Industrial, Scientific, and Medical (ISM) Frequency Bands

ISM Frequency Band (MHz)	Available Bandwidth (MHz)
902–928	26.0
2400–2483	83.5
5725–5870	125.0

DCF to provide access to the physical layer. It is the responsibility of the PC to ensure only one of the stations using the PCF transmits at a time.

IEEE 802.11 also has provisions for a station to operate in a power-save mode, only "waking-up" at specified intervals to determine if there is traffic bound for it. Stations that need to transmit frames to a station that is in power-save mode queue the frames till the destination station can receive them. Further details about this operating mode can be found in [Edi97].

2.2.3.1 The Distributed Coordination Function

IEEE 802.11 prioritizes access to the medium by specifying a time interval between frames known as the inter-frame space (IFS). By definition, during an IFS the medium is idle. The different types of IFSs, along with the backoff mechanism described below, are the core mechanism a station uses to determine whether it may transmit. This core mechanism is known as the basic access method.

There are four types of IFS: Short IFS (SIFS), PCF IFS (PIFS), DCF IFS (DIFS), and Extended IFS (EIFS). EIFS, which is the longest IFS in terms of time, is used when bit errors introduced by the physical medium cannot be corrected by the radio receiver; it will not be discussed further. Transmission after SIFS, the shortest IFS, is reserved for the PC to send any type of frame required or for other stations to begin transmission of an acknowledgment (ACK) frame, a clear to send (CTS) frame, to respond to polling by

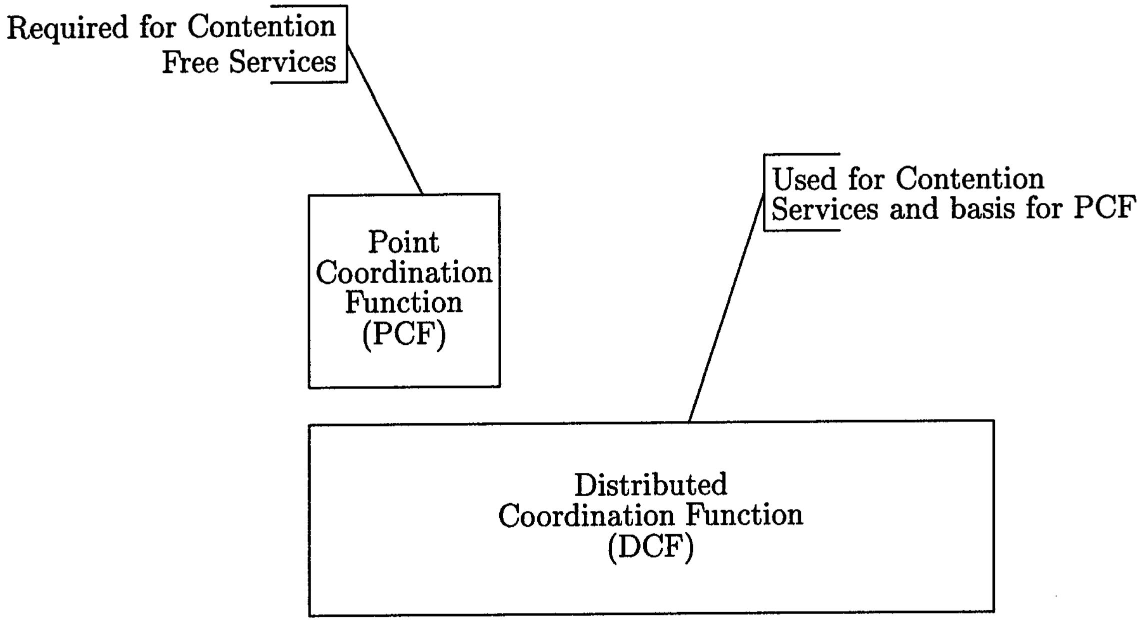


Figure 2.4: MAC Architecture

the PC, or to send a fragmented MAC protocol data unit (MPDU). Similarly, access after PIFS is reserved for stations to begin transmission of PCF traffic. This type of traffic will be discussed in greater detail in the next section. After DIFS, in general, if a station determines that the medium is idle, it may transmit a pending frame. If the medium is not idle after DIFS, a backoff timer is set by selecting a random integer (i.e., a backoff value (BV)) from a uniform distribution over the interval [0, CW-1], where CW is the width (in slots) of the contention window range. This BV is the number of idle slots the station must wait until it is allowed to transmit. For every idle slot detected (after a DIFS), the timer is decremented by one. If the medium becomes busy prior to the timer expiring, the timer is frozen until the next DIFS, upon which the timer decrements again. Upon expiring, the station transmits its frame. If there is a collision, CW is doubled until it reaches a predefined maximum value, CWmax. Upon a successful transmission, CW is reset to the default minimum value of CWmin. Figure 2.5 [Edi97] shows the structure of the basic access method.

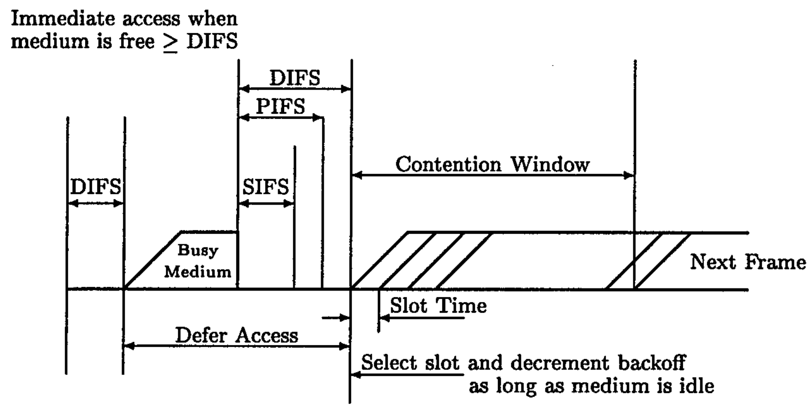


Figure 2.5: IEEE 802.11 Basic Access Method

2.2.3.2 Point Coordination Function

The PCF within the PC controls transfers during a Contention Free Period (CFP). Within IEEE 802.11, CFPs alternate with Contention Periods (CPs) (when the DCF controls transfers) as shown in Figure 2.6 [Edi97]. The PC determines the rate at which CFPs are generated. At the beginning of a CFP, the PC transmits a beacon frame. That beacon signals the beginning of the CFP and includes timestamp, beacon interval, and maximum duration information (CFPMaxDuration) for this CFP. All stations set their Network Allocation Vector (NAV) with the CFPMaxDuration. During the duration specified by CFPMaxDuration, stations may only transmit in response to a poll by the PC, or transmit ACKs in response to frames sent to them. This continues for CFPMaxDuration or until the PC explicitly declares the CFP terminated, whichever occurs first. As can be seen in Figure 2.6, the beacon interval is a nominal value, that is, it may be delayed due to a busy medium. In those cases, the CFP is shortened by the amount of the delay.

During the CFP, the PC may send unicast or multi-cast frames and/or poll stations that have indicated that they would like the opportunity to transmit during the CFP.

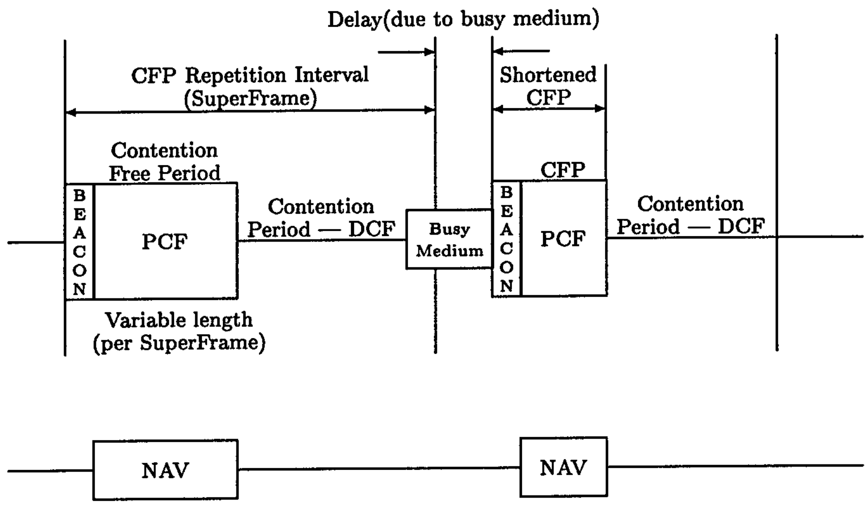


Figure 2.6: CFP/CP Alternation

2.2.3.3 IEEE 802.11 Performance

The performance of IEEE 802.11 compares favorably with the best performance of ALOHA and its variants, as well as non-persistent CSMA (see Figure 2.7). Assuming a virtually perfect channel ($BER = 10^{-10}$), as was done for the other protocols, IEEE 802.11 achieves a constant throughput of about $S = 0.88$ for $0.88 < G < 3.6$ [CWKS96]. R-ALOHA requires $G > 10.0$ before it reaches that level of throughput. Assuming IEEE 802.11 has similar performance as reported in [CWKS96] for $G \geq 3.6$, the performance of IEEE 802.11 is clearly comparable with R-ALOHA and non-persistent CSMA, especially in relatively lightly-loaded networks.

2.2.4 Real-time Medium Access Control (MAC) Protocols

Much, if not most, of past and current research has been focused on making LANs more efficient and faster. More recently, a measure of attention has turned to the area of real-time wireless LANs where individual packet delivery times are the foremost concern. Examples of

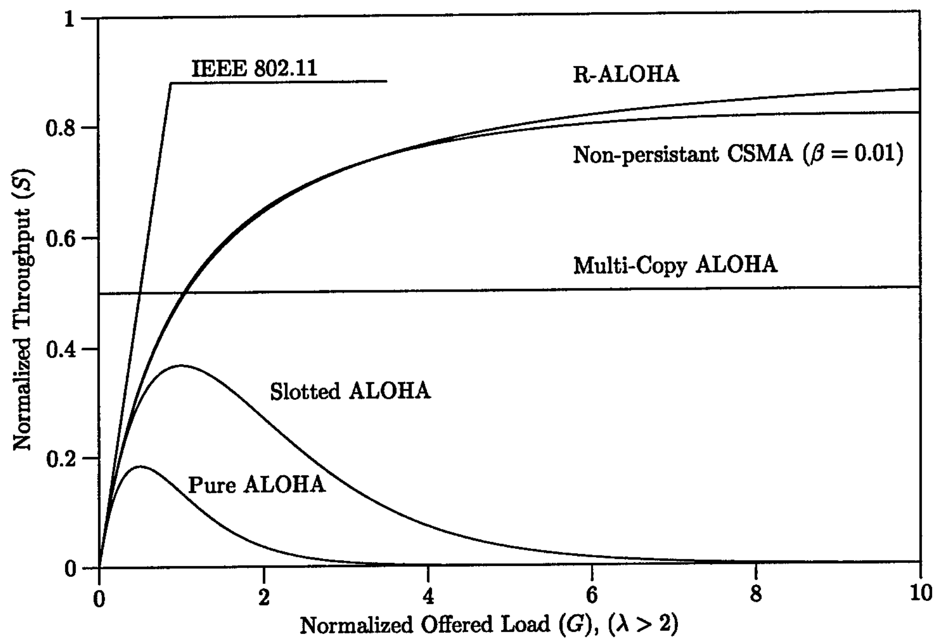


Figure 2.7: Performance of IEEE 802.11 versus ALOHA and CSMA

real-time applications are packetized voice and video, multi-media, and automated control systems. Excellent surveys of work in real-time LANs can be found in [KSY84] and [MZ95].

According to the taxonomy in Figure 2.8 [KSY84], there are two ways in which a MAC can gain access to the medium; through contention or through some method of controlled access. Controlled access is either predetermined or it adapts to the demand for the medium.

2.2.4.1 Contention-based MAC Protocols

Some contention-based probabilistic protocols have already been discussed (ALOHA, DCF in IEEE 802.11). In real-time systems however, the transmission of packets is rarely purely probabilistic. Usually, some criteria are used to prioritize access to the medium. Virtual time CSMA [WZ87] is an example of a contention-based time protocol. In virtual time CSMA, messages have explicit deadlines. Each station maintains two clocks: a real clock and a virtual clock, which runs at a higher rate than the real clock. When a station determines that the medium is idle (after a transmission or collision), it resets its virtual clock to the real clock

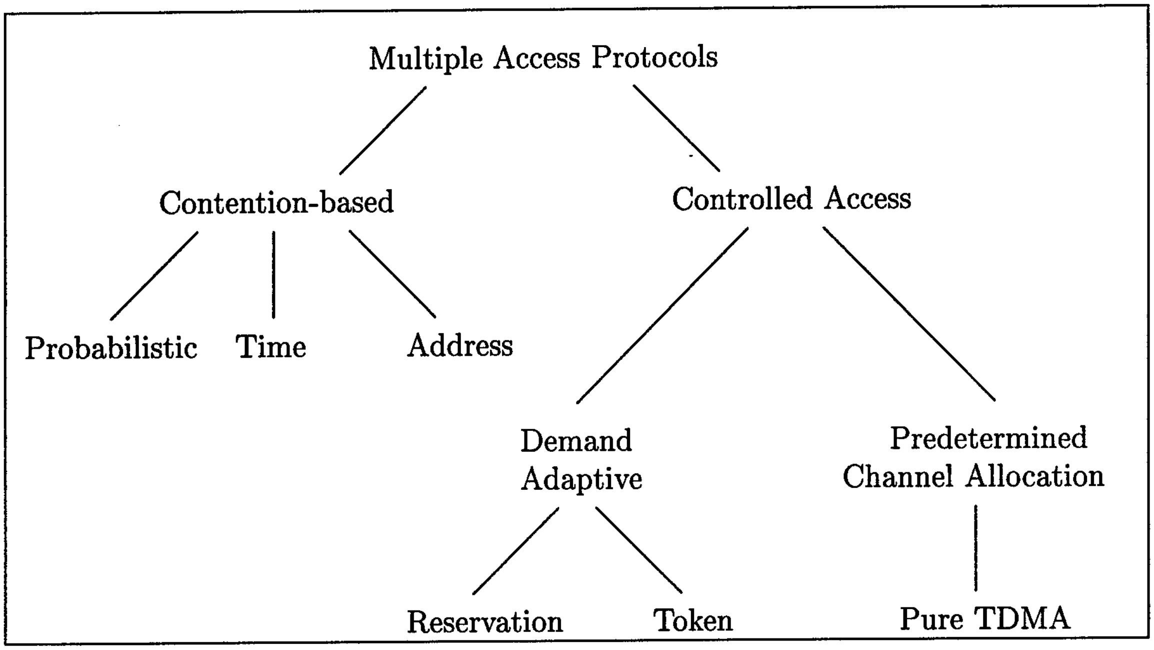


Figure 2.8: Taxonomy for multiple-access protocols

time. The station will transmit its message when its virtual clock equals some parameter in the message to be transmitted. Parameters of the message can include arrival time (i.e., first-come-first-served (FCFS)), transmission time (shortest-job-first (SJF)), deadline (earliest-deadline-first (EDF)), or others.

Figure 2.9 is an example of a message transmission using the virtual time protocol with the message deadline as the parameter to which the virtual clock is compared. Note that at real-time clock times 3, 8, 10, and 13, the virtual clock is set back to the real-time clock time in response to an idle period after a transmission. If a collision does occur, the parameter is set to a random number between the current real time and the message deadline.

A contention-based address protocol based on a binary tree of station addresses was proposed by [Hay78]. In this protocol, station addresses form a binary tree. If a collision occurs, the tree is halved and only stations in the "enabled" half are allowed to transmit. Upon further collisions, the tree continues to be halved until either (a) there is a successful transmission, or (b) the medium is idle. In the case of an idle medium, the other half of the tree is enabled

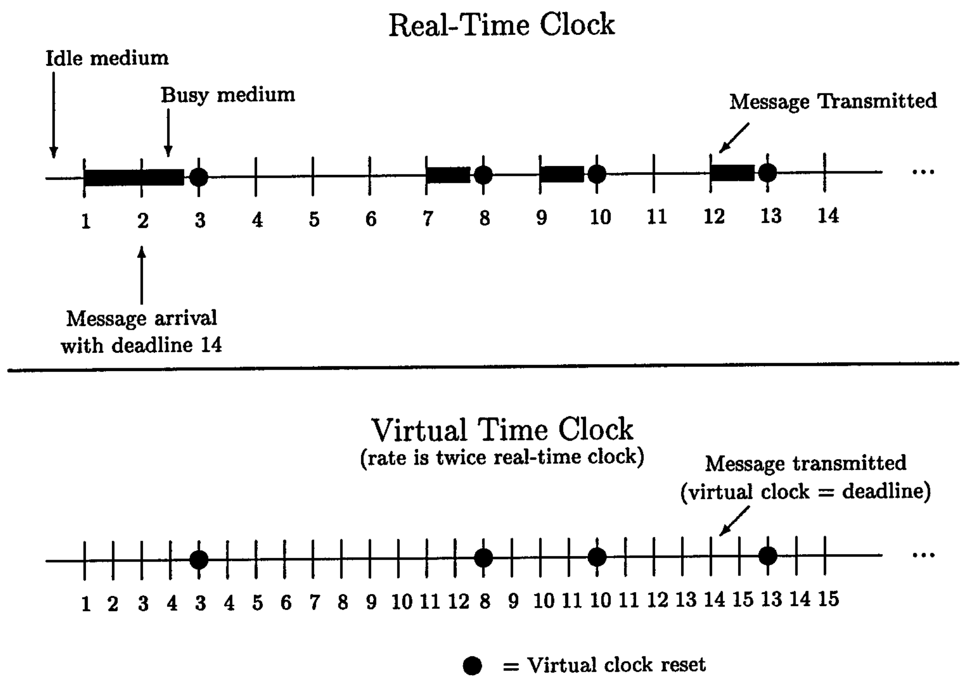


Figure 2.9: Virtual Time Protocol Example Timeline

and the process continues until a successful transmission. It is obvious that this method results in bounded access to the medium as a function of the number of stations.

2.2.4.2 Controlled Access MAC Protocols

In the context of real-time communications, predetermined access to the medium guarantees a fixed time delay for each message. Since access is deterministic; message arrivals can be easily predicted (barring corruption of the message in the medium). The problem with predetermined access is that it is horribly inefficient. If a station does not have anything to transmit, the time is wasted. In addition, once the channel allocation is made, any stations not included in that allocation are denied access. That is, a station either has 100% opportunity for access or 0%. This type of access is best suited for stations that have synchronous, streamlike data transmission and probably will not coexist well with stations with bursty transmissions [KSY84]. As a result of this, demand adaptive MACs have received more attention both in literature and in practice.

Reservation-based demand adaptive protocols include any that allocate access prior to transmission. One example, already discussed in Section 2.2.1, is R-ALOHA. Another is the Distributed-Queueing Request Update Multiple Access (DQRUMA) [KLE95]. R-ALOHA uses the same channel to transmit reservation requests and data. DQRUMA uses a separate channel for reservation requests which reduces collisions. In addition, DQRUMA permits the piggy-backing of reservation requests onto data packets further reducing collisions.

Token based protocols require a station to be in possession of a real or imaginary token in order to transmit. Any polling scheme is an example of real tokens. The polling of the station is the token. IEEE 802.4, a token bus standard, has formally defined one approach to real token passing among stations. Imaginary or implicit tokens are passed in the Broadcast Recognition Access Method (BRAM) [CFL79]. In BRAM, the token is "passed" among stations in order of their address. If station 1 is in possession of the token and wants to transmit, it does; otherwise it remains idle. After station 1 transmits, or after a given amount of idle time, station 2 is implicitly "passed" the token, and so on. Often real-time applications employ a timed token protocol where stations are only allowed to hold the token for a bounded amount of time. This ensures that other stations wanting to transmit have a finite delay.

2.3 Traffic and Channel Models

2.3.1 Traffic Models

Traffic modeling is a subject that has always generated considerable interest. Within the context of modeling and analysis of communications networks, the reason for this interest is clear. The performance of the network is highly dependent on the traffic presented to it. A network that performs well with traffic that arrives according to a Poisson process may perform poorly with traffic that is bursty. A network that efficiently transports bulk data may be very inefficient with multi-media data. The difficulty in accurately characterizing the traffic that will be presented to the network can be attributed to at least two factors [FM94]. First, the demand on the network resources may be poorly understood. Second, the type of data on the network is constantly changing. Voice, video, and HTTP (Hyper Text Transport Protocol) traffic that accounted for only a modest level of the network traffic several years ago, now dominates all other traffic types. Accurate performance modeling of a network, then, presupposes a knowledge of the application domain (e.g., telemetry, avionics, multi-media) that generated the network traffic. In this section, several traffic source models are discussed and the data characteristics of the telemetry and avionics application domains are reviewed.

The most commonly used stochastic model for packet arrivals is the Poisson model [JR86], [FM94], [PF95]. A Poisson process can be characterized in two ways. It is a process in which interarrival times $\{A_n\}$ are exponentially distributed with parameter $\lambda : P\{A_n \leq t\} = 1 - e^{-\lambda t}$, or it is a counting process that satisfies $P\{N(t) = n\} = (\lambda t)^n \frac{e^{-\lambda t}}{n!}$ where $N(t)$ is the number of arrivals up to time t [FM94]. One of the reasons that the Poisson process has seen widespread use is that the memoryless property of exponential distribution makes analysis relatively simple since prior events do not affect the current probability of an event occurring. Additionally, since the combination of two or more Poisson processes results in another Poisson process, the analysis of multiple traffic sources is straight-forward. These compound Poisson processes have been used to model batch arrivals where the interbatch arrival time are independent and exponentially distributed [JR86].

It has long been recognized that packet arrivals in networks are not necessarily Poisson [JR86]. Recent studies have shown that wide-area network traffic is self-similar [LTWW94], [PF95]. Self-similar traffic can be visually characterized by its scale-invariance. If packet arrivals per unit time is plotted in units of 10 seconds and compared to the same plot using units of 1 second, the burstiness of the interarrivals would look the same. Using a smaller time unit of 100 ms or 1 ms would result in plots that look the same as the larger time unit plot. In contrast, using smaller and smaller time units on plots of traffic that arrives according to a Poisson process would result in plots that at a larger time scale look relatively smooth and become more and more bursty as the time scale gets smaller (cf., [LTWW94]). In citeWTSW97, it is proposed that the physical explanation for self-similar traffic is due to the superposition of many ON/OFF sources whose ON/OFF distributions have infinite variances.

Several models that generate self-similar traffic have been proposed. A model based on doubly stochastic Poisson processes where the intensity of arrivals is modeled as a continuous stochastic process was proposed by [SL95]. The Random Midpoint Displacement (RMD) algorithm [LEWW95] focuses on fast generation of self-similar traffic by recursively generating midpoint values (i.e., interarrival times), $Z\left(\frac{a+b}{2}\right)$, in the interval $[a, b]$, from the endpoints, $Z(a)$ and $Z(b)$. If the generated values were self-similar, the midpoint value, $Z\left(\frac{a+b}{2}\right)$, would be independent of the interval, $Z(b) - Z(a)$. That is, it would be scale-invariant. The RMD algorithm speeds up the process of choosing the values by picking the values independently at the time they are needed. Other self-similar traffic generations methods can be found in [Nor95] and [PSS96].

By far the simplest way to generate self-similar traffic is to draw interarrival times from the Pareto distribution [JK70], [PF95]. The Pareto distribution was first used to describe the distribution of income among a population. It has since been used to describe such phenomena as the sizes of asteroids, cities, and, more recently, CPU time consumption and packet interarrival times [PF95]. The Pareto distribution is heavy-tailed. Informally, that means it is quite probable that a value far exceeding the mean will occur. The most common form of the Pareto distribution (others can be found in [JK70]) has a cumulative distribution function (CDF) of $F_X(x) = 1 - (\frac{k}{x})^a \quad k > 0, a > 0; x \geq k$ where k is the minimum value of the distribution and a is the "shape" parameter of the distribution. The Pareto distribution has the characteristic that the mean and variance are infinite for $a \leq 1$, the mean is finite for $a > 1$, and both the mean and variance are finite for $a > 2$.

Random variates, x, can be generated easily using the transform method [JBS92] since the Pareto distribution has a closed-form CDF. Pareto random variates are generated by using $x = \frac{k}{U^{\frac{1}{a}}}$ where x is the random variate, k is the minimum value of the distribution, a is the shape parameter, and U is a uniform random number on (0,1).

The density function of the Pareto distribution is $p_X(x) = \frac{ak^a}{x^{a+1}} \quad a > 0, x \geq k > 0$. Using this, the mean of the Pareto distribution can be determined to be $m = \frac{ak}{a-1}$ for $a > 1$. In practice, as $a \to 1$ it takes an increasingly large number of samples to achieve the m value given by the above formula. This is due to the fact that as $a \to 1$, $m \to \infty$. While this is indeed the behavior that is exhibited by self-similar traffic, it makes it difficult to compare the behavior of systems with traffic that have the same a parameter. For instance, for $a = 1.12$ and $k = 1$, $m = 9.333$. However, the mean value obtained using the random variate generation method described above was typically less than 7.0 for 100,000 samples. Results varied widely, as would be expected, and sometimes the mean was as high as 50. The mean value for $a \geq 1.4$ seemed to stabilize as the variance of the distribution moved towards its finite characteristic.

Another type of traffic model is the Markov-modulated model. In this type of model, different arrival probabilities are used for each of the k states in the Markov model. That is, each state, k, specifies a different process by which the probability of an arrival is determined. The amount of time spent in the state is "modulated" by the underlying Markov process. This type of model is also know as doubly stochastic [FM94]. In [SL95], this model was used to generate self-similar traffic.

The ON/OFF model [Bra69] is widely-used to model bursty data such as voice traffic. Although ON/OFF models that can model speech events such as double-talk and mutual silence can be constructed, a simpler two-state Markov chain is often used to model voice traffic [Pru95], [VZ95], [CPR96], [HS96], [STE96]. One state is a "talk" state and the other is a silent state. The time spent in each state is exponentially distributed with different means. Typical mean values for the talk and silent state are 1.00 seconds and 1.35 seconds respectively [CPR96]. During the "talk" state, bits arrive at a constant rate, with 32kbps and 64kbps being typical values. The bits are then packetized and transmitted. The International Telecommunications Union (ITU) has developed numerous speech coding standards including the G.726 adaptive differential pulse code modulation (ADPCM) standard which uses a 32kbps rate and the G.711 PCM standard uses a 64kbps rate [Cox97].

Latency requirements for packetized voice is highly dependent on the user. In the ITU G.114 recommendation [ITU96] cited in [KBS+98], some users found a 300-800 ms delay acceptable while others would not accept anything beyond 200 ms. Voice packet loss in the range of 5-10% was found acceptable for random packet losses. If the losses occurred in bursts, some type of codec (voice encoding) that compensated for the loss was recommended [KBS+98].

There are many other types of traffic models as well as numerous techniques for generating traffic efficiently for simulation. Surveys of traffic models and generation techniques can be found in [FM94], [SAG94], and [RK96].

Two application domains with relatively well characterized traffic are the telemetry and avionics data bus. Both areas are characterized by traffic that have constant periodic interarrivals and little variability in arrival times. Telemetry data tends to have small packets as evidenced by a very common data bus, MIL-STD-1553 [ASC78], which can transmit a maximum of 32 16-bit words in a "packet". Flight data and remote vehicle status are examples of typical telemetry applications. An avionics data bus tends to have larger packet sizes. The requirements for the Boeing 777 Airplane Information Management System (AIMS) is an example [CDHC94]. There are approximately 63 separate processes that use the data bus. Their periodic execution frequency ranges from 5 to 80 Hz. The packet (or message) transmission time (which is proportional to the message size) ranges from less than one millisecond to a maximum of 14 milliseconds. These types of systems may also have message latency requirements. In many applications a message (or packet) must be delivered before the next message arrives (i.e., the message latency requirement is equal to the arrival period). In AIMS, message latencies (in milliseconds) have a minimum of 12, a maximum of 1000

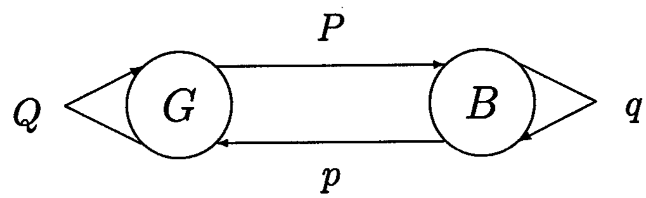


Figure 2.10: Gilbert Model Transition Diagram

with a mean of 380 [CDHC94].

2.3.2 Channel Models

A common figure of merit used in digital links is the bit-error-rate (BER) — the probability that a bit is received in error. The BER for a digital link is analogous to signal-to-noise ratio (SNR) for analog links [PB86]. Two types of BERs are commonly used in modeling channels. A *static* BER remains constant during the entire time the model is being used. A *dynamic* BER can change based on some parameter such as elapsed time or the number of bits transmitted. Static BER models assume that bit errors are statistically independent. It is well-known that errors in wireless networks tend occur in "bursts" and therefore cannot be accurately modeled using the assumption of independent errors [Gil60], [Fri67], [DMM88]. The classic dynamic BER model for digital channels is the Gilbert model [Gil60]. The Gilbert model is based on a two-state Markov chain shown in Figure 2.10. In the G or "good" state, no bit errors occur. In the B or "bad" state, errors occur with probability $1 - h$ where h is the probability of no bit error. A G-to-B state transition occurs with probability P; a B-to-G transition occurs with probability p. The model remains in state G with probability $Q = 1 - P$ and remains in state B with probability $q = 1 - p$. This model has been shown to model errors that occur in a wireless channel more accurately that a static BER model [DR92], [SF94], [WM95]. Models with more than two states have been proposed and shown to be even more accurate in modeling a wireless channel (with a corresponding increase in complexity). Some of these include [Fri67], [DMM88], [NKNS96], [LvS97].

The probability of a state transition in the Gilbert model is evaluated upon the presentation of a bit to the channel. That is, state transitions are evaluated on a bit-by-bit basis. This type of model can be termed a "transmission modulated model". In the context of simulation, this can require an inordinate amount of computation. A common technique to reduce this computational burden is to model the number of bits between state transitions as a geometrically distributed random variable. Therefore, rather than evaluating each bit for a possible state transition, a single calculation gives the number of bits between state transitions. Consider a 1 Mbps wireless channel with an average BER of 10^{-6}. To observe a single error, an average of 10^6 bits must be transmitted while the channel is in the bad state. Of course, if the channel is in a good state, no errors occur. Further, a transmission modulated model makes the improbable assumption that the state of the channel does not change when there are no bits are in the channel.

An alternative to a transmission modulated model is a time modulated model. In this type of model, state transitions occur based on elapsed time rather than the number of bits transmitted. Using the two-state Gilbert model as an example, the time spent in the good or bad state is modeled as an exponentially distributed random variable with different means. This significantly reduced the computational burden and appeals to the intuition that the state of the channel does indeed change even though no bits are being transmitted. Research that has used this approach to channel modeling include [BBKT96], [BBKT97], [DRT97].

2.4 Related Research Efforts

Driven by the desire for voice and video over a wireless link, coupled with the demand for mobility, real-time wireless local area networks are seeing an increase in interest. Since access to the medium is vital in real-time applications, research has focused on the MAC layer. Most research into unmodified IEEE 802.11 focuses on the soft real-time aspects (i.e., voice/video). No research was found that investigated hard real-time use of IEEE 802.11. Other research into IEEE 802.11 focused on improving the fairness of the protocol by modifying the backoff algorithm.

2.4.1 IEEE 802.11

2.4.1.1 Voice over IEEE 802.11

Visser *et al.* [VZ95] use the CFP of IEEE 802.11 to transport voice data and use the CP to transport ordinary data. Depending on the length of the superframe (i.e., one CFP/CP pair), speech may be outdated when a poll arrives. If so, the data is clipped. Their research focuses on analyzing the quality of the voice conversations in terms of the percentage of bits clipped. In their research, they vary the superframe length and percentage of clipping, as well as the number of conversations that can be transported during one superframe. They conclude that, due to the high overhead introduced by the CFP polling scheme, the number of conversations that can be supported is relatively low — five to twelve depending on the number of conversations transported during one superframe. If, however, two percent clipping is allowed, the number of ongoing conversations can be doubled.

2.4.1.2 Modified Backoff Algorithms

In standard IEEE 802.11, the backoff algorithm specifies that, upon detecting a busy medium or upon a collision, an exponentially increasing integer must be used in the algorithm to determine the number of idle slots that a station must wait before transmitting again. While this algorithm may have a measure of fairness for stations that all attempt to gain access to the medium for the first time simultaneously, it can potentially allow another station to transmit prior to any of the waiting stations simply because it is trying now. That is, the backoff scheme in IEEE 802.11 favors the transmission of "newer" data.

Woesner *et al.* [WWW96] propose two different modifications to IEEE 802.11: weighted slot selection probabilities and load adaptive slot selection. Both schemes try to improve performance by increasing the probability that stations wanting to transmit initially choose a larger slot count. The weighted slot selection scheme does this statically, thereby wasting bandwidth in lightly loaded networks. The load adaptive scheme attempts to overcome this defect by counting the number of idle slots between transmissions. Stations with new packets to transmit choose the number of slots to delay transmission from the range of [(CW-Idles), CW], where CW is the upper boundary of the range of slots to choose from and Idles is the number of idles slots counted between the last transmission and the current transmission. If the number of idle slots is small, it is assumed that the network is under heavy load. This modification makes it more likely that newly arriving packets will not transmit prior to packets that are already queued. Simulation indicates an improvement of up to 20% in throughput and 15% in access delay.

Bianchi *et al.* [BFO96] takes a slightly different approach and adaptively modifies CWmin (cf., Section 2.2.3.1) depending on an estimate of the number of stations currently in the network. Stated simplistically, the algorithm reduces CWmin for networks with a small number of stations and increases it as the number of stations increase. This adaptive algorithm, in effect, removes the network throughput's dependence on the number of stations in the network. Simulations show that, when using the adaptive algorithm, saturated throughput remained at about 0.81 as the number of stations increased from 5 to 50. In contrast, using a fixed value of 31 for CWmin, saturated throughput declined from 0.81 to 0.61 as the number of stations increased from 5 to 50. Other schemes that dynamically alter the value of CWmin and/or CWmax have been proposed and can be found in [Bha98] and [CCG98].

2.4.2 Real-time Wireless Medium Access Control

2.4.2.1 IEEE 802.11 Compatible Schemes

Sobrinho and Krishnakumar [SK96] contend that the IEEE 802.11 CFP is so inefficient, it is not suitable for many real-time applications. They propose a scheme that is compatible with, but does not use IEEE 802.11. That is, their protocol can co-exist with IEEE 802.11, but gives the stations using the scheme undisputed access to the medium once access has been obtained.

In their scheme, a real-time station waits for an idle medium, then issues a "black burst" or pulses of energy of length proportional to the length of time it has been waiting for the medium. After the "black burst," the station listens to the medium to determine if another station has a longer burst, implying that it has been waiting longer. If the medium is idle, the station is free to transmit its data. Since in IEEE 802.11 all stations defer to a busy medium, no conflicts due to IEEE 802.11 stations will occur. Performance of this scheme was measured in terms of average data delay. Delays ranged from 0.0 to 13.0 ms for normalized loads up to 0.73, and were generally unbounded with loads above that level.

2.4.2.2 Hard Real-Time Schemes

The two MAC protocols discussed in Section 2.2.1 (R-ALOHA) and Section 2.2.4.1 (Virtual Time CSMA) have been proposed for hard real-time systems. As these protocols have already been presented, only their performance will be reviewed here.

Liu *et al.*, using R-ALOHA, reports in [LSP95] a deadline failure probability of almost 10^{-12} for a fixed deadline of 4 frames and a constant packet error probability of 0.001. A more detailed presentation of this approach can be found in [Liu96]. Using virtual time CSMA [WZ87], the percentage of messages lost due to a missed deadline is seldom less than 20% for any scenario investigated, except in the case of network loads less than 0.5. This fact alone seems to make this protocol unsuitable for any hard real-time system expecting even a moderately loaded network.

Though not dealing with wireless networks specifically, [Mal94] proposes using multi-version messages. During light network loading, full length messages would be sent; during high load periods, shorter length versions of the full length messages would be used-effectively lowering the network load.

2.5 Summary

This chapter highlights real-time wireless LANs. As a subset of wireless LANs, it was shown that they have unique challenges associated with their implementation — packet delivery is time-constrained.

Section 2.1 presented an overview of the Open Systems Interconnection (OSI) model. The importance of the MAC sublayer within the DLC layer of the OSI model was noted. Since the MAC controls access to the medium, it is logical that it be the focus of intense research in terms of performance; both real-time and average case.

Significant MAC protocols are presented in Section 2.2 including ALOHA, CSMA, IEEE 802.11, and others. The performance of each is presented along with a brief tutorial of IEEE 802.11. The operation of the protocol is explained and its performance is highlighted.

Models of network traffic and wireless channels were discussed in Section 2.3. Basic aspects of the Poisson process and self-similar traffic models were presented. The theory and performance of finite-state Markov channel models such as the Gilbert model was discussed.

Finally, related research into real-time wireless networks was presented in Section 2.4. Modifications to the IEEE 802.11 backoff scheme were discussed. Most research focused on how to transport soft real-time data effectively. Relatively little has been done in the area of hard real-time wireless systems.

Chapter 3

Analytic Network Analysis Techniques

Queueing network analysis is a valuable tool for determining the performance and operating characteristics of real-world systems. Its use in modeling such diverse areas as communications networks, manufacturing environments, the economy, computers, and numerous other applications is testimony to its value and flexibility. To get the most benefit from any tool however, one should understand what problems it was intended to solve—"the right tool for the right job" as the axiom goes. It may be the case in a particular situation (as it was in this research) that analytic analysis techniques are not suitable (cf., Section 4.6). Even so, knowledge of the concepts and terminology encountered in queueing network analysis will be of benefit in determining whether such techniques can be profitably employed and aid in choosing the proper queueing network analysis tools to analyze a problem.

3.1 Introduction

A queueing network is a collection of two or more single queues or "nodes" where customers receive service. Customers arriving at the network request service at one or more of the nodes and then may leave the network. Section 3.2 introduces and defines terms used to classify queueing networks. It helps answer the questions of whether the network is open or closed, continuous or discrete, and small or large. Are the individual queues independent? Is the network reversible? The answer to these (and other) questions is a primary factor in choosing the proper analysis tool. Section 3.3 presents various analytical techniques along with examples. References for more advanced or more detailed information is included throughout.

3.2 Queuing Network Classification

Classification is especially important in queueing networks. Many classes of networks have no known closed-form solutions. Other networks have state spaces that are so large that certain analysis techniques, while theoretically possible, become intractable. For these cases, approximations (or perhaps simulation) may be appropriate. The following sections introduce terms and concepts used to classify queueing networks.

3.2.1 Open, Closed, and Mixed Networks

A fundamental and simple characteristic of queueing networks is whether they are open or closed. An open network (Figure 3.1) permits arrivals and departures from outside the network. In a closed network (Figure 3.2), customers are "trapped" and circulate among the various nodes in the network. The dashed box in the figures indicates the logical boundary of the queueing network. The circles are the nodes where customers receive service. The arrows indicate the paths customers may take within the network.

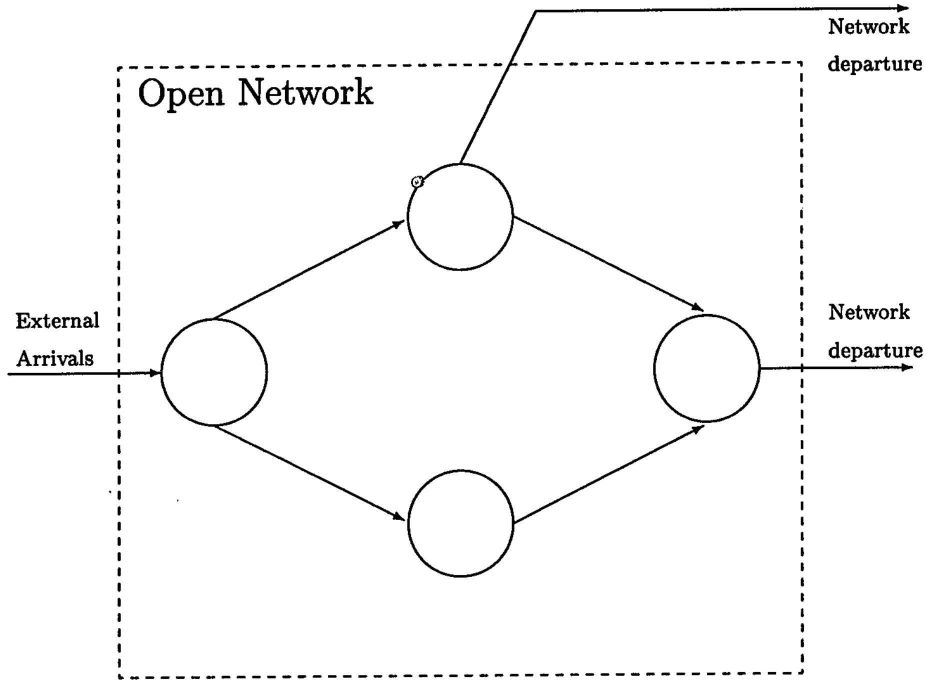


Figure 3.1: An Open Network

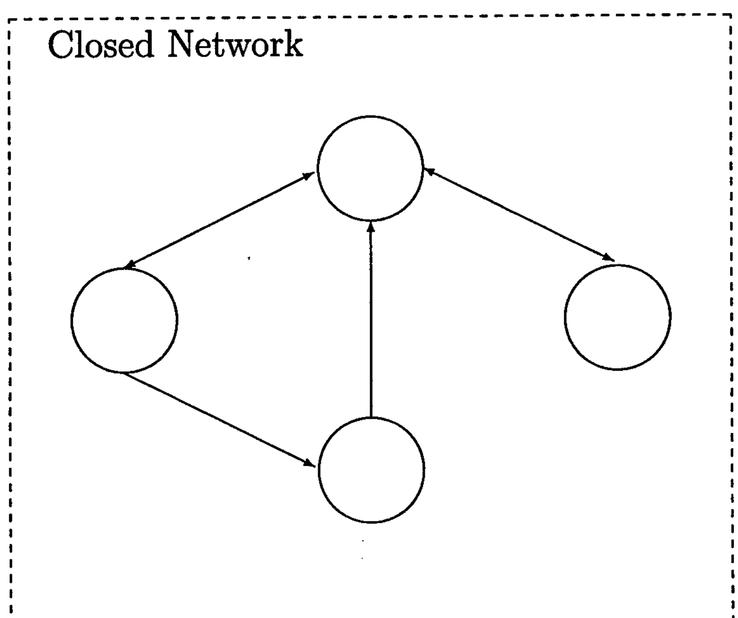


Figure 3.2: A Closed Network

It is conceivable that a network might contain different classes of customers and that the network may be open to one class and closed to another. An example of this can be found in computer systems where user jobs enter and exit the system but certain system-level jobs are always present and circulate continuously within the system. This is a mixed network. Techniques that can be used to analyze these networks are discussed later.

3.2.2 Customer Arrivals, Service, and Routing

Except where explicitly noted, it is assumed that customers arrive one-at-a-time according to a Poisson process. Customers are served one-at-a-time and service times are assumed to be exponentially distributed. Further, routing within the network is independent of the network state. While these assumptions may seem restrictive, there are many cases where valid results are obtained by treating queueing networks as if these assumptions hold when, in fact, they may not. Cases where more than one customer can arrive, obtain service, and/or depart are known as bulk or batch arrival, service, and/or departure, respectively.

Allowing general arrival and service distributions can result in solutions that are quite complex or even non-existent. For results with relaxed arrival and service assumptions, the interested reader may find it valuable to consult the following [BD96], [BG92], [Dij93], [HT90], [HT91], [HNT95], [HPTvD90], [Kel79], [Mar79], [Puj95], [Ser93], [Woo94], [Woo97], and [ZC96]. Real-time Queueing Theory can be used to analyze customers with deadlines. Details can be found in [Leh96], [Leh97a], [Leh97b]. A tutorial presentation can be found in [BDKM98].

3.2.3 Continuous and Discrete Time Networks

Classical queueing theory was developed almost exclusively using the assumption of continuous time [Woo94] where time progresses in infinitesimally small increments. The increments are so small that, so the assumption goes, the possibility of a given state occurring due to two or more state changes occurring is virtually zero. This assumption greatly simplifies the analysis task. The concept of "virtually zero" has been formally defined in the function $o(t)$ where t is time. A function that is $o(t)$ goes to zero with t, faster than t itself, i.e., $\lim_{t \to 0} \frac{o(t)}{t} = 0$ [Kle75]. Using this definition, the probability of a given state occurring may be described as $f(t) + o(t)$ where $f(t)$ is the probability of the state occurring due to a single state change and $o(t)$ is the probability of the state occurring due to two or more state changes.

In discrete time, time progresses in arbitrarily small, rather than infinitesimally small, increments. This seemingly minor change induces huge analytic difficulties, for now the possibility of a state occurring due to two or more state changes is no longer $o(t)$. Discrete-time networks are attractive, despite these difficulties, because they can more accurately model what actually happens in a network with nodes that operate on a time-slotted basis [Woo94]. Examples of these networks include communications protocols such as slotted ALOHA [Abr77], IEEE 802.11 [Edi97], or Asynchronous Transfer Mode (ATM) (which is ultimately transported by a synchronous slotted protocol, SONET) [BG92], [BC89].

Whether one chooses to use a continuous or discrete-time model, sometimes the complexity of the network requires the use of approximations in order to get any solution at all. While research into exact product-form solutions for queueing networks goes on, it has long been recognized that approximations are inevitable [ICH84] or even preferable [Kle76] given the simplifying assumptions that are often introduced into the analysis. Some of these approximation techniques are described in Section 3.3.2.

3.2.4 Interfering Queues

In many queueing networks, customers are served without regard to whether another customer at a different node is receiving service at the same time. That is, the nodes within the network are independent. There are instances; however, where this is not the case. In packet radio networks and computer communication networks such as Ethernet, nodes serve packets by transmitting them. Nodes within the network use a common resource to provide that service—a single transmission channel. When two or more nodes attempt to use the transmission channel at the same time, a collision is said to occur. While algorithms are used to reduce collisions as much as possible, collisions can, and will, occur. In a collision, both packet transmissions are assumed to fail which reduces system throughput. Such queueing networks are said to have interfering queues. Stated simply, queue interference occurs when service provided by Node 1 and Node 2 overlap in time. Note that this is not the same as blocking. With blocking, Node 1 can successfully use the transmission channel while preventing Node 2 from using it.

Networks with interfering queues cannot be solved exactly using classical queueing network theory [KY80], [YH91] since the next node the customer will visit depends on whether a collision has occurred (i.e., the individual node routing probabilities are no longer independent). If a collision did occur, the customer may stay at the current node. If a collision did not occur, then the customer may go to a different node for service or leave the network. Several special cases do have exact solutions; but the restrictions imposed on the networks, which typically involve only two nodes, are considerable. An excellent bibliography of these types of solutions can be found in [YH91].

For the purposes of this chapter, once a network has been identified as containing interfering queues, an approximation technique such as those described in Section 3.3.2 to analyze the network should be employed.

3.2.5 Global, Local, and Detailed Balance

The *state* of a network, $\mathbf{n}$, is an M–tuple, $(n_1, n_2, n_3, \ldots, n_M)$, where each n_i is the number of customers at node i including customers that are in service. *Balance*, with respect to queueing networks, refers to the state of the network due to a flow of customers in and out of a given portion of the network. *Global balance* means that the probabilistic rate at which the network leaves a state must equal the probabilistic rate at which the network enters that state. With global balance, the portion of the network is the entire network. Local balance is similar except that the portion is a single node. *Local balance* means that the probabilistic rate at which the network leaves a given state due to a departure from a given node must equal the probabilistic rate at which the network enters that same state due to an arrival at that same node [Kle75]. *Detailed balance* says that the rate at which the network leaves a given state to arrive at a new state must equal the rate at which the network leaves that new state to arrive at the given state [Kel79]. Examples to clarify these concepts are presented in the following sections.

The terminology used for global, local, and detailed balance is somewhat muddled. What [Kle75] refers to as global balance, [Kel79] calls full balance, and [Ser93] calls total balance. Similarly, what [Kle75] calls local balance, [Kel79] and [Ser93] call partial balance. There appears to be some agreement on the term detailed balance. In this chapter, the terms global, local, and detailed balance will be used.

Balance equations are the set of equations that are true if global, local, or detailed balance holds. Their solution, if it exists, provides the equilibrium probability distribution of a network—the probability of a given network state. All the networks discussed in this chapter exhibit global and local balance since they are assumed to be in equilibrium. A network in equilibrium may or may not have detailed balance. Discussion of the existence and uniqueness of the equilibrium distribution solutions found using balance equations can be found in [Kle75]. If a network has detailed balance, its equilibrium distribution has a known canonical form and it is said to be reversible. Reversibility is discussed in Section 3.2.6. A simple example exploiting the canonical form of a reversible network is contained in Section 3.2.6.2. Extensive details can be found in [Kel79].

The network shown in Figure 3.3 is a slight modification of the example used in [Kle75] and will be used to demonstrate global and local balance. The arrival and service distributions are assumed to be exponential. The circles represent nodes within the network, the labeled arcs represent the direction and probability that a customer will take a particular path out of a node. The number of nodes, M, is 3, μ_i is the service rate of the ith node, and the

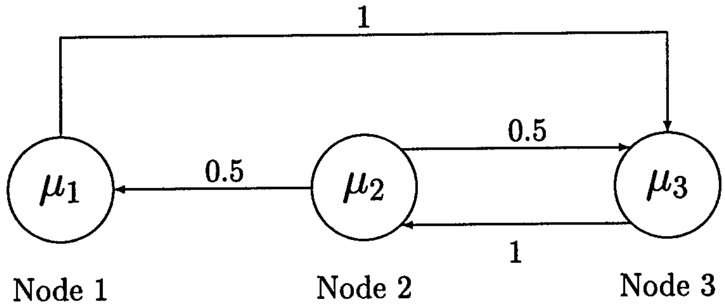


Figure 3.3: Closed Queueing Network - $M = 3, N = 2$

number of customers within the network (not shown in the figure), N, is 2.

3.2.5.1 Global Balance

To determine the global balance equations, one must first determine all the possible states the network can be in. This is most easily done by the construction of a state-transition diagram. The total number of states can be computed by using

$$\binom{M+N-1}{M-1}.$$

The number of ways $N = 2$ customers can be distributed among $M = 3$ nodes is 6. Incidentally, using even slightly larger values for M and N results in a staggering increase in the state space. Consider a network with $M = 10$ and $N = 10$; 10 customers distributed among 10 nodes. The number of states is 92,378!

Using the number of possible states (i.e., 6) and Figure 3.3, the state-transition diagram for the network can be constructed and is shown in Figure 3.4. Note how the state transition diagram reflects the assumption of continuous time. There is no direct path between state (2,0,0) and (0,0,2) since this would require two state changes; first to (1,0,1) as a customer moves from Node 1 to Node 3, and then to (0,0,2) as the other customer at Node 1 moves to Node 3.

This network has six global balance equations (one for each state). It will always be the case

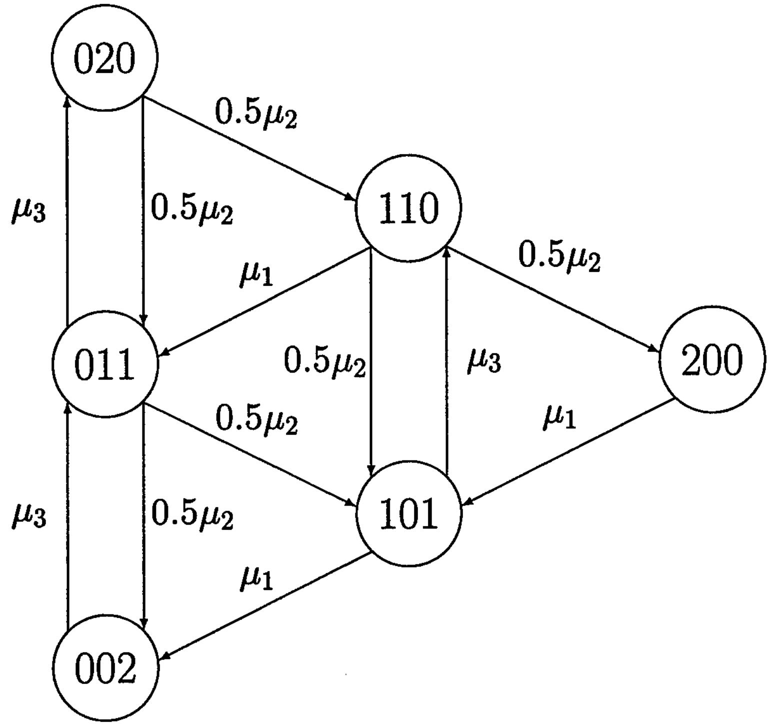


Figure 3.4: State Transition Diagram

that one equation has a linear dependence; therefore, the fact that all the state probabilities must sum to 1 is also used. The general global balance equation is [Kel79]

$$p(\mathbf{n}) \sum_{M} \sum_{M} \mu_{jk} = \sum_{M} \sum_{M} p(T_{jk}\mathbf{n}) \mu_{kj} \tag{3.1}$$

where $p(\mathbf{n})$ is the probability of being in state $\mathbf{n}$, M is the number of nodes in the network, j and k are particular nodes in the network, μ_{jk} is the rate at which customers leave node j to arrive at node k, and $T_{jk}\mathbf{n}$ is an operator that takes a customer from node j and places it in k when the network is in state $\mathbf{n}$. For example, $T_{13}(2,0,0) = (1,0,1)$.

While (3.1) seems formidable, in practice many of the terms are zero and it is often possible to simply write the global balance equations by inspecting the state diagram. We will develop the global balance equation for the network in state (2,0,0) in detail and state the rest. The global balance equation for the network in state (2,0,0) is

$$p(2,0,0)[\mu_{11} + \mu_{12} + \mu_{13} + \mu_{21} + \mu_{22} + \mu_{23} + \mu_{31} + \mu_{32} + \mu_{33}]$$

$$= p(T_{11}(2,0,0))\mu_{11} + p(T_{12}(2,0,0))\mu_{21} + p(T_{13}(2,0,0))\mu_{31} \quad (3.2)$$
$$+p(T_{21}(2,0,0))\mu_{12} + p(T_{22}(2,0,0))\mu_{22} + p(T_{23}(2,0,0))\mu_{32}$$
$$+p(T_{31}(2,0,0))\mu_{13} + p(T_{32}(2,0,0))\mu_{23} + p(T_{33}(2,0,0))\mu_{33}.$$

Due to the topology of the network, the only non-zero rates (i.e., the μ_{jk} terms) are μ_{13}, μ_{21}, μ_{23}, and μ_{32} which are μ_1, $0.5\mu_2$, $0.5\mu_2$, and μ_3 respectively. This reduces the above equation to

$$\begin{aligned} p(2,0,0)[\mu_1+\mu_2+\mu_3] &= p(T_{31}(2,0,0))\mu_1 + p(T_{12}(2,0,0))0.5\mu_2 \\ &\quad +p(T_{32}(2,0,0))0.5\mu_2 + p(T_{23}(2,0,0))\mu_3. \end{aligned} \quad (3.3)$$

Focusing on the left-hand side of (3.3), note that there are no customers at nodes 2 and 3 in state (2,0,0); therefore, $\mu_2 = \mu_3 = 0$ and the equation becomes

$$\begin{aligned} \mu_1 p(2,0,0) &= p(T_{31}(2,0,0))\mu_1 + p(T_{12}(2,0,0))0.5\mu_2 \\ &\quad +p(T_{32}(2,0,0))0.5\mu_2 + p(T_{23}(2,0,0))\mu_3. \end{aligned} \quad (3.4)$$

Again, since there are only customers at Node 1, the only non-zero term on the right-hand side is $p(T_{12}(2,0,0))0.5\mu_2$. This reduces the equation to

$$\mu_1 p(2,0,0) = p(T_{12}(2,0,0))0.5\mu_2. \quad (3.5)$$

Evaluating the operator $T_{12}(2,0,0)$, we finally arrive at the first global balance equation

$$\mu_1 p(2,0,0) = 0.5\mu_2 p(1,1,0). \quad (3.6)$$

This equation can easily be verified by inspecting Figure 3.4. The remaining five global balance equations for the network in Figure 3.3 are determined in the same manner and are

$$\mu_2 p(0,2,0) = \mu_3 p(0,1,1) \quad (3.7)$$
$$\mu_3 p(0,0,2) = \mu_1 p(1,0,1) + 0.5\mu_2 p(0,1,1) \quad (3.8)$$
$$(\mu_2+\mu_3)p(0,1,1) = \mu_1 p(1,1,0) + 0.5\mu_2 p(0,2,0) + \mu_3 p(0,0,2) \quad (3.9)$$
$$(\mu_1+\mu_2)p(1,1,0) = 0.5\mu_2 p(0,2,0) + \mu_3 p(1,0,1) \quad (3.10)$$
$$(\mu_1+\mu_3)p(1,0,1) = \mu_1 p(2,0,0) + 0.5\mu_2 p(0,1,1) + 0.5\mu_2 p(1,1,0). \quad (3.11)$$

Of course, to ensure all probabilities sum to one, the following must also hold

$$p(2,0,0)+p(0,2,0)+p(0,0,2)+p(0,1,1)+p(1,1,0)+p(1,0,1)=1. \tag{3.12}$$

We could proceed by solving these equations in the normal fashion (as simultaneous linear equations). However, the local balance equations can provide an easier way to obtain a solution.

3.2.5.2 Local Balance

A local balance equation accounts for the flow to and from a network state due to arrivals at and departures from an *individual* node in the network. A global balance equation for a given state, in contrast, accounts for the state probability flow to and from *all* network states. Local balance equations are usually simpler than the global equations and have the useful property that their solution, if it exists, is also a solution to the global balance equations. The general local balance equation is [Kel79]

$$p(\mathbf{n})\sum_{N}\mu_{jk}=\sum_{N}p(T_{jk}\mathbf{n})\mu_{kj} \tag{3.13}$$

where $p(\mathbf{n})$ is the probability of being in state $\mathbf{n}$, N is the number of customers in the network, j and k are particular nodes in the network, μ_{jk} is the rate at which customers leave node j to arrive at node k, and $T_{jk}\mathbf{n}$ is an operator that takes a customer from node j and places it in k when the network is in state $\mathbf{n}$. Referring to Figure 3.3, the local balance equations for Node 1 (i.e., $j=1$) are

$$\mu_1 p(2,0,0) = 0.5\mu_2 p(1,1,0) \tag{3.14}$$
$$\mu_1 p(1,0,1) = 0.5\mu_2 p(0,1,1) \tag{3.15}$$
$$\mu_1 p(1,1,0) = 0.5\mu_2 p(0,2,0). \tag{3.16}$$

There are three equations since there are three network states which can result in customers departing from Node 1 (e.g., (2,0,0), (1,0,1), (1,1,0)). The cases where Node 1 has zero customers (e.g., (0,2,0), etc.) balance trivially. Equation (3.14) represents the rate of leaving state (2,0,0) due to customer departures from Node 1 equaling the rate of entering into state (2,0,0) due to customers arriving at Node 1 from Node 2. The only way the network could be in state (2,0,0) is due to customers arriving from Node 2 when the network was in state (1,1,0). Recall that we are assuming the system is in equilibrium and that time is continuous. Equation (3.14) also happens to be the same as (3.6) in the global balance equations. The equations for Node 2 (e.g., $j = 2$) provide cases that cannot be read directly from the global equations. The Node 2 equations are

$$\mu_2 p(0,2,0) = \mu_3 p(0,1,1) \tag{3.17}$$

$$\mu_2 p(1,1,0) = \mu_3 p(1,0,1) \tag{3.18}$$

$$\mu_2 p(0,1,1) = \mu_3 p(0,0,2). \tag{3.19}$$

Note that these equations are much simpler than the global balance equations. The equations for Node 3 are more interesting since customers come from multiple sources. The Node 3 equations are

$$\mu_3 p(0,0,2) = \mu_1 p(1,0,1) + 0.5\mu_2 p(0,1,1) \tag{3.20}$$

$$\mu_3 p(1,0,1) = \mu_1 p(2,0,0) + 0.5\mu_2 p(1,1,0) \tag{3.21}$$

$$\mu_3 p(0,1,1) = \mu_1 p(1,1,0) + 0.5\mu_2 p(0,2,0). \tag{3.22}$$

Reading (3.20), the rate of leaving state (0,0,2) due to customer departures at Node 3 is equal to rate of entering into state (0,0,2) due to customers arriving from Nodes 1 and 2.

Solving these equations is much easier than the corresponding global equations. Solving in terms of $p(2,0,0)$ is straightforward and results in the following

$$p(0,2,0) = \frac{4\mu_1^2}{\mu_2^2} p(2,0,0) \tag{3.23}$$

$$p(0,0,2) = \frac{4\mu_1^2}{\mu_3^2} p(2,0,0) \tag{3.24}$$

$$p(1,1,0) = \frac{2\mu_1}{\mu_2} p(2,0,0) \tag{3.25}$$

$$p(0,1,1) = \frac{4\mu_1^2}{\mu_2\mu_3}p(2,0,0) \quad (3.26)$$

$$p(1,0,1) = \frac{2\mu_1}{\mu_3}p(2,0,0)\,. \quad (3.27)$$

Using (3.12), we determine $p(2,0,0)$ to be

$$p(2,0,0) = \left[1 + \frac{4\mu_1^2}{\mu_2^2} + \frac{4\mu_1^2}{\mu_3^2} + \frac{2\mu_1}{\mu_2} + \frac{4\mu_1^2}{\mu_2\mu_3} + \frac{2\mu_1}{\mu_3}\right]^{-1}. \quad (3.28)$$

The skeptical reader can verify that (3.23)–(3.28) indeed satisfy the global balance equations given in (3.6)–(3.11).

3.2.5.3 Detailed Balance

As stated above, for detailed balance the rate at which the network leaves a given state to enter a new state must equal the rate at which the network leaves that new state to enter the given state [Kel79]. There is a subtle distinction between this and global balance. In global balance, the rate of leaving a given state to all other states must equal the rate of entering a given state from all other states. In detailed balance, the rate of leaving a state $\mathbf{n}$ to arrive at $\mathbf{m}$ must equal the rate of leaving $\mathbf{m}$ to arrive at $\mathbf{n}$. As with local balance equations, solutions to the detailed balance equations, if they exist, will solve the corresponding global balance equations.

The general detailed balance equation is [Kel79]

$$p(\mathbf{n})\mu_{jk} = p(T_{jk}\mathbf{n})\mu_{kj} \quad (3.29)$$

where $p(\mathbf{n})$ is the probability of being in state $\mathbf{n}$, j and k are particular nodes in the network, μ_{jk} is the rate at which customers leave node j to arrive at node k, and $T_{jk}\mathbf{n}$ is an operator that takes a customer from node j and places it in k when the network is in state $\mathbf{n}$. The detailed balance equations for state (2,0,0) are

$$p(2,0,0)\mu_{11} = p(T_{11}(2,0,0))\mu_{11} \quad (3.30)$$

$$p(2,0,0)\mu_{12} = p(T_{12}(2,0,0))\mu_{21} \quad (3.31)$$

$$p(2,0,0)\mu_{13} = p(T_{13}(2,0,0))\mu_{31} \tag{3.32}$$

$$p(2,0,0)\mu_{21} = p(T_{21}(2,0,0))\mu_{12} \tag{3.33}$$

$$p(2,0,0)\mu_{22} = p(T_{22}(2,0,0))\mu_{22} \tag{3.34}$$

$$p(2,0,0)\mu_{23} = p(T_{23}(2,0,0))\mu_{32} \tag{3.35}$$

$$p(2,0,0)\mu_{31} = p(T_{31}(2,0,0))\mu_{13} \tag{3.36}$$

$$p(2,0,0)\mu_{32} = p(T_{32}(2,0,0))\mu_{23} \tag{3.37}$$

$$p(2,0,0)\mu_{33} = p(T_{33}(2,0,0))\mu_{33}\,. \tag{3.38}$$

The equations (3.30), (3.34), and (3.38) are satisfied trivially (i.e., $0 = 0$). Looking closer at (3.32), and substituting in for the transition rates, μ_{jk}, we find that

$$p(2,0,0)\mu_1 \neq 0. \tag{3.39}$$

Since the two sides are not equal, detailed balance does not hold. It is not necessary to check any other equations since each detailed balance equation must hold.

3.2.6 Reversibility

In the previous section, it was stated that the reversibility of a network can be exploited to determine the equilibrium distribution. Many reversible networks have a known canonical form for their equilibrium distributions. In this section, we illustrate the concept of reversibility and give an example using a simple network.

In [Kel79], reversibility is described conceptually as a series of photographs taken of the changing states of a reversible random process. After taking the pictures, if we go back through them in reverse order, the process will be statistically indistinguishable although reversed in time.

Also in [Kel79], it was shown that a network is reversible if and only if the detailed balance equations hold. Using the simple network shown in Figure 3.5, we construct the detailed balance equations and from these, derive the equilibrium distribution of customers in the

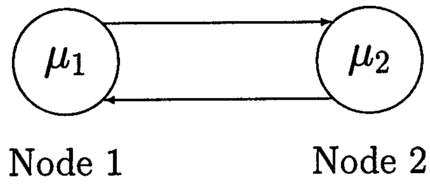


Figure 3.5: Closed Tandem Queueing Network – $M = 2, N = 3$

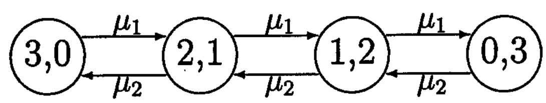


Figure 3.6: State Transition Diagram – Closed Tandem Queueing Network

network. If the detailed balance equations hold, the network is reversible. We then show how the equilibrium distribution can be determined directly using the known canonical form of this reversible network. Of course, to do this we *assume* rather than demonstrate reversibility. This is often the approach taken in practice since most interesting networks are more complex than those presented here. If the assumption of reversibility is incorrect, the canonical form will yield inconsistent results.

3.2.6.1 Detailed Balance Equations

The arrival and service distributions are assumed to be exponential. The number of nodes, M, is 2 and the number of customers within the network, N, is 3.

This network has 4 states: (3,0), (2,1), (1,2) and (0,3). The state transition diagram of this network is shown in Fig 3.6. The detailed balance equations that must hold for this network to be reversible are (eliminating redundancies)

$$p(3,0)\mu_1 \quad = \quad p(2,1)\mu_2 \tag{3.40}$$

$$p(2,1)\mu_1 = p(1,2)\mu_2 \tag{3.41}$$

$$p(1,2)\mu_1 = p(0,3)\mu_2 \tag{3.42}$$

and, of course, since the state probabilities must add to one

$$p(3,0) + p(2,1) + p(1,2) + p(0,3) = 1. \tag{3.43}$$

Solving these equations is trivial and the equilibrium distribution is

$$p(3,0) = \frac{1}{\left(1 + \frac{\mu_1}{\mu_2} + \left(\frac{\mu_1}{\mu_2}\right)^2 + \left(\frac{\mu_1}{\mu_2}\right)^3\right)} \tag{3.44}$$

$$p(2,1) = \frac{\mu_1}{\mu_2\left(1 + \frac{\mu_1}{\mu_2} + \left(\frac{\mu_1}{\mu_2}\right)^2 + \left(\frac{\mu_1}{\mu_2}\right)^3\right)} \tag{3.45}$$

$$p(1,2) = \frac{\mu_1^2}{\mu_2^2\left(1 + \frac{\mu_1}{\mu_2} + \left(\frac{\mu_1}{\mu_2}\right)^2 + \left(\frac{\mu_1}{\mu_2}\right)^3\right)} \tag{3.46}$$

$$p(0,3) = \frac{\mu_1^3}{\mu_2^3\left(1 + \frac{\mu_1}{\mu_2} + \left(\frac{\mu_1}{\mu_2}\right)^2 + \left(\frac{\mu_1}{\mu_2}\right)^3\right)}. \tag{3.47}$$

3.2.6.2 Canonical Form

The canonical form of the equilibrium distribution for a reversible closed network is [Ser93]

$$p(\mathbf{n}) = c\Phi(\mathbf{n}) \prod_{j=1}^{M} w_j^{n_j} \tag{3.48}$$

where $\mathbf{n}$ is the state of the network, c is a normalization constant, $\Phi(\mathbf{n})$ is a positive function on the network state space, M is the number of nodes in the network, n_j is the number of customers at the jth node, and the w_j are positive numbers that satisfy the routing equations

$$w_j \sum_k \mu_{jk} = \sum_k w_k \mu_{kj} \tag{3.49}$$

where j and k are nodes in the network and μ_{jk} is the rate at which customers move from j to k.

First, we determine the w_j's that satisfy the routing equations. Using (3.49), the routing equations for the network shown in Figure 3.5 are

$$w_1(\mu_{11} + \mu_{12}) = w_1\mu_{11} + w_2\mu_{21} \tag{3.50}$$

$$w_2(\mu_{21} + \mu_{22}) = w_1\mu_{12} + w_2\mu_{22}. \tag{3.51}$$

In this network, the rate at which customers move among the nodes of the network is simply the service rate of the node. Substituting those service rates into the above equations and solving them we find that they both have the same non-unique solution

$$\frac{w_1}{w_2} = \frac{\mu_2}{\mu_1}. \tag{3.52}$$

We will take the most straight-forward approach and set $w_1 = \mu_2$ and $w_2 = \mu_1$.

The function $\Phi(\mathbf{n})$ is a function of the network state. It is defined in terms of routing intensities where the route a particular customer takes may depend on the state of the network as a whole. In the case of the simple network under consideration, routing is not a function of network state and $\Phi(\mathbf{n}) = 1$ in all cases. Incidentally, if the routing intensities are a function of only the number of customers at a particular node, i.e., the nodes are independent, then the process is a Jackson network. We discuss this type of network in Section 3.3.1.1.

We now have all the values needed to solve the network using the canonical form given in (3.48). For the network in state (3,0), (3.48) becomes

$$p(3,0) = c\mu_2^3\mu_1^0 = c\mu_2^3. \tag{3.53}$$

Solving for states (2,1), (1,2), and (0,3) respectively, in the same manner, we have

$$p(2,1) = c\mu_2^2\mu_1 \tag{3.54}$$

$$p(1,2) = c\mu_2\mu_1^2 \tag{3.55}$$

$$p(0,3) = c\mu_2^0\mu_1^3 = c\mu_1^3. \tag{3.56}$$

Solving for the normalization constant c

$$c\mu_1^3 + c\mu_1^2\mu_2 + c\mu_1\mu_2^2 + c\mu_2^3 = 1 \tag{3.57}$$

and

$$c = \frac{1}{\mu_1^3 + \mu_1^2\mu_2 + \mu_1\mu_2^2 + \mu_2^3}. \tag{3.58}$$

Substituting (3.58) back into (3.53)–(3.56) and writing them in the same form as the detailed balance equations, we obtain the same solution as the detailed balance equations, as expected.

The value of the canonical form is that it provides a means of solving a network that is known, or assumed, to be reversible when the complexity of the network precludes solving the detailed balance equations. To enhance the clarity of the presentation, a simple network was used as an example. As stated before, often reversibility is assumed and the canonical form of network equilibrium is used to check the assumption. Canonical forms differ for different types of networks (e.g., open, closed, independent or dependent routing, etc.).

A note of caution—one should not conclude that only reversible networks have canonical forms. Canonical forms have been discovered for many non-reversible networks including those with batch arrivals and batch service [HT90]; more are being discovered all the time. For more detailed information on the concept of reversibility, the interested reader is encouraged to refer to [Ser93], [Dij93], and [Kel79] which provide a comprehensive treatment.

3.2.7 Normalization Constant

Customers do not arrive to or depart from a closed network; therefore, the number of customers within the network is fixed. These customers circulate among the nodes within the network forever. This being the case, the rate at which customers arrive at the individual nodes depends solely on the rate that the customers are served within the network. In a closed network, this arrival rate is normalized to 1. If we used the equilibrium equations for closed networks at this point, the result would not be the equilibrium probability of the network being in a certain state. Rather, the result would be the relative frequency that the network was in a certain state. Further, these numbers would not add up to 1 as required for a probability distribution. A normalization constant is introduced to convert the relative frequencies into probabilities.

The normalization constant has been computed several times in the previous sections with ease (e.g., (3.12), (3.43), and (3.58)). For a network of any appreciable size, enumerating all possible network states (as was done in the previous cases) is not feasible. In this section, we explore two alternate ways of calculating a normalization constant. Other computational algorithms can be found in [BB80].

3.2.7.1 z–transform Method

The first method of calculating the normalization constant uses z–transforms [Kel79]. An excellent refresher on transforms, including the z–transform, can be found in [Kle75]. In this section, we will again use the network shown in Figure 3.5. First, we define the generating function

$$\Psi_j(z) = \sum_{n=0}^{N+1} (w_j z)^n \tag{3.59}$$

and

$$B(z) = \sum_{k=0}^{\infty} \frac{z^k}{B_k} \tag{3.60}$$

where N is the number of customers in the network, w_j are positive numbers that satisfy the routing equations in (3.49), and $B(z)$ is the z–transform of the normalization constants, B_k, for $0 \leq k \leq \infty$. Without proof, we state

$$B(z) = \prod_{j=1}^{M} \Psi_j(z) \tag{3.61}$$

where M is the number of nodes in the network. Referring to the network in Figure 3.5, and recalling that $w_1 = \mu_2$ and $w_2 = \mu_1$ for that network, we have, using (3.59)

$$\Psi_1(z) = (\mu_2 z)^0 + (\mu_2 z)^1 + (\mu_2 z)^2 + (\mu_2 z)^3 + (\mu_2 z)^4 \tag{3.62}$$

or

$$\Psi_1(z) = 1 + \mu_2 z + \mu_2^2 z^2 + \mu_2^3 z^3 + \mu_2^4 z^4 \tag{3.63}$$

and

$$\Psi_2(z) = (\mu_1 z)^0 + (\mu_1 z)^1 + (\mu_1 z)^2 + (\mu_1 z)^3 + (\mu_1 z)^4 \tag{3.64}$$

or

$$\Psi_2(z) = 1 + \mu_1 z + \mu_1^2 z^2 + \mu_1^3 z^3 + \mu_1^4 z^4. \tag{3.65}$$

Substituting (3.63) and (3.65) into (3.61) results in

$$\begin{aligned} B(z) &= 1 + (\mu_1 + \mu_2)z + (\mu_1^2 + \mu_1\mu_2 + \mu_2^2)z^2 \\ &\quad + (\mu_1^3 + \mu_1^2\mu_2 + \mu_1\mu_2^2 + \mu_2^3)z^3 + \cdots + (\mu_1^4\mu_2^4)z^8. \end{aligned} \tag{3.66}$$

We see that for $N = 3$, the number of customers in the network, the normalization constant is

$$\frac{1}{B_3} = \mu_1^3 + \mu_1^2\mu_2 + \mu_1\mu_2^2 + \mu_2^3 \tag{3.67}$$

or

$$B_3 = \frac{1}{\mu_1^3 + \mu_1^2\mu_2 + \mu_1\mu_2^2 + \mu_2^3} \tag{3.68}$$

which is the same normalization constant found in (3.58) as required.

3.2.7.2 Convolution Algorithm

A second way to calculate a normalization constant due to [Buz73] is called the convolution algorithm. It performs the same task as the z–transform method but is formulated in such a way that z–transforms are not necessary. We will adopt the notation of [GN67] for the normalization constant, $G(N)$, where N is the number of customers in the network. Using the convolution algorithm, as will be seen in Section 3.2.7.3, we can use the intermediate results (i.e., the $G(i)$, $1 \leq i \leq N$ terms) to determine performance information about the network. Note that the $G(i)$ terms will not be equal to the B_i terms of Section 3.2.7.1, nor to their reciprocal (i.e., $G(i) \neq B_i \neq \frac{1}{B_i}$, $1 \leq i \leq N$).

In this section, we allow for the modeling of terminals within the network that will represent delays that are sometimes referred to as think time; the time a customer "thinks" prior to releasing a job to a node within the network. These terminal nodes are not included in the node count, M, and should be thought of collectively as node zero. With this background, we now proceed to describe how one can use the convolution algorithm to compute the normalization constant for a closed network. The following presentation generally follows that of [Jai91].

Gordon and Newell [GN67] found that the probability of a network being in state $\mathbf{n}$ is

$$p(n_0, n_1, \ldots, n_M) = \frac{D_0^{n_0} D_1^{n_1} \cdots D_M^{n_M}}{n_0! G(N)} \tag{3.69}$$

where D_i is the total service demand per customer on the ith node, n_i is the number of customer jobs at the ith device, and $G(N)$ is

$$G(N) = \sum_{\mathbf{n}} (D_1^{n_1} D_2^{n_2} \ldots D_M^{n_M}). \tag{3.70}$$

For example, if a customer's job makes 20 requests to a node, each request requiring 100 milliseconds of service, the service demand, D, would be $D = 20(0.100) = 2.0$. Note how this formulation differs from the z–transform method. The convolution algorithm requires that we know the average number of calls an average customer's job makes to each node in the system (as well as the average service time for each call to a node). The z–transform method, in contrast, used the information embedded in the routing equations (e.g., (3.49)).

Equations (3.69) and (3.70) are not used directly as this would require enumerating all possible network states. Further, calculating $G(N)$ this way could induce overflow or underflow problems if calculated by a computer. To preclude this, the service demands, D, are scaled by α, where

$$\alpha = \frac{1}{\frac{1}{M} \sum_{i=1} M D_i}. \tag{3.71}$$

Thus, the scaled service demand for the ith node is $y_i = \alpha D_i$. The scaled versions of (3.69) and (3.70) are

$$p(n_0, n_1, \ldots, n_M) = \frac{y_0^{n_0} y_1^{n_1} \cdots y_M^{n_M}}{n_0! G(N)} \tag{3.72}$$

where y_i is the scaled total service demand per customer on the ith node, n_i is the number of customer jobs at the ith node, and

$$G(N) = \sum_{\mathbf{n}} (y_1^{n_0} y_2^{n_1} \ldots y_M^{n_M}). \tag{3.73}$$

The convolution algorithm is based on the equation

$$g(n,k) = g(n,k-1) + y_k g(n-1,k) \tag{3.74}$$

and the relationship

$$G(N) = g(N,M) \tag{3.75}$$

where $g(n,k)$ is an auxiliary function, $n = 1,2,\ldots,N$, $k = 1,2,\ldots,M$, y_k is the scaled service demand for the kth node, and N and M are the number of customers and number of nodes in the network, respectively. The initial values for the auxiliary function are

$$g(n,0) = \frac{y_0^n}{n!}, \quad n = 1,2,\ldots,N \tag{3.76}$$

where y_0 is the scaled "think time" or average delay at the customer terminal and

$$g(0,k) = 1, \quad k = 1,2,\ldots,M. \tag{3.77}$$

If there are no terminals in the network then

$$g(n,0) = 0, \quad n = 1,2,\ldots,N. \tag{3.78}$$

Using (3.74), along with the initial values of the auxiliary function in (3.76)–(3.78), we have a simple way to calculate $G(N)$. This is best illustrated using a table. The table has $N+1$ rows labeled with the values $n, \quad 0 \leq n \leq N$, and $M+1$ columns labeled with the values of $y_k, \quad 0 \leq k \leq M$. Table 3.1 shows the initial auxiliary function values.

Entry (n,k) in the table is $g(n,k)$. The value for $g(1,1)$ is calculated by adding the entry immediately to the left of (1,1), $\frac{y_0^1}{1!}$, to the entry immediately above (1,1) which has been multiplied by the value of the column label (i.e., $y_1 \times 1$). The result is $\frac{y_0^1}{1!} + y_1(1)$ or $g(1,1) =$

Table 3.1: Convolution Algorithm

$n \Downarrow k \Rightarrow$	y_0	y_1	$\cdots$	y_k	$\cdots$	y_M
0		1	$\cdots$	1	$\cdots$	1
1	$\frac{y_0^1}{1!}$					
$\vdots$	$\vdots$			$g(n-1,k)$ $\downarrow \times y_k$		
n	$\frac{y_0^n}{n!}$		$g(n,k-1) \rightarrow$	$g(n,k)$		
$\vdots$	$\vdots$					
N	$\frac{y_0^N}{N!}$					$g(N,M)$

$y_0 + y_1$, which is simply a realization of (3.74). This process is repeated until all the entries in the table are filled. The right-most column contains valuable intermediate results as discussed above. The value of $g(N,M)$ is normalization constant $G(N)$.

Let us again use the network of Figure 3.5 and compare the equilibrium state probability results to the answer obtained using the z–transform method. Recall that the network has three customers and two nodes, therefore $N = 3$ and $M = 2$. There are no terminals in this network; therefore, there will be no y_0 node. In this network, each customer makes an equal number of calls to each node and has a unit amount of work to do; therefore, the scaled service demand on Node 1 (using a scaling factor $\alpha = 1$ since underflow or overflow are not a concern) will simply be $D_1 = y_1 = \frac{1}{\mu_1}$. Similarly, the scaled service demand on Node 2 is $D_2 = y_2 = \frac{1}{\mu_2}$. Table 3.2 shows the complete results.

We see that the value of the normalization constant is

$$G(3) = g(3,2) = \frac{1}{\mu_1^3} + \frac{1}{\mu_1^2\mu_2} + \frac{1}{\mu_1\mu_2^2} + \frac{1}{\mu_2^3} = \frac{\mu_2^3 + \mu_1\mu_2^2 + \mu_1^2\mu_2 + \mu_1^3}{\mu_1^3\mu_2^3}. \tag{3.79}$$

Table 3.2: Convolution Algorithm for Tandem Network of Figure 3.5

$n \Downarrow k \Rightarrow$	$y_0 = 0$	$y_1 = \frac{1}{\mu_1}$	$y_2 = \frac{1}{\mu_2}$
0		1	1
1	0	$\frac{1}{\mu_1}$	$\frac{1}{\mu_1} + \frac{1}{\mu_2}$
2	0	$\frac{1}{\mu_1^2}$	$\frac{1}{\mu_1^2} + \frac{1}{\mu_1\mu_2} + \frac{1}{\mu_2^2}$
3	0	$\frac{1}{\mu_1^3}$	$\frac{1}{\mu_1^3} + \frac{1}{\mu_1^2\mu_2} + \frac{1}{\mu_1\mu_2^2} + \frac{1}{\mu_2^3}$

Using the values for $G(3)$, y_1, y_2, and (3.72), the equilibrium state probabilities are

$$p(3,0) = \frac{\frac{1}{\mu_1^3}}{\frac{\mu_2^3+\mu_1\mu_2^2+\mu_1^2\mu_2+\mu_1^3}{\mu_1^3\mu_2^3}} = \frac{1}{\left(1+\frac{\mu_1}{\mu_2}+\left(\frac{\mu_1}{\mu_2}\right)^2+\left(\frac{\mu_1}{\mu_2}\right)^3\right)} \tag{3.80}$$

$$p(2,1) = \frac{\frac{1}{\mu_1^2\mu_2}}{\frac{\mu_2^3+\mu_1\mu_2^2+\mu_1^2\mu_2+\mu_1^3}{\mu_1^3\mu_2^3}} = \frac{\mu_1}{\mu_2\left(1+\frac{\mu_1}{\mu_2}+\left(\frac{\mu_1}{\mu_2}\right)^2+\left(\frac{\mu_1}{\mu_2}\right)^3\right)} \tag{3.81}$$

$$p(1,2) = \frac{\frac{1}{\mu_1\mu_2^2}}{\frac{\mu_2^3+\mu_1\mu_2^2+\mu_1^2\mu_2+\mu_1^3}{\mu_1^3\mu_2^3}} = \frac{\mu_1^2}{\mu_2^2\left(1+\frac{\mu_1}{\mu_2}+\left(\frac{\mu_1}{\mu_2}\right)^2+\left(\frac{\mu_1}{\mu_2}\right)^3\right)} \tag{3.82}$$

$$p(0,3) = \frac{\frac{1}{\mu_2^3}}{\frac{\mu_2^3+\mu_1\mu_2^2+\mu_1^2\mu_2+\mu_1^3}{\mu_1^3\mu_2^3}} = \frac{\mu_1^3}{\mu_2^3\left(1+\frac{\mu_1}{\mu_2}+\left(\frac{\mu_1}{\mu_2}\right)^2+\left(\frac{\mu_1}{\mu_2}\right)^3\right)} \tag{3.83}$$

as before in (3.44)–(3.47).

3.2.7.3 Performance Metrics

As stated above, other performance metrics can be determined using the intermediate results (i.e., the $G(i) \quad 1 \leq i \leq N$ terms or the right-most column of Table 3.1). These metrics are simply stated here for reference [Jai91]. Note that the queue length distributions do not apply to the terminal. Refer to [Buz73] for those calculations.

Queue Length Distributions

The probability of having j or more customers at the ith node is

$$p(n \geq j) = \sum_{\mathbf{n}|n_i \leq j} \frac{y_1^{n_1} y_2^{n_2} \cdots y_M^{n_M}}{G(N)} = y_i^j \frac{G(N-j)}{G(N)}. \tag{3.84}$$

The probability of exactly j customers at the ith node is

$$p(n_i = j) = p(n_i \geq j) - p(n_i \geq j+1) = \frac{y_i^j}{G(N)} \left[G(N-j) - y_i G(N-j-1) \right]. \tag{3.85}$$

The mean number of customers at the ith node is

$$Q_i = \sum_{j=1}^{N} p(n_i \geq j) = \sum_{j=1}^{N} y_i^j \frac{G(N-j)}{G(N)}. \tag{3.86}$$

The joint probability of having j or more customers at the ith node and l or more customers at the kth node is

$$p(n_i \geq j, n_k \geq l) = y_i^j y_k^l \frac{G(N-j-l)}{G(N)}. \tag{3.87}$$

Utilization

Node utilizations are

$$U_i = p(n_i \geq 1) = y_i \frac{G(N-1)}{G(N)}. \tag{3.88}$$

System Throughput

The network throughput is given by

$$X = \alpha \frac{G(N-1)}{G(N)}. \tag{3.89}$$

3.3 Analysis Methods

In this section, particular analysis methods are discussed. The methods have been divided arbitrarily into two types: exact and approximate. The terminology used to classify the analysis methods is not precise. Exact, in the sense used here, means a solution that is exact with respect to the assumptions. Whether the assumptions are reasonable and/or whether the model accurately corresponds to any realizable network is not addressed. Approximate means that the solution, more or less, corresponds to what occurs in a (presumably) more accurate model of a network.

It would be naïve to assume that "exact" analysis methods are "better" than approximations. Which is better or worse depends largely on the purpose for modeling the network in the first place and how much time is available to obtain an answer.

3.3.1 Exact Analysis Models

3.3.1.1 Jackson Networks

A Jackson network [Jac57], [Jac63] consists of M nodes that satisfy the following conditions [All90].

(1) Each node consists of c_i identical exponential servers where the service rate of the ith node is μ_i.

(2) Customers arrive from outside the system to the ith node according to a Poisson process with rate s_i. Customers may also arrive from other nodes within the network.

(3) Customers from node i are routed to node j with probability r_{ij} or leave the network with probability $1 - \sum_{j=1}^{M} r_{ij}$.

The arrival rate, λ_i, to each node i from all sources (external and internal) is

$$\lambda_i = s_i + \sum_{j=1}^{M} r_{ji}\lambda_j. \tag{3.90}$$

For a given network, there will be M arrival rate equations for the network with M unknowns. These M equations form a linear system that can be solved if and only if every customer eventually leaves the network.

For networks that satisfy the above conditions, Jackson proved that nodes can be treated *as if* they were independent M/M/c_i queues with arrival rate λ_i and service rate μ_i. If the service rate exceeds the arrival rate for all nodes in the network (to preserve stability), then

$$p(\mathbf{n}) = p_1(n_1)p_2(n_2)\cdots p_M(n_M) \tag{3.91}$$

where $p(\mathbf{n})$ is the probability of the network being in state $\mathbf{n}$ and $p_i(n_i)$ is the probability that there are n_i customers at node i treating it as an M/M/c queue. The probability an M/M/c queue with traffic intensity ρ contains n_i customers is

$$p(n_i) = \begin{cases} q_0 \frac{(c\rho)^{n_i}}{n_i!}, & n_i \leq c \\ \\ q_0 \frac{\rho^{n_i} c^c}{c!}, & n_i \geq c \end{cases} \tag{3.92}$$

where

$$q_0 = \left[\sum_{k=0}^{c-1} \frac{(c\rho)^k}{k!} + \frac{(c\rho)^c}{c!(1-\rho)}\right]^{-1}$$

$$\rho = \frac{\lambda}{c\mu}.$$

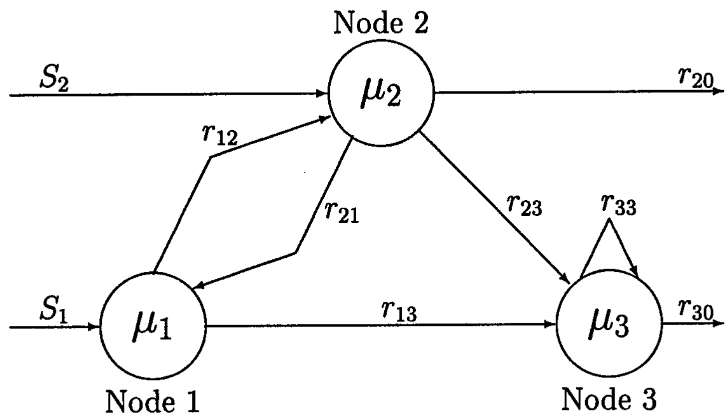


Figure 3.7: Open Jackson Network, $M = 3$

Jackson's results were later extended to include closed networks [GN67]. An astute reader will recognize that the network examples used in the previous sections were closed Jackson networks.

Figure 3.7 shows an open Jackson network with single server nodes, which we will analyze to find the network equilibrium probabilities. Suppose the arrival and service parameters for the nodes and the routing probabilities for the network (where Node 0 is outside the network) are

$$\begin{array}{llllllllllllll} s_1 &=& 2 & s_2 &=& 3 & \mu_1 &=& 3 & \mu_2 &=& 5 & \mu_3 &=& 3 \\ r_{12} &=& 0.5 & r_{13} &=& 0.5 & r_{20} &=& 0.7 & r_{21} &=& 0.1 & r_{23} &=& 0.2 \\ r_{30} &=& 0.9 & r_{33} &=& 0.1. \end{array} \tag{3.93}$$

Using (3.90), the arrival rate equation for each node is

$$\lambda_1 = s_1 + \sum_{j=1}^{3} r_{j1}\lambda_j = 2.0 + 0.1\lambda_2 \tag{3.94}$$

$$\lambda_2 = s_2 + \sum_{j=1}^{3} r_{j2}\lambda_j = 3.0 + 0.5\lambda_1 \tag{3.95}$$

$$\lambda_3 = s_3 + \sum_{j=1}^{3} r_{j3}\lambda_j = 0.5\lambda_1 + 0.2\lambda_2 + 0.1\lambda_3. \tag{3.96}$$

Solving these equations yields $\lambda_1 = 2.42, \lambda_2 = 4.21, \lambda_3 = 2.28$. Equation (3.92) simplifies to the following for the ith node with a single server (i.e., an M/M/1 queue)

$$\begin{aligned} p_i(n_i) &= (1-\rho_i)\rho_i^{n_i} \\ \rho_i &= \frac{\lambda_i}{\mu_i}. \end{aligned} \tag{3.97}$$

Thus, by using (3.91) and (3.97) the equilibrium probability for any network configuration can be determined. The equations for the network in Figure 3.7 are

$$p_1(n_1) = 0.19(0.81^{n_1}) \tag{3.98}$$

$$p_2(n_2) = 0.158(0.842^{n_2}) \tag{3.99}$$

$$p_3(n_3) = 0.24(0.76^{n_3}). \tag{3.100}$$

3.3.1.2 BCMP Networks

BCMP networks can be used to analyze open, closed, or mixed networks where customers may require different classes of service. In [BCMP75], Jackson networks are extended to allow different customer classes, different service requirements, and service distributions other than exponential. Furthermore, customers can change classes after receiving service.

Four different types of service centers (nodes) are defined [BCMP75].

(1) In a Type 1 service center, all customers have the same service distribution (exponential), and are served on a first-come-first-served (FCFS) basis. The service rate can be dependent on the number of customers at the node.

(2) A Type 2 service center is a processor sharing service center. Each customer receives an equal share of the processor time. Each class of customer may have a distinct service distribution which must have a rational Laplace transform (e.g., exponential, hyper-exponential, hypo-exponential). This generally means that the service time distributions are represented by stages of exponential servers [All90].

(3) In a Type 3 service center, the number of servers always exceeds the number of customers; therefore, a customer always begins service immediately. Each class of customer may have a different service distribution, which must have a rational Laplace transform.

(4) In a Type 4 service center, there is a single server and the service discipline is last-come-first-served (LCFS) with preempt-resume (i.e., the preempted customer will be the next one served). As before, each class of customer may have a different service distribution, which must have a rational Laplace transform.

The general probability equilibrium equation for a BCMP network is

$$p(\mathbf{n}) = cd(\mathbf{n}) f_1(x_1) f_2(x_2) \cdots f_M(x_M) \tag{3.101}$$

where c is a normalizing constant, $d(\mathbf{n})$ is an arrival rate function dependent on the number of customers in the system, and $f_i(x_i)$ is a function for the ith node that has condition x_i. The terms f_i and x_i in the equations above are defined differently for different types of service centers and networks. Before giving those definitions, we introduce the terms that appear in the definitions.

Customers travel through the network and change classes according to transition probabilities. A customer of class a that leaves node i will go to node j as a class b customer with probability $r_{i,a;j,b}$. These probabilities can be formed into a transition matrix $R = [r_{i,a;j,b}]$. This can be considered as the one-step transition matrix for a Markov chain with states (i, a) where i represents the customer's next state and a represents the customer's next class. This Markov chain is assumed to be reducible into l ergodic subchains. The states contained in these subchains are represented by the sets $E_1, E_2, \ldots, E_l$.

For each set of these ergodic subchains, E_k, there is an arrival equation defined which is similar to the arrival equation (3.90) except that it is extended to distinguish between arrivals of different classes of customers. The arrival rate to node j of a customer of class b, λ_{jb}, is

$$\lambda_{jb} = s_{jb} + \sum_{(i,a)\in E_l} r_{i,a;j,b}\lambda_{ia}, \qquad \forall(j,b) \in E_k \tag{3.102}$$

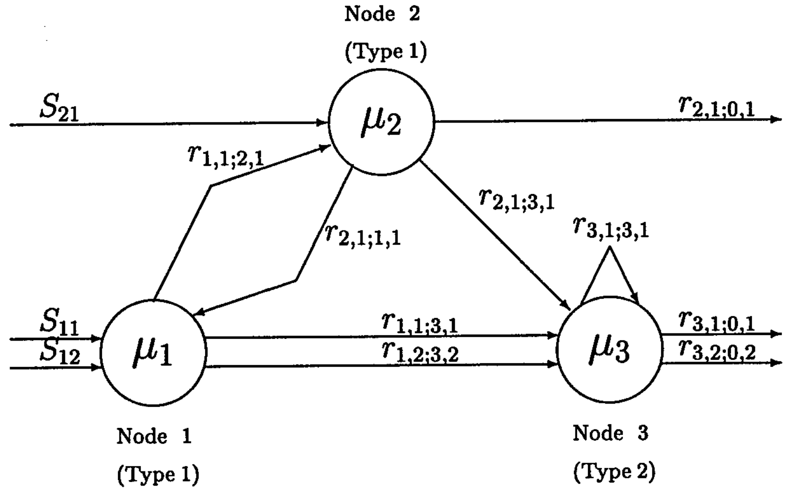


Figure 3.8: BCMP Network

where s_{jb} is the external arrival rate of class b customers to node j, $r_{i,a;j,b}$ is the probability that a customer of class a that leaves node i will go to node j as a class b customer, λ_{ia} is the arrival rate to node i of a customer of class a, and (i,a) and (j,b) are states within the subchain E_k.

As an example, consider the network shown in Figure 3.8 which is the same network as Figure 3.7, but includes customers of different classes, 1 and 2. Suppose the arrival and service parameters for the nodes and the routing probabilities for the network (where Node 0 is outside the network) are

$$\begin{aligned}
s_{11} &= 2.0 & s_{12} &= 1.0 & s_{21} &= 3.0 \\
\mu_1 &= 4.0 & \mu_2 &= 6.0 & \mu_3 &= 4.0 \\
r_{1,1;2,1} &= 0.5 & r_{1,1;3,1} &= 0.5 & r_{1,2;3,2} &= 1.0 \\
r_{2,1;0,1} &= 0.7 & r_{2,1;3,1} &= 0.2 & r_{2,1;1,1} &= 0.1 \\
r_{3,1;0,1} &= 0.9 & r_{3,1;3,1} &= 0.1 & r_{3,2;0,2} &= 1.0.
\end{aligned} \tag{3.103}$$

The transition matrix for the network is shown in Table 3.3. The subchain sets for this network are $E_1 = \{(0,1),(1,1),(2,1),(3,1)\}$ and $E_2 = \{(0,2),(1,2),(3,2)\}$. Constructing the arrival rate equations for E_1 and E_2 using (3.102) we have

$$\lambda_{01} = s_{11} + s_{21} \tag{3.104}$$

Table 3.3: BCMP Network Transition Matrix

Next ⇒ / *Current* ⇓	(0,1)	(0,2)	(1,1)	(1,2)	(2,1)	(3,1)	(3,2)
(0,1)	0.0	0.0	0.4	0.0	0.6	0.0	0.0
(0,2)	0.0	0.0	0.0	1.0	0.0	0.0	0.0
(1,1)	0.0	0.0	0.0	0.0	0.5	0.5	0.0
(1,2)	0.0	0.0	0.0	0.0	0.0	0.0	1.0
(2,1)	0.7	0.0	0.1	0.0	0.0	0.2	0.0
(3,1)	0.9	0.0	0.0	0.0	0.0	0.1	0.0
(3,2)	0.0	1.0	0.0	0.0	0.0	0.0	0.0

$$\lambda_{11} = s_{11} + r_{1,1;1,1}\lambda_{11} + r_{2,1;1,1}\lambda_{21} + r_{3,1;1,1}\lambda_{31} \quad (3.105)$$

$$\lambda_{21} = s_{21} + r_{1,1;2,1}\lambda_{11} + r_{2,1;2,1}\lambda_{21} + r_{3,1;2,1}\lambda_{31} \quad (3.106)$$

$$\lambda_{31} = s_{31} + r_{1,1;3,1}\lambda_{11} + r_{2,1;3,1}\lambda_{21} + r_{3,1;3,1}\lambda_{31} \quad (3.107)$$

$$\lambda_{02} = s_{12} \quad (3.108)$$

$$\lambda_{12} = s_{12} + r_{1,2;1,2}\lambda_{12} + r_{2,1;1,2}\lambda_{32} \quad (3.109)$$

$$\lambda_{32} = s_{32} + r_{1,2;3,2}\lambda_{12} + r_{3,2;3,2}\lambda_{32}. \quad (3.110)$$

Substituting the known values into these equations results in

$$\lambda_{01} = 2.0 + 3.0 \quad (3.111)$$

$$\lambda_{11} = 2.0 + 0.1\lambda_{21} \quad (3.112)$$

$$\lambda_{21} = 3.0 + 0.5\lambda_{11} \quad (3.113)$$

$$\lambda_{31} = 0.5\lambda_{11} + 0.2\lambda_{21} + 0.1\lambda_{31} \quad (3.114)$$

$$\lambda_{02} = 1.0 \quad (3.115)$$

$$\lambda_{12} = 1.0 \quad (3.116)$$

$$\lambda_{32} = \lambda_{12}. \quad (3.117)$$

Solving these equations yields $\lambda_{01} = 5.0, \lambda_{02} = 1.0, \lambda_{11} = 2.42, \lambda_{21} = 4.21, \lambda_{31} = 2.28, \lambda_{12} =$

$1.0, \lambda_{32} = 1.0$.

Now we define the terms of (3.101). For completeness, we describe the network state in general and then introduce a simpler form that works in most cases. The state of the network is $\mathbf{n} = (x_1, x_2, \cdots, x_M)$. The term x_i has the following definitions depending on the service center type.

(1) Type 1: $x_i = (x_{i1}, x_{i2}, \ldots, x_{in_i})$ where n_i is the number of customers at node i and x_{ij} $(1 \leq j \leq n_i,\ 1 \leq x_{ij} \leq Q)$ is the class of customer who is jth in the FCFS order, and Q is the number of customer classes. An example of a Type 1 node, x_i (for $Q = 4$), is $x_i = (1, 2, 1, 3, 1, 1)$. In this example, the first customer (i.e., the left-most) is a class 1 customer and is currently receiving service. There are $n_i = 6$ customers at the node; 4 class 1, 1 class 2, 1 class 3, and no class 4. The next customer to receive service will be the class 2 customer.

(2) Type 2 or 3: $x_i = (v_{i1}, v_{i2}, \ldots, v_{iQ})$ where v_{iq} is a vector $(m_{1q}, m_{2q}, \ldots, m_{u_{iq}q})$. The lth component of v_{iq}, m_{lq}, is the number of customers of class q at node i in the lth stage of service. The u_{iq} term is the number of stages for a class q customer at node i. An example of a Type 2 or 3 node, x_i (for $Q = 2, u_{i1} = u_{i2} = 2$), is $x_i = ((0, 1), (1, 2))$. In this example, there is 1 class 1 customer in the second stage of service and 3 class 2 customers; one in the first stage of service and two in the second stage of service. There are $n_i = 4$ customers at the node.

(3) Type 4: $x_i = ((r_1, m_1), (r_2, m_2), \ldots, (r_{n_i}, m_{n_i}))$ where n_i is the number of customers at node i in LCFS order and (r_j, m_j) is a pair describing the jth customer at the queue. The r_j term is the class of the customer and m_j is the stage of service. An example of a Type 4 node, x_i (for $Q = 2, u_{i1} = u_{i2} = 2$ as in the Type 2 and 3 example), is $x_i = ((1, 1), (1, 2))$. In this example, there is 1 class 1 customers in the first stage of service and 1 class 1 customer in the second stage of service. There are $n_i = 2$ customers at the node.

While these definitions of x_i are the most complete, usually a simpler state description will suffice, namely

$$\mathbf{n} = (y_1, y_2, \ldots, y_M) \tag{3.118}$$

where $y_i = (n_{i1}, n_{i2}, \ldots, n_{iQ})$ and n_{iq} is the number of customers of class q at node i. Readers that need to use the fuller state description should consult [BCMP75]. This simpler state description results in an equilibrium state probability equation

$$p(\mathbf{n}) = cd(\mathbf{n})g_1(y_1)g_2(y_2)\cdots g_M(y_M). \tag{3.119}$$

For a Type 1 node, g_i is

$$g_i(y_i) = \frac{n_i!}{\mu_i^{n_i}}\left[\prod_{q=1}^{Q} \frac{\lambda_{iq}^{n_{iq}}}{n_{iq}!}\right] \tag{3.120}$$

where n_i is the number of customers at node i, μ_i is the service rate at node i, n_{iq} is the number of customers of class q at node i, and λ_{iq} is the arrival rate of class q customers to node i. If the node is a Type 2 or 4 node, then

$$g(y_i) = n_i! \prod_{q=1}^{Q} \frac{\lambda_{iq}^{n_{iq}}}{\mu_{iq}^{n_{iq}} n_{iq}!} \tag{3.121}$$

where n_i is the number of customers at node i, μ_{iq} is the service rate at node i for customer class q, n_{iq} is the number of customers of class q at node i, and λ_{iq} is the arrival rate of class q customers to node i. If the node is a Type 3 node, then

$$g(y_i) = \prod_{q=1}^{Q} \frac{\lambda_{iq}^{n_{iq}}}{\mu_{iq}^{n_{iq}} n_{iq}!} \tag{3.122}$$

where μ_{iq} is the service rate at node i for customer class q, n_{iq} is the number of customers of class q at node i, and λ_{iq} is the arrival rate of class q customers to node i.

The term $d(\mathbf{n})$ has two definitions depending on the type of arrivals and whether the network is closed. If the arrivals to the network are Poisson and depend on the total number of customers in the network, N, and the arrivals to nodes of different customer classes have fixed probabilities then

$$d(\mathbf{n}) = \prod_{i=0}^{N-1} \lambda(i) \tag{3.123}$$

where $\lambda(i)$ is the mean arrival rate at node i. If the arrivals to the network consist of l Poisson streams corresponding to the l subchains described above, $E_1, E_2, \ldots, E_l$,

$$d(\mathbf{n}) = \prod_{j=1}^{l} \prod_{i=0}^{\mathbf{n}_{E_j}-1} \lambda_j(i) \tag{3.124}$$

where l is the number of subchains, $\mathbf{n}_{E_j}$ is the number of customers in the jth subchain, and λ_j is the mean arrival rate of the jth subchain. If the network is closed

$$d(\mathbf{n}) = 1. \tag{3.125}$$

As an example, we solve the network shown in Figure 3.8 for a particular network state to within the normalization constant c. The normalization constant for an open BCMP network generally does not have a closed form solution and must be determined numerically [RTW94]. The particular system state we solve for is described by (3.118) and is

$$\mathbf{n} = ((1,1),(2,0),(1,1)) \tag{3.126}$$

which states that there is one customer of class 1 and 2 at node 1, two customers of class 1 at node 2, and one customer of class 1 and 2 at node 3. Substituting in the network parameters of (3.103) and the solutions to (3.111)–(3.117) into (3.120) for Type 1 nodes and (3.121) for Type 2 nodes

$$g_1((1,1)) = \frac{2!}{4^2}\left[\left(\frac{2.42}{1!}\right)^1 \left(\frac{1}{1!}\right)^1\right] = 0.3025 \tag{3.127}$$

$$g_2((2,0)) = \frac{2!}{6^2}\left[\left(\frac{4.21}{2!}\right)^2 \left(\frac{0}{0!}\right)^0\right] = 0.4923 \tag{3.128}$$

$$g_3((1,1)) = 2!\left[\left(\frac{1}{1!}\right)\left(\frac{2.28}{2}\right)^1 \left(\frac{1}{1!}\right)\left(\frac{1}{2}\right)^1\right] = 1.140. \tag{3.129}$$

Using (3.123) yields

$$d(\mathbf{n}) = \prod_{i=0}^{6-1} 6 = 6^6 = 46,656. \tag{3.130}$$

Combining (3.127)–(3.129) yields the equilibrium probability

$$p((1,1),(2,0),(1,1)) = c(46,656)(0.3025)(0.4923)(1.140) = 7.92c. \tag{3.131}$$

A closed form for c exists for the equilibrium probability that a node will have a given number of customers, irrespective of their class. For Type 1, 2, and 4 nodes, the equilibrium probability that a node will have a given number of customers is

$$p_i(n_i) = (1 - \rho_i)\rho_i^{n_i} \tag{3.132}$$

or for a Type 3 node

$$p_i(n_i) = e^{-\rho_i}\left(\frac{\rho_i^{n_i}}{n_i!}\right) \tag{3.133}$$

where for Type 1 nodes

$$\rho_i = \sum_{q \in Q_i} \frac{\lambda_{iq}}{\mu_i} \tag{3.134}$$

or for Type 2, 3, and 4 nodes

$$\rho_i = \sum_{q \in Q_i} \frac{\lambda_{iq}}{\mu_{iq}}. \tag{3.135}$$

where $Q_i = \{q : \text{class } q \text{ customers that may require service at node } i\}$.

For this special case, (3.132) is similar to the Jackson network solution, (3.97), which corresponds to an M/M/1 queue. Similarly, (3.133) can be recognized as the equilibrium solution for the number of customers in an $M/G/\infty$ queue.

3.3.2 Approximate Analysis Methods

3.3.2.1 Mean Value Analysis

Closed Networks

The first approximation technique we examine is mean value analysis (MVA) for closed networks [Jai91]. MVA is an algorithm based on the observation [Sch79], [RL80] that for nodes that have an exponentially distributed service time, the average response time, r_i, for the ith node as seen by an arriving customer is

$$r_i(N) = \mu_i^{-1}(1 + Q_i(N-1)) \tag{3.136}$$

where $r_i(N)$ is the response of the ith node when the network has N jobs, μ_i^{-1} is the mean service time of the ith node, and $Q_i(N-1)$ is the average number of jobs at the ith node when the network has $N-1$ jobs in it. The arriving job sees $Q_i(N-1)$ jobs ahead of it; therefore, it will take $\mu_i^{-1}Q_i(N-1)$ seconds before it will receive service. By including the arriving job's service time, we have (3.136). Taking advantage of a set of relationships known as operational laws [Buz76] (i.e., assumptions that can be demonstrated by testing), we can recursively determine $r_i(N)$ for any number of jobs. These operational laws are

$$r(N) = \sum_{i=1}^{M} v_i r_i(N) \tag{3.137}$$

where $r(N)$ is the network response time, v_i is the number of visits to the ith node, M is the number of nodes in the network, and $r_i(N)$ is defined by (3.136). Network throughput is

$$X(N) = \frac{N}{r(N) + z} \tag{3.138}$$

where $r(N)$ is defined by (3.137) and z is the customer "think time" (cf., Section 3.2.7.2). The response time for a delay center (since all jobs receive immediate service) is

$$r_i(N) = \mu_i^{-1}. \tag{3.139}$$

Individual node throughputs are

$$X_i(N) = X(N)v_i. \tag{3.140}$$

The node queue lengths with N jobs in the network are

$$Q_i(N) = X_i(N)r_i(N) = X(N)v_i r_i(N). \tag{3.141}$$

Node utilizations are

$$U_i = X(N)\mu_i^{-1}v_i. \tag{3.142}$$

Using (3.136)–(3.138) and (3.141) we can find performance parameters for a closed system with any number of jobs.

Let us use the network of Figure 3.3 and compare the results obtained by using the convolution algorithm (Section 3.2.7.2) and MVA. Setting $\mu_1 = 2$, $\mu_2 = 3$ and using Table 3.2, we find that the values for the normalization constants using the convolution algorithm are $G(0) = 1$, $G(1) = \frac{180}{216}$, $G(2) = \frac{114}{216}$, $G(3) = \frac{65}{216}$. Using (3.86), (3.88), and (3.89) we find that $Q_1 = 1.99$, $Q_2 = 1.02$, $U_1 = 0.88$, $U_2 = 0.58$, and $X = 1.75$. Applying the MVA equations (3.136)–(3.141) iteratively results in the values contained in Table 3.4.

Using the values in the right-most column of Table 3.4 and (3.142), we find that the MVA values are $Q_1 = 2.0$, $Q_2 = 1.03$, $U_1 = 0.71$, $U_2 = 0.47$, and $X = 1.42$. These compare reasonably well with those obtained using the convolution algorithm.

Open Networks

MVA also applies to open networks. The equations are similar, but do not require iterative application as in a closed network. The open network MVA equations are stated below. The average response time, r_i, for the ith node as seen by an arriving customer is

$$r_i = \begin{cases} \frac{\mu_i^{-1}}{1-U_i}, & \text{Ordinary node,} \\ \\ \mu^{-1}, & \text{Delay centers} \end{cases} \tag{3.143}$$

where r_i is the response of the ith node, μ_i^{-1} is the mean service time of the ith node, and U_i is the utilization of ith node. The system response time is

$$r = \sum_{i=1}^{M} v_i r_i \tag{3.144}$$

where v_i is the number of visits to the ith node, M is the number of nodes in the network, and r_i is defined by (3.143). Network throughput is (assuming equilibrium) simply

$$X = \lambda \tag{3.145}$$

where λ is the job arrival rate. Individual node throughputs are

$$X_i = X v_i. \tag{3.146}$$

Table 3.4: MVA Algorithm

$N \Rightarrow$	0	1	2	3
$r_1(N)$ (3.136)	—	$\frac{1}{2}$	$\frac{14}{10}$	$\frac{67}{50}$
$r_2(N)$ (3.136)	—	$\frac{1}{3}$	$\frac{11}{15}$	$\frac{58}{75}$
$r_1(N)$ (3.137)	—	$\frac{5}{6}$	$\frac{32}{15}$	$\frac{317}{150}$
$r_1(N)$ (3.138)	—	$\frac{18}{5}$	$\frac{45}{32}$	$\frac{450}{317}$
$r_1(N)$ (3.141)	0	$\frac{9}{5}$	$\frac{42}{25}$	$\frac{64}{32}$
$r_1(N)$ (3.141)	0	$\frac{6}{5}$	$\frac{33}{25}$	$\frac{33}{32}$

Node utilizations are

$$U_i = X\mu_i^{-1}v_i. \tag{3.147}$$

The node queue lengths are

$$Q_i = \frac{U_i}{1 - U_i}. \tag{3.148}$$

In this discussion, we focused on MVA as it applies to fixed-capacity nodes (i.e., nodes where the service rate is independent of the number of jobs). In fact, MVA can be used to analyze more complex networks than those presented here. The interested reader should consult [Jai91].

3.3.2.2 Equilibrium Point Analysis

In Section 3.2.3, we mentioned the difficulty of analyzing discrete-time queues and, in Section 3.2.4, the difficulties introduced by interfering queues were discussed. In this section, we discuss an approximation technique called Equilibrium Point Analysis (EPA) which can be used to analyze these types of queueing networks. Although our discussion is limited to a rather simple packet radio network, this widely used technique can be applied to networks with bulk arrivals and service, discrete-time networks, networks with different customer classes, and local area networks such as Ethernet, token bus and token ring. The reader is encouraged to consult [Woo94] for details. This presentation of EPA is due to [Woo94].

As the name indicates, EPA is an approximation technique that applies only when the network is in equilibrium. This greatly simplifies the solution of the network since the network balance equations (c.f., Section 3.2.5) are not solved, but assumed. With EPA; however, we do not balance network state probabilities, we balance network customer flow, i.e.,

$$\lambda_i = \sum_{j=1}^{M} \lambda_j r_{ji}, \quad 1 \le i \le M \tag{3.149}$$

where λ_i is the mean arrival rate to the ith node, r_{ji} is the routing probability from node j to i, and M is the number of nodes in the system. We can write (3.149) in an equivalent form by applying Little's result (i.e., $n_i = \lambda_i \mu_i^{-1}$) to give

$$E[n_i]\mu_i = \sum_{j=1}^{M} E[n_j]\mu_j r_{ji}, \quad 1 \le i \le M. \tag{3.150}$$

The expected values, $E[n_i]$, $E[n_j]$, are then approximated by the point values, x_i and x_j, that solve the equations

$$x_i \mu_i = \sum_{j=1}^{M} x_j \mu_j r_{ji}, \quad 1 \le i \le M. \tag{3.151}$$

The equations formed by (3.151) are the equilibrium point equations. As with the other closed networks we have seen, one of the equations from (3.151) has a linear dependence and is replaced by

$$\sum_{i=1}^{M} x_i = N \tag{3.152}$$

where N is the number of customers in the network. Using (3.151) and (3.152), we have, as before, M independent equations that can be solved to obtain an equilibrium point

$$x^e = (x_1^e, x_2^e, \ldots, x_M^e). \tag{3.153}$$

This is done assuming that the state vector components are real-valued and not integers.

The expected value of a network performance measure of interest, $S(x)$, that is a function of x, is

$$E[S(x)] = \int S(x)\delta(x - x^e)dx = S(x^e) \tag{3.154}$$

which states that mean values of performance measures can be approximated by their value at the equilibrium point.

As an example, consider a slotted ALOHA packet radio network [Abr77] with a delayed first transmission. Figure 3.9 depicts a radio in the network. Each radio can be idle (Node 2) or waiting to transmit (Node 1). Time is slotted with state changes allowed only at set points in time. If the radio is idle (i.e., at Node 2), a packet can arrive during the time slot with probability σ. At the end of the time slot, the radio moves to Node 1 and is waiting to transmit. While at Node 1, the radio transmits during a time slot with probability p. If no other radios in the network transmit during that time slot, the transmission is successful and

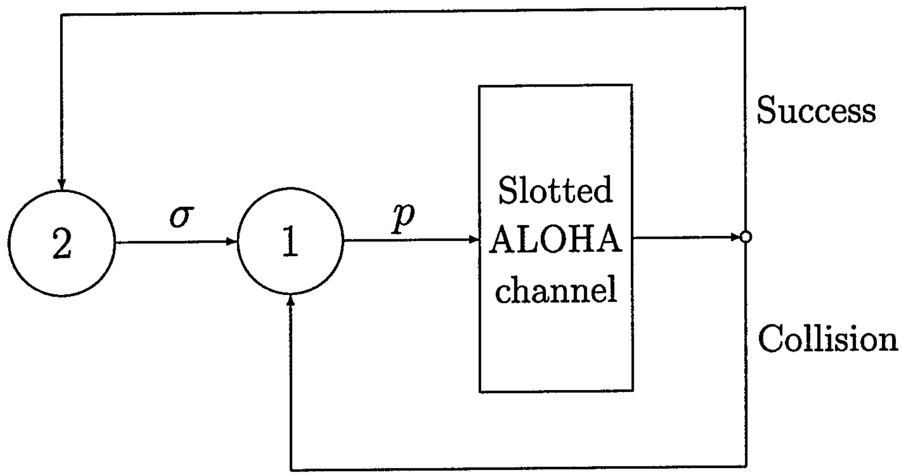


Figure 3.9: Slotted ALOHA Network

the radio becomes idle (i.e., returns to Node 2). Otherwise, if two or more radios transmit during a time slot, there is a collision, the transmission is not successful and the radio remains waiting to transmit (i.e., at Node 1).

The service rates of the nodes are $\mu_1 = p$, and $\mu_2 = \sigma$. The routing probability from Node 2 to Node 1 is $r_{21} = 1$. The routing probability r_{12} is the probability that only one customer at Node 1 attempts to depart or

$$r_{12} = (1-p)^{x_1-1}. \tag{3.155}$$

Obviously r_{11} is

$$r_{11} = 1-(1-p)^{x_1-1}. \tag{3.156}$$

The system state is

$$x = x_1 \tag{3.157}$$

since by knowing x_1, we know $x_2 = N - x_1$.

Notice that (3.155) and (3.156) depend on the state of the system. This is an interfering queue as discussed in Section 3.2.4.

We apply EPA to this network by substituting in the service rates of the nodes and the routing probabilities, (3.155) and (3.156), into (3.151) to obtain

$$x_2\sigma = x_1 p(1-p)^{x_1-1}. \tag{3.158}$$

Using (3.152), the second equation is

$$x_1 + x_2 = N. \tag{3.159}$$

Solving (3.158) and (3.159) for x_1, yields

$$x_1 = \frac{N\frac{\sigma}{p}}{\frac{\sigma}{p} + (1-p)^{x_1-1}} \tag{3.160}$$

which is a fixed point equation of the form $x_1 = f(x_1)$. These equations can be solved by using methods such as simple iteration or bisection [PFTV92].

The throughput of the network, given it is in state x_1, is simply

$$S(x_1) = x_1 p(1-p)^{x_1-1}. \tag{3.161}$$

Using (3.154), the expected value of (3.161) is

$$E[S(x_1)] \approx S(x_1^e) = x_1^e p(1-p)^{x_1^e}. \tag{3.162}$$

Thus, the network in Figure 3.9 that could not be solved using exact network queueing analysis due to interfering queues is solved, quite simply, by an approximation.

3.4 Overview of Analysis Techniques

In this section, an overview of the analysis techniques discussed is presented. Recall that in most of the networks described, customers arrive according to a Poisson process and service times are exponentially distributed. An exception is BCMP networks in which customers arrivals and service time distributions that have rational Laplace transforms may also be analyzed.

Balance equations can be used to determine the probability of a network being in a given state for continuous-time networks that are either open or closed. Balance equations may also be used on reversible networks. The set of local balance and detailed balance equations may be easier to solve than the global balance equations. The solution to the local and detailed balance equations are also solutions to the global balance equations.

Reversible networks may have a solution to the equilibrium state probability in a known canonical form. Often, reversibility is assumed and canonical forms are used to verify the assumption.

Normalization constants can be used to determine many performance metrics of a network. Some of these metrics include queue length distributions, the probability of having a given number of customers at a node, node utilization, system throughput, and others.

Jackson networks are used to determine the probability of a given network state. In a Jackson network each node is treated as if it were an independent M/M/c queue.

Using BCMP networks, several different types of queues can be modeled. These include not only queues with Poisson arrivals and exponential service times but also queues in which: (1) the service rate can be dependent on the number of customers in the queue, (2) each customer receives an equal portion of the service time (processor sharing), (3) a customer always receives immediate service, and (4) the service discipline is last-come-first-served. Additionally, BCMP networks support the analysis of networks with different customer classes and customers with service times that have rational Laplace transforms.

Mean Value Analysis is an approximation technique that is based on the observation that the mean response time of a queue (the time until an arriving customer will receive service) is the mean service time times the number of customers ahead of the arriving customer. Using this simple observation, system response time, and node throughputs, utilizations, and queue lengths can be approximated.

Equilibrium Point Analysis can be applied to discrete-time networks and networks with interfering queues (cf., Section 3.2.4). EPA *assumes* rather than solves the balance equations discussed in Section 3.2.5. Some networks whose performance cannot be determined using the above techniques can be solved using EPA.

Table 3.5 summarizes these analysis techniques and the networks that they may be applied to. The table is not a complete list of networks types that the analysis techniques can be applied to. For that information, the reader is encouraged to consult the supplied references for more detailed information.

3.5 Summary

The fundamental terms, concepts, and techniques of queueing network analysis have been presented. Terms used to classify queueing networks such as open, closed, and mixed were defined. The concepts of continuous-time, discrete-time, and interfering queues were presented and the impact of analyzing networks with these characteristics was discussed. We illustrated essential concepts such as balance (the conservation of customer flow) and reversibility (a network where state changes in forward or reversed time are statistically indistinguishable). We showed how balance equations can be used to determine the probability of a given network state. Several analytical analysis methods were discussed and their application and limitations demonstrated. These included "exact" analysis techniques including Jackson networks, and BCMP networks as well as approximations such as the Normalization Constant, Mean Value Analysis, and Equilibrium Point Analysis. We intended to present the essential concepts used in queueing network analysis without overwhelming the reader with technical details. Readers are encouraged to use the supplied references. These will enable the reader to apply queueing network analysis to more general classes of networks than could be covered here.

Table 3.5: Analysis Methods for Queueing Networks

Analysis Technique (Section)	Network Type			
	Open or Closed, Continuous-Time	Open or Closed, Continuous-Time, Reversible	Open, Closed, or Mixed, Continuous-Time, Multi-Class Customers	Open, Closed, or Mixed, Continuous or Discrete-Time, Multi-Class Customers, Interfering Queues
Global Balance Eqn. (3.2.5.1)	×	×		
Local Balance Eqn. (3.2.5.2)	×	×		
Detailed Balance Eqn. (3.2.5.3, 3.2.6.1)		×		
Canonical Form (3.2.6.2)	×	×		
Normalization Constant (3.2.7)	×	×		
Jackson Networks (3.3.1.1)	×	×		
BCMP (3.3.1.2)	×	×	×	
MVA (3.3.2.1)	×	×		
EPA (3.3.2.2)	×	×	×	×

Chapter 4

Objectives and Methodology

This chapter presents the objectives and methodology used throughout this research. It is widely recognized that the research methodology employed can be as important as the capabilities of the researcher; therefore, the methodology must be carefully chosen. The research methodology used herein has been strongly influenced by [Jai91]. In that work, a systematic, ten-step approach to system performance evaluation is presented. The first eight steps (listed below), are discussed in this chapter. The other steps will be covered in the remaining chapters.

1. State goals and define system boundaries (Section 4.1)
2. List system services and possible outcomes (Section 4.2)
3. Select performance metrics (Section 4.3)
4. List system model parameters (Section 4.4)
5. Select factors (Section 4.5)
6. Select evaluation technique (Section 4.6)
7. Select workload (Section 4.7)

8. Design experiments (Section 4.8)

A summary of this chapter is presented in Section 4.9.

4.1 Problem Definition

Chapter 1 presented motivation for research into real-time data transport via wireless LANs. Chapters 2 and 3 discussed, among other things, some proposed methods for implementing real-time wireless LANs and difficulties experienced when analytically analyzing real-time systems. Generally, there have been two approaches used to reduce the inherent difficulty of analyzing the ability of a real-time system to meet deadlines. The first approach includes constraining the input to the system to a deterministic customer arrival rate, constraining the service times to a deterministic rate, and introducing restrictive assumptions about customer deadline characteristics. This type of approach is used in Rate Monotonic Analysis [KRPO93]. This approach, however, effectively limits a solution to those problems which can meet the (perhaps unrealistic) assumptions. In other words, the problem is forced to conform to the available solutions. The second typical approach has been to assume worst case arrival and service scenarios. This approach obviously results in underutilized systems and presumes that worst-case behavior can be determined. In this research, a less restrictive approach to specifying input and service characteristics is taken by using simulation to characterize and predict system behavior.

4.1.1 Research Thesis and Objectives

The thesis of this research is that the ability of an *ad hoc* packet data network to successfully transport real-time data will be dramatically improved by better utilization of channel capacity and by reducing packet collisions.

The overall objectives of this research are to develop an *ad hoc* real-time wireless LAN that successfully delivers real-time data and to develop regression models of the real-time wireless LAN which accurately predicts the deadline performance of stations participating in the network. To meet these objectives, this research addresses the following specific areas.

A new MAC protocol is developed (RT-MAC) which provides timely access to the wireless channel. This protocol uses the IEEE 802.11 MAC protocol as a point of departure. Modifications to the protocol include implementing a transmission control algorithm which prevents the transmission of packets that have (or will) exceed their deadline. A collision reduction algorithm dynamically alters the range of backoff values stations choose from as a function of the number of transmitting stations in the network. Also included in the collision reduction algorithm is the sharing of station backoff values with other stations in the network to reduce, via a distributed algorithm, packet collisions.

Regression models are developed that predict the throughput, average delay, percentage of packet deadline failures, and percentage of packet collisions. The models incorporate the BER of the channel, the number of stations in the network, the offered load, as well as whether the network is using the IEEE 802.11 protocol or RT-MAC.

Obviously, bit errors introduced by the channel will influence packet transmission times in the form of retransmissions. A two-state Markov model similar to the Gilbert model [Gil60] is used to introduce bursty bit errors into packets. In contrast to the well known Gilbert model where state transitions are "modulated" by packet transmissions (cf., Section 2.3.2), state transitions in the model used in this research are "modulated" by time.

In real-time systems, the service discipline (or the order in which customers receive service) can have a dramatic effect on the ability of a system to meet deadlines. It has long been known [LL73] that in the context of processes running on a computer system, certain disciplines are optimal in meeting computational deadlines (e.g., earliest-deadline-first (EDF)). In application domains which permitted out of order packet delivery, several service disciplines were investigated to attempt to improve the deadline performance of the network.

The focus and approach of this research is somewhat uncommon. It extends the existing body of knowledge within the real-time wireless network domain in several areas. To date, there have been no known attempts to improve, or even establish, the hard real-time transmission capabilities of IEEE 802.11. As was presented in Chapter 2, any modifications to the MAC protocol have been with the intent of improving data throughput or lowering mean delay.

Incorporating channel induced bit errors into the performance analysis has seldom been done for real-time IEEE 802.11 systems—never in the context of hard real-time performance. In Chapter 2, it was shown that most research focused on the throughput of a network in the presence of collisions from other transmitting stations. In simulations, the probability of bit errors due to channel effects was either assumed to be virtually zero (as in wired channels) or constant. An exception to this was [CWKS96], which modeled bit errors using a Gilbert model [Gil60].

Finally, there have been no known regression models developed to predict the real-time performance of wireless computer networks. As was shown in Chapter 3, the real-time performance of networks with interfering queues cannot be determined analytically (other than average case behavior) given the current state of theoretic analysis of such networks.

Computer networks have numerous parameters and can exist in numerous configurations. The following sections further define the network investigated by this research.

4.1.2 System Boundaries

The system considered in this research consists of an arbitrary number of stations networked together via a wireless LAN. This set of stations form (in IEEE 802.11 terminology) an independent basic service set (IBSS). The network operates independent of any other networks. That is, the network is not connected to a distribution system which could transport packets generated within the network beyond the transmission capacity of a station in the IBSS.

4.1.2.1 Propagation Delay

Since stations in an IEEE 802.11 IBSS are necessarily situated close together, propagation delay is assumed to be zero with respect to packet transmission time.

4.1.2.2 Packet Length

The length of the packet can dramatically affect network performance. In real-time systems, it is advantageous to introduce predictability wherever practicable; therefore, fixed length packets are used to give the network a measure of predictability. The length of these packets is dependent on the application domain and is specified in Section 4.7.

4.1.2.3 MAC and Physical Layer Implementations

As stated in Chapter 1, adhering to standards offers the potential for low-cost implementations. It can also enhance acceptance in the marketplace. Therefore, the MAC protocol developed is compatible with IEEE 802.11. Further, the two protocols are interoperable. That is, they can co-exist within the same network. Although the physical layer implementation is assumed to be direct sequence spread spectrum (DSSS), this research does not depend on any physical layer attribute directly. Therefore, different physical layers can be used without any change in the MAC protocol (though some change in performance is to be expected).

4.2 System Services

Data communications by transmission of packets is the single service provided by the system. The class of service is guaranteed on-time delivery or hard deadlines. This class of service guarantees delivery of packets prior to the deadline of the packet expiring. There are three possible outcomes: delivery prior to packet deadline (success), delivery after packet deadline (failure), or no delivery (failure).

Transmission of packets that have, or will certainly, miss their deadlines constitutes a double failure. One failure is the missed deadline itself, the other is the wasted channel capacity used to deliver an unusable packet. Therefore, when a station can detect that a packet will be delivered late prior to its transmission, that packet will be discarded and a failure recorded.

4.3 Performance Metrics

4.3.1 Throughput

The most common system performance metric used when studying LANs is normalized throughput (the bits per second normalized to channel data rate). In this effort, however, throughput is of secondary importance. Since this research deals with real-time systems, the timeliness of the packet (i.e., the actual delivery time compared to the delivery deadline) is the critical performance measure. Throughput, however, is reported for purposes of comparison with other systems.

4.3.2 Mean Delay

Mean delay is another common performance metric. For the same reasons as throughput, mean delay is of secondary importance in this research but is reported for purposes of comparison with other systems.

4.3.3 Missed Deadline Ratio

For guaranteed delivery service, the ratio of messages lost due to delivery failure is the primary performance metric. This is the number of packets that exceed their deadlines over the number of packets removed from the queue for transmission. A packet that is discarded (due to exceeding the transmission attempt count or due to the transmission control algorithm) is deemed to have exceeded its deadline.

4.3.4 Collision Ratio

To measure the effectiveness of the collision reduction algorithm, the packet collision ratio is tracked. This is the number of packet collisions over number of transmission attempts. Regardless of the number of packets involved in a collision, it is counted as a single collision. For example, if three stations transmit simultaneously, one collision is said to occur even though three packets are involved in the collision.

4.4 System Model Parameters

The following sections document the parameters in the network under consideration. The assumptions made about these parameters are intended to strike a balance between a system that has practical application and one that can be simulated in a reasonable amount of time.

4.4.1 Network Topology

The topology assumed for this effort is a bus. That is, every station in the network can receive the transmissions of every other station in the network. This assumption implies that the request to send/clear to send (RTS/CTS) capability of IEEE 802.11 will not be used.

4.4.2 Capture

As explained in Chapter 2, capture is a technique whereby the receiving station may recover one signal from many that were transmitted, given sufficient signal strength and additional signal processing. In order to simplify the analysis and simulation, and reduce the number of parameters within the system that can be varied, stations in the network do not employ capture.

4.4.3 Power Considerations

IEEE 802.11 incorporates a power save (PS) mode whereby a station can "sleep" for a time in order to conserve power, then "wake up" at specified intervals to receive messages queued by other stations. This effort does not address any power saving features of IEEE 802.11. That is, a station never sleeps.

4.4.4 Wireless MAC Functions

As discussed in Section 2.2.3.1, the distributed coordination function (DCF) is used in the system model to access the transmission channel.

4.4.5 Number of Stations

The number of stations in a network can be a critical factor in network performance. The number of stations in the network under investigation varies from 2 to 80 depending on the application domain.

4.4.6 Normalized Offered Load

Normalized offered load is the amount of traffic stations in a network generate for transmission relative to the maximum transmission capability of the network. The amount of traffic each station in the network offers to the network is equal, that is, the stations are homogeneous. The normalized offered load is the combined load offered by all the stations in the network.

4.4.7 Traffic Model

The characteristics of the arriving traffic have a significant influence on network performance. Different application domains are characterized by different traffic arrival patterns. The specific traffic models chosen for this effort are described below in Section 4.7.

4.4.8 Channel Model

The transmission channel is modeled as a dynamically changing environment. Errors occur in bursts and are introduced via a two-state model (described below in Section 4.5.3). In selected simulations, the effect of a static BER model on network performance is investigated.

4.4.9 MAC Protocol

The MAC protocol used in the network is either IEEE 802.11 or RT-MAC. RT-MAC is described fully in Chapter 5.

4.4.10 MAC Protocol Parameters

There are several important MAC protocol parameters. The minimum width of the contention window (cf., Section 2.2.3.1), CWmin, is 31. The maximum width of the contention window, CWmax, is 1023. The slot time is set to the default value for a DSSS system, $20\mu s$. The short inter-frame space (SIFS) is set to $10\mu s$, while the distributed IFS (DIFS) is calculated using other IEEE 802.11 parameters as defined in the standard. Also calculated using the definitions in IEEE 802.11 are the ACK length, PHY header length, and the value for the ACK timeout.

4.4.11 Physical Layer Parameters

The single significant physical layer parameter considered is the channel bit rate. For most simulations the 1 Mbps data rate is assumed. Selected simulation studies use bit rates up to 10 Mbps.

4.4.12 Other Parameters

There are numerous other parameters that are specified in IEEE 802.11 standard. Those that have been implemented in the simulation model are listed in Appendix A. Those not specifically mentioned above use the default values described in Appendix A.

4.5 System Factors

Factors are parameters that are varied during the simulation such that they significantly impact system performance when altered [Jai91]. Levels are the particular values that a factor can assume. The parameters discussed above that fit this criteria include the number of stations (N), normalized offered load (G), channel model (E), and the MAC protocol. A table with the factors and their levels can be found in Tables 4.1, 4.2 and 4.3.

Table 4.1: Simulation Factors - Telemetry, Avionics Traffic Models

Factor	Levels
Number of Stations (N)	5, 10, 20, 30, 40, 50
Offered Load (G)	0.3, 0.5, 0.7, 0.9
Channel Model (E)	ideal, bursty
MAC Protocol	IEEE 802.11, RT-MAC

Table 4.2: Simulation Factors - 1 Mbps Voice Traffic Model

Factor	Levels
Number of Stations (N)	4, 10, 14, 20, 24, 30
Offered Load (G)	$G = G_{RT} + G_{NRT}$
G_{RT}	$0.0136N$
G_{NRT}	0.0, 0.2, 0.4, 0.6, 0.8
Channel Model (E)	ideal, bursty
MAC Protocol	IEEE 802.11, RT-MAC

Table 4.3: Simulation Factors - 10 Mbps Voice Traffic Model

Factor	Levels
Number of Stations (N)	10, 20, 30, 40, 50, 60, 70, 80
Offered Load (G)	$G = G_{RT} + G_{NRT}$
G_{RT}	$0.00136N$
G_{NRT}	0.0, 0.2, 0.4, 0.6, 0.8
Channel Model (E)	ideal, bursty
MAC Protocol	IEEE 802.11, RT-MAC

4.5.1 Number of Stations

An *ad hoc* network implies that the number of stations in the network can change arbitrarily. To determine the performance of this type of network, the levels of 5, 10, 20, 30, 40, and 50 stations were chosen for the telemetry and avionics traffic models. The levels of 4, 10, 14, 20, 24, and 30 were used for 1 Mbps voice traffic and 10, 20, 30, 40, 50, 60, 70, and 80 were used for 10 Mbps voice traffic.

4.5.2 Normalized Offered Load

The normalized offered load is the traffic generated by the stations in the network over the capacity of the channel. If the traffic generated by a network is 2 Mbps and the channel can transmit a maximum of 3 Mbps, the normalized offered load is 0.667. The normalized offered load used in this research was intended to range from a lightly loaded network to a heavily loaded network. For the telemetry and avionics traffic models (described below in Section 4.7) the levels used are 0.3, 0.5, 0.7, and 0.9.

For the voice traffic model a mixture of real-time and non real-time traffic is generated by the stations. The real-time traffic offered to the network is a function of the number of stations in the network and is determined by the equation $G_{RT} = 0.0136\frac{N}{R}$ where N is the number of stations in the network, R is the channel data rate in Mbps, and 0.0136 is the fraction of the channel capacity used by a single station transmitting voice data (cf., Sections 2.3.1, 4.7). The non real-time traffic load levels, G_{NRT}, are 0.0, 0.2, 0.4, 0.6, and 0.8. The total offered load, G, is simply $G = G_{RT} + G_{NRT}$. Note that this sometimes results in $G > 1.0$ for networks with large N.

4.5.3 Channel Model

This effort used two levels for the channel model factor: bursty and ideal. As described in Section 2.3.2, the bursty error model is a two-state Markov model. In the "good" state (G), no bit errors occur. In the "bad" state (B), errors occur with a fixed probability, $1-h$, where h is the probability of no bit error. The amount of time spent in each state is exponentially distributed with mean t_G and t_B for states G and B respectively. This research uses the parameter values used in [BBKT96], [BBKT97], [DRT97] where $t_G = 5.0$ sec, $t_B = 0.1$ sec, and $h = 0.2$. In the ideal channel, no bit errors ever occur. Since in the bursty error model state transitions are "time-modulated", the actual BER varies depending on the offered load, G. A typical value for the BER is 2×10^{-2}. This results in a packet error rate (PER) of between 1-5%. While this is quite high, recent proposals [Sak99] for evaluating errors induced by multipath effects suggest that a 10% PER should be used as rule of thumb for certain applications.

In certain simulations, a static BER is employed. The value of the BER in the static channel model is 1×10^{-3} and 1×10^{-5}.

4.5.4 MAC Protocol

Two levels are used for the MAC protocol factor: IEEE 802.11 and RT-MAC. IEEE 802.11 is briefly described in Section 2.2.3 and completely described in [Edi97]. RT-MAC is described in Chapter 5.

4.6 Evaluation Technique

There are three techniques to evaluate performance: analytical modeling, simulation, and measurement [Jai91]. Chapter 3 surveys exact and approximate analytic techniques for evaluation of networks. It was not feasible to use this evaluation technique in this research since it could not provide the primary performance metric, the ratio of packet deadline failures. Since multiple stations share a common medium to transmit data, successful access to the medium in no longer independent of the other stations in the network—a key assumption for exact analysis in queuing networks. By using appropriate approximations, metrics such as mean throughput and delay can be determined, but metrics such as the ratio of packet deadline failures cannot. Direct measurement was prohibitively expensive given the desired number of stations in the network, so simulation was chosen as the only viable alternative.

This research uses the simulation data collected to determine the performance of RT-MAC and to construct the regression models. The simulation implements a subset of capabilities specified in the full IEEE 802.11 implementation. It uses the System Description Language (SDL-92) [EHS97] description of IEEE 802.11 found in Appendix C of [Edi97] as a specification. Since this SDL description is normative for all IEEE 802.11 implementations, the simulation is a very accurate model of the behavior of an actual system. The simulation model, including its validation, is documented in Appendix A.

4.7 Traffic Models (Workload)

Three classes of traffic are investigated corresponding to three application domains: telemetry, avionics, and packetized voice. The telemetry traffic model is representative of the type of traffic that can be found on the MIL-STD-1553B data bus (cf., Section 2.3.1). The packet size is 83 bytes. Packets arrive at a constant periodic rate and packet deadlines are equal to the arrival period. That is, the packet must be delivered prior to the next packet arrival.

The avionics traffic model is representative of the Boeing 777 data bus as described in [CDHC94]. The packet size is 775 bytes. Packets arrive according to a Poisson process (to approximate the 63 processes that periodically place packets on the bus). Packet deadlines are drawn from a truncated normal distribution with a mean of 380 ms. Deadlines have an upper bound of 1000 ms and a lower bound of 12 ms. In this class of traffic, a percentage of the packets that are discarded due to being late or due to a full transmission queue are assumed to still be useful to the receiving station. Therefore, 50% of the discarded packets are randomly chosen to be resubmitted to the transmission queue.

The packetized voice traffic model uses an ON/OFF source to model speech (cf., Section 2.3.1). The time spent in the ON/OFF state is exponentially distributed with a mean of 1.00 seconds and 1.35 seconds respectively. In the ON state, the voice data is assumed to be encoded using the ITU G.726 encoding [Cox97]. Each packet contains 20 ms of speech at a 32 kbps rate or 80 bytes. The last packet in the ON state may be truncated if the time in the ON state is not a multiple of 20 ms. To investigate the effect of non-real-time traffic on the real-time voice traffic, various levels of background traffic are introduced into the network. The normalized offered load of the background traffic is 0.0, 0.2, 0.4, 0.6, and 0.8. Background traffic arrives according to a Pareto process (with parameter $a = 1.6$) to approximate self-similar interarrivals (cf., Section 2.3.1). Table 4.4 summarizes the three classes of traffic used in this effort.

4.8 Experimental Design

Since regression models are constructed using the simulation data gathered and further, since the power of today's computers make it feasible, a full factorial experimental design was used for this research effort. In order to obtain a suitable confidence interval for the response variables, five replications of each combination of factors was chosen [Jai91], [Mac92]. For the factors and number of levels in the telemetry and avionics traffic models this resulted in a total of 480 simulation runs. For the 1 Mbps voice traffic model a total of 600 simulation runs were required. For the 10 Mbps voice traffic model a total of 900 simulation runs were required.

The sections below describe the type of data collected and the termination criteria used for the simulation runs.

Table 4.4: Traffic Models

Model	Factor	Value
Telemetry	Interarrival Distribution	Constant
	Deadline Distribution	Constant (same as interarrival time)
	Packet Size (bytes)	83
	Discarded Packets Resubmitted	0%
Avionics	Interarrival Distribution	Poisson
	Deadline Distribution	Truncated Normal Mean = 380 ms, Min = 21 ms, Max = 1 sec
	Packet Size (bytes)	775
	Discarded Packets Resubmitted	50%
Voice	Interarrival Distribution	ON/OFF (real-time) Pareto (non real-time)
	Deadline Distribution	Constant (100 ms, real-time) None (non real-time)
	Packet Size (bytes)	80 (real-time) 400 (non real-time)
	Discarded Packets Resubmitted	0%

```
******************************************************************************************************************
============================================SIMULATION TERMINATION CRITERIA (THROUGHPUT-ENABLED)====================================
[>A<] Mean (current) throughput: >B< (>C<) Samples: >D< Samples Req'd for Rqstd Wdth: >E< BER: >F< PER: >G<
Conf. Int Wdth:    >H< Rqstd Wdth # (%): >I< (>J<) Std Dev: >K< Current HRT Queue Size: >L< Current DATA Queue Size: >M<
Pcnt HRT Pkts Blcked at Q: >N<
==================================================================================================================

============================================SIMULATION TERMINATION CRITERIA (MEAN DELAY-ENABLED)====================================
[>A<] Mean (current) delay: >O< (>P<) Samples: >Q< Samples Req'd for Rqstd Wdth: >R<
Conf. Int Wdth: >S< Rqstd Wdth # (%): >T< (>U<) Std Dev: >V< Pcnt Pkts Blckd at Q: >W<
==================================================================================================================

============================================SIMULATION TERMINATION CRITERIA (HRT FAILURES-ENABLED)==================================
[>A<] Mean failures: >X< Failures (Trials): >Y< (>Z<) Trials Req'd for Rqstd Wdth: >AA<
Conf. Int Wdth: >BB< Rqstd Wdth # (%): >CC< (>DD<) Std Dev: >EE<
==================================================================================================================

============================================SIMULATION TERMINATION CRITERIA (COLLISION-ENABLED)=====================================
[>A<] Mean collisions: >FF< Collisions (Trials): >GG< (>HH<) Trials Req'd for Rqstd Wdth: >II<
Conf. Int Wdth: >JJ< Rqstd Wdth # (%): >KK< (>LL<) Std Dev: >MM<
==================================================================================================================
******************************************************************************************************************
```

Figure 4.1: Sample Simulation Output

4.8.1 Data Collected

In addition to the performance metrics described in Section 4.3, several other data items are collected during the simulation runs. Figure 4.1 shows a sample portion of a simulation output file. The confidence level used when calculating confidence intervals is 90%. The letter(s) surrounded by >< in Figure 4.1 (e.g., >A<) correspond to a data item. Each data item is described in Table 4.5. Along with this output, the exact network configuration and random number generator seed is saved so that the run can be repeated if necessary.

4.8.2 Termination Criteria

The confidence interval widths of throughput, mean delay, failure ratio (a.k.a. missed deadline ratio), and collision ratio can be used as termination criteria for a simulation run. If, in Figure 4.1, ENABLED appears next to the name of the performance metric, the confidence interval width of that performance metric is being used as termination criteria for the simu-

Table 4.5: Simulation Data

Data Item	Description	Data Item	Description
A	Simulation time (seconds)	B	Mean throughput (bps)
C	Instantaneous throughput (bps)	D	Throughput samples
E	Required D for C.I. width I	F	Mean bit error rate
G	Mean packet error rate	H	Current throughput C.I. width
I	Requested throughput C.I. width	J	Throughput C.I. width as % of B
K	Throughput standard deviation	L	Current Node 0 hard real-time packet queue size
M	Current Node 0 data packet queue size	N	% HRT packets blocked from entering transmission queue
O	Mean delay (seconds)	P	Instantaneous delay (seconds)
Q	Delay samples	R	Required Q for C.I. width T
S	Current delay C.I. width	T	Requested delay C.I. width
U	Delay C.I. width as % of O	V	Delay standard deviation
W	% packets blocked from entering transmission queue	X	Mean failure ratio, $\frac{Y}{Z}$
Y	Number of failures	Z	Number of packets removed from transmission queue
AA	Required Z for C.I. width CC	BB	Current failure ratio C.I. width
CC	Requested failure ratio C.I. width	DD	Failure ratio C.I. width as % of X
EE	Failure ratio standard deviation	FF	Mean collision ratio, $\frac{GG}{HH}$
GG	Number of collisions	HH	Number of transmission attempts
II	Required HH for C.I. width KK	JJ	Current collision ratio C.I. width
KK	Requested collision ratio C.I. width	LL	Collision ratio C.I. width as % of FF
MM	Collision ratio standard deviation		

lation. When *all* the `ENABLED` performance metrics confidence interval widths are less than or equal to the requested confidence interval widths, the simulation will terminate. The simulation will also terminate if the maximum simulation time is reached.

4.9 Summary

This chapter presents the objectives of this research and methods used to obtain those objectives. The methodology is essentially that proposed by Jain in [Jai91]. Section 4.1 defined the problem and goals. Section 4.2 described the system services. Section 4.3 identified the performance metrics and Section 4.4 explained significant parameters of the system. Simulation factors were presented in Section 4.5. The selection of simulation as an evaluation technique was described in Section 4.6. The three workload classes (traffic models) were identified in Section 4.7. Finally, the experimental design was described in Section 4.8.

Chapter 5

Real-time MAC (RT-MAC)

This chapter presents the medium access control (MAC) protocol, real-time MAC (RT-MAC). As the name suggests, RT-MAC is intended to transport real-time data over a shared medium. Two major factors impact the ability of a real-time WLAN to meet packet deadlines: (1) the transmission of packets that have already missed their deadlines and (2) packet collisions. Packets that have missed their deadlines are assumed to be unusable by the receiving station so transmitting them constitutes a double failure. The first failure is the missed deadline itself, the other is the wasted channel capacity that could have been used to transmit a usable packet. IEEE 802.11 does not provide any means of detecting whether a packet has exceeded its deadline; collision avoidance is achieved by deferring backoff timer decrements while the medium is busy and by doubling CW upon transmission failure as described in Section 2.2.3.

RT-MAC uses two additional pieces of information to achieve its result: a transmission deadline and the transmitting station's *next* backoff value (BV). Section 5.1 describes how the transmission deadline is used in the transmission control algorithm. Section 5.2 describes how a station's *next* BV is used in the enhanced collision avoidance (ECA) algorithm.

5.1 Transmission Control

When a real-time packet is submitted for transmission, a transmission deadline (i.e., the time by which transmission must begin) is associated with the packet. This value is only needed until the packet is either successfully transmitted or discarded and therefore does not become part of the packet itself. This transmission deadline is examined at three key points to determine whether to discard the packet. By discarding a packet as soon as possible after determining that its deadline has been exceeded, the transmission queue throughput is increased and as a result, the likelihood that other packets in the queue will meet their deadlines is increased. The examination points (described below) were chosen because each point follows an unpredictable delay that a packet suffers prior to transmission.

A packet is first examined when it is removed from the transmission queue in preparation for transmission. If the packet has already exceeded its transmission deadline, it is discarded and the next eligible packet in the queue (if any) is selected. At this point, the station may need to wait for the backoff timer to expire. During this time, other stations could possibly transmit. After the backoff timer expires, the packet is examined again. If the packet deadline has been exceeded the packet is discarded, otherwise, it is transmitted. Assuming the transmission is successful, the next eligible packet is selected and the process repeats. If the transmission is not successful (that is, no acknowledgement packet is received), the packet deadline is again examined and the packet is discarded if the deadline has been exceeded. If the deadline has not yet been exceeded, the packet is submitted for retransmission. Note that by using this transmission control algorithm, a packet that is successfully received will never be late. This algorithm is summarized in Figure 5.1.

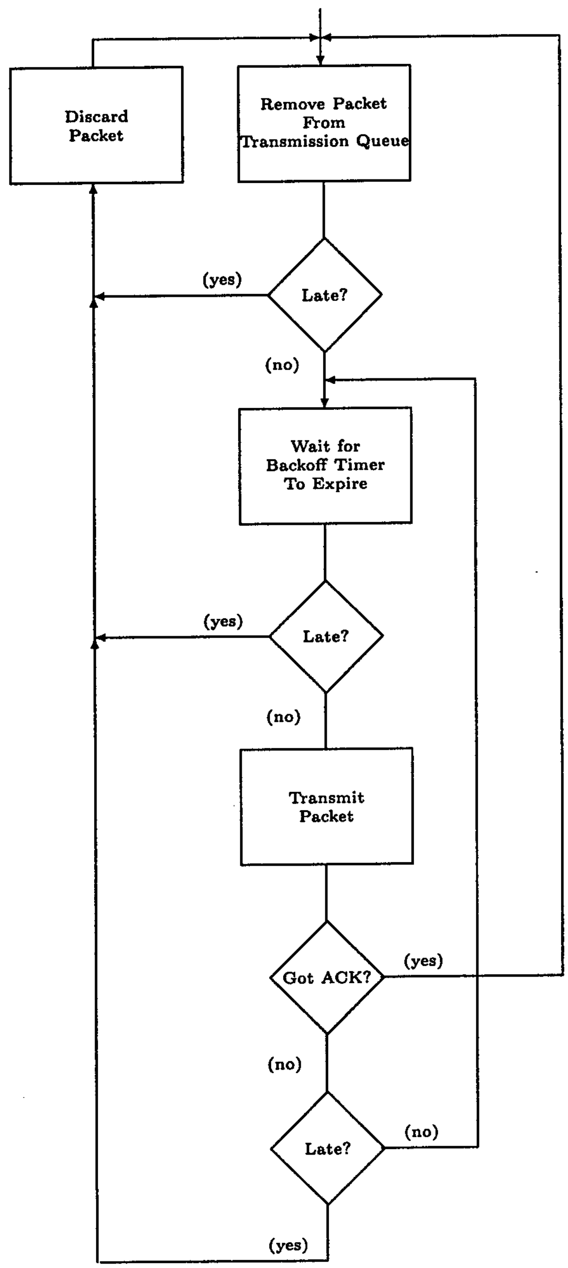


Figure 5.1: RT-MAC Transmission Control Algorithm

5.2 Enhanced Collision Avoidance (ECA) Algorithm

The ECA algorithm has two components. First, rather than use a fixed initial value for CW, the initial CW value is set to $(2 + \lfloor \frac{6}{\sqrt{R}} \rfloor)\hat{N})$. Where $\hat{N}$ is an estimate of the number of stations in the network and R is the channel data rate in Mbps. $\hat{N}$ is assumed to be determined either by tracking the number of unique station addresses that have transmitted over the last t seconds where t is a suitable value, or by a method such as the one described in [BFO96] where $\hat{N}$ is estimated as a function of channel load. The ratio used to expand the contention window (i.e., $(2 + \lfloor \frac{6}{\sqrt{R}} \rfloor)$) is loosely based on CW expansion ratios found in [BFO96]. The predominant effect of this CW expansion is to make the number of collisions a network suffers less dependent on the number of stations in the network. In order to counter the collisions that will still occur despite the expansion of the CW, the second component of the ECA is used.

In IEEE 802.11, if a station is not in backoff and has no packets to transmit, it will transmit immediately an arriving packet (assuming an idle channel). In order to reduce to possibility of collisions among stations in this situation that have simultaneous arrivals, RT-MAC will, first set the backoff timer and after it expires, it will then transmit the arriving packet.

The second component of the ECA algorithm consists in advertising the transmitting station's *next* BV as well as tracking the BVs of other stations in the network. Previous research has expended much effort in accurately estimating channel loading and number of active stations in order to determine an optimum CW size (cf., Section 2.4.1). The advertisement of BVs reduces the need for such an accurate estimate and thus, a coarser estimate will suffice. As long as the CW value is not excessively large, delays should not increase appreciably. Further, since the next BV will be advertised, and stations will select another BV if the transmitting station inadvertently chooses a BV already in use, a smaller range for next BVs (described below) is used. This restricted range for next BVs will further reduce unnecessary delays.

Prior to transmitting a data packet, the transmitting station will select a BV from the range of [0, CWmin] (cf., Section 2.2.3.1), excluding BVs that are known to be in use. This selected BV will be the BV used following the current transmission. It will be placed in the packet header and transmitted along with the packet. Prior to transmitting an (ACK) packet, a station transmitting the ACK will place its current BV (CBV) in the packet header. Stations that receive the transmission will place the BV in a table of BVs "in use". During idle slots, a station will decrement its own BV (as in IEEE 802.11) as well as every BV in its table of BVs. If the packet does not contain a BV in the header (i.e., it is a IEEE 802.11 rather than a RT-MAC packet), it is treated as a normal packet.

A station may receive a RT-MAC packet that indicates the sending station has chosen the same BV as the receiving station. This could occur due to new stations joining the network or due to BVs not being received because of collisions or bit errors. In such cases, the receiving station chooses another BV since a collision will certainly occur (assuming both stations have a packet to transmit). To prevent a station that must choose a new BV from being unduly penalized, the new BV is chosen (if possible) from the range of [0, CBV-1] where CBV is the receiving stations current BV. If a suitable value cannot be found, the range of values will be doubled (i.e., [0, 2CBV-1]) until a suitable value can be found. Figure 5.2 summarizes the second component of the ECA algorithm for data packets. Acknowledgement packets are transmitted immediately upon successful receipt of a data packet by the destination station (cf., Section 2.2.3).

5.3 Summary

In this chapter RT-MAC was described. It has two primary components. The transmission control algorithm prevents the transmission of packets that have exceeded their deadlines. The enhanced collision avoidance algorithm reduces collisions by expanding the contention window and by advertising station backoff values in use within the network.

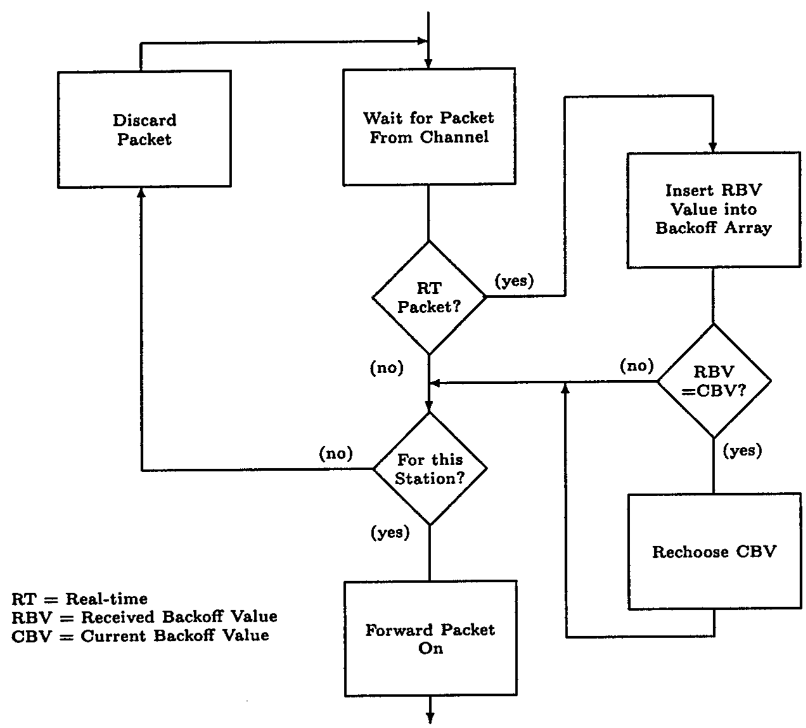


Figure 5.2: RT-MAC ECA Backoff Value Algorithm

Chapter 6

Simulation Results

This chapter presents the results obtained during the simulations. It compares the performance of IEEE 802.11 and RT-MAC for a variety of network configurations. It is divided into five main sections. Sections 6.1, 6.2, and 6.3 present the results for the telemetry traffic model, the avionics traffic model, and the voice traffic models respectively. The performance of IEEE 802.11 and RT-MAC is discussed in context of the four response variables (throughput, mean delay, missed deadline ratio, and collision ratio). Section 6.4 discusses other simulations studies conducted to investigate particular aspects of IEEE 802.11 or RT-MAC. Examples of these simulations include running RT-MAC with certain aspects of the protocol disabled, varying service disciplines, and others. Section 6.5 summarizes the simulation results obtained.

The data (including confidence intervals) from which the figures in this chapter were generated are contained in tabular form in Appendix B. The captions used in those tables are the same as those used herein. An explanation of the statistical comparison method used to determine relative performance between IEEE 802.11 and RT-MAC can be found in Section C.1.

6.1 Telemetry Traffic Model

As discussed in Section 4.7 and summarized in Table 4.4, the telemetry traffic model is characterized by short fixed-length packets (83 bytes), and a constant packet interarrival time. Packets must be delivered prior to the next packet arrival. That is, the deadline is equal to the interarrival time. This traffic model is used to stress the network. The short packet size will induce a high overhead on the network as well as increase the number of transmissions when compared to a larger packet size.

6.1.1 Normalized Throughput

For a given number of stations, N, IEEE 802.11 throughput (Figures 6.1 and 6.2), tends to reach a local maximum at an offered load (G) of 0.5 and roughly maintain that local maximum value as G increases. That local maximum throughput monotonically decreases as the number of stations, N, increases. This effect can be more easily seen in the regression model of the throughput in Figure 7.3.

RT-MAC also tends to reach a local maximum throughput at $G = 0.5$ but in contrast to IEEE 802.11, the throughput then decreases as G increases. This decrease is due to the RT-MAC transmission control algorithm (cf., Section 5.1) discarding packets that are late rather than transmitting them as IEEE 802.11 does.

Curiously, for a given G, throughput resembles a low frequency sine wave (see Figure 7.4). This can be attributed to two causes. The first results in an increased throughput. For a given G, as N increases, the load offered by each individual station decreases (i.e., the interarrival time increases). Since the deadline is equal to the interarrival time, fewer packets are discarded and this tends to increase throughput. The second cause results in a decreased throughput. This second cause involves both the contention window size, CW, and the backoff algorithm (cf., Section 2.2.3.1). As N increases, CW increases (cf., Section 5.2), thereby increasing the amount of time a packet must (potentially) wait prior to transmission.

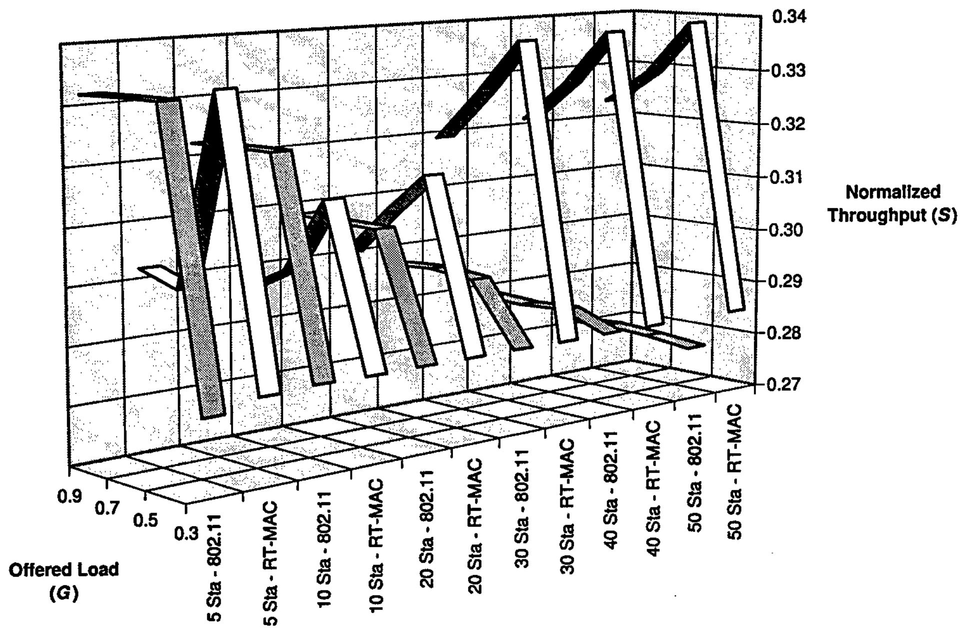


Figure 6.1: Telemetry Throughput - Ideal Channel

This increased waiting time, coupled with an increased number of stations contending for the channel, increases the probability that a packet will exceed its deadline and be discarded. As one cause becomes more dominant than the other, the cyclic throughput behavior results. While these two causes likely explain the observed effect, further studies would need to be done to confirm this hypothesis.

6.1.1.1 Throughput Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 throughput is given in Figures 6.3 and 6.4 for the ideal and bursty error channels respectively. Unless otherwise noted, the level of significance used is 0.1. The region in the figures demarcated by thick lines is where RT-MAC performance is statistically better than IEEE 802.11.

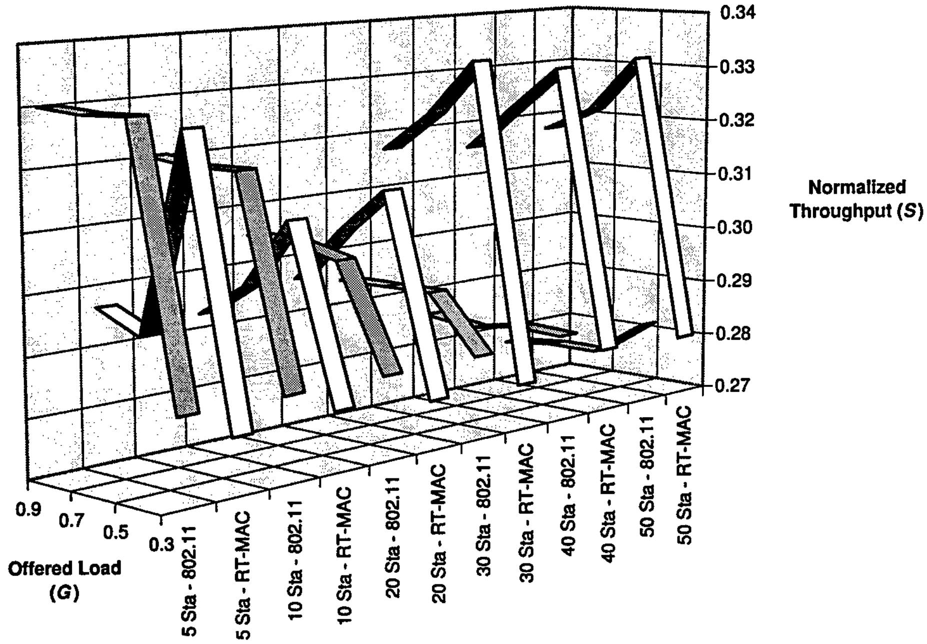


Figure 6.2: Telemetry Throughput - Bursty Error Channel

Offered Load (G)	5	10	20	30	40	50
0.9	W	W	W	B	B	B
0.7	W	W	B*	B	B	B
0.5	N	W	B	B	B	B
0.3	B*	W	N	W	N	N

Stations (N)

Legend
With respect to IEEE 802.11

- B Better
- N Not Different
- W Worse
- * Determined by t-test

Figure 6.3: Telemetry Throughput Performance Comparison - Ideal Channel

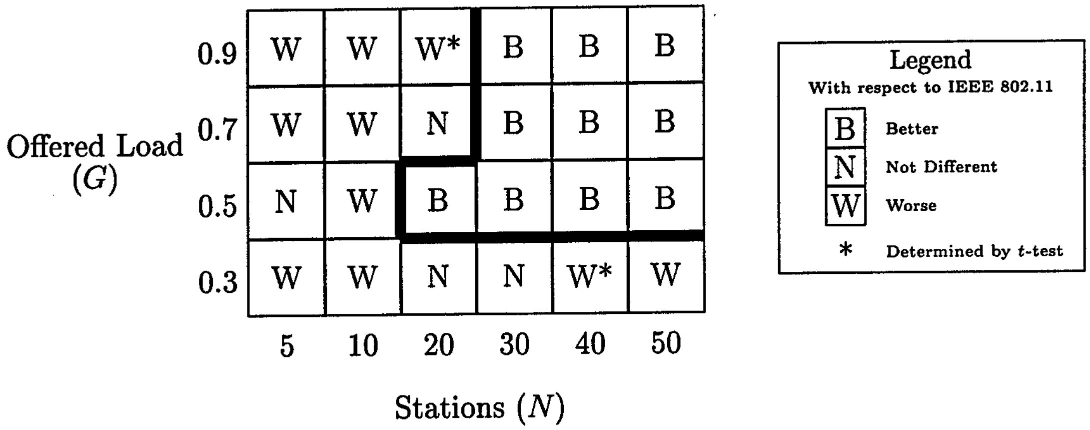


Figure 6.4: Telemetry Throughput Performance Comparison - Bursty Error Channel

6.1.1.2 Usable Throughput

The raw throughput of IEEE 802.11 and RT-MAC is similar for $G = 0.3$ and IEEE 802.11 throughput exceeds RT-MAC for $G > 0.3$. Considered in isolation, the throughput of IEEE 802.11 would seem to indicate superior performance compared to RT-MAC. However, when packet deadlines are also considered, the opposite is indicated. For $G > 0.3$, virtually all the received IEEE 802.11 packets are late. Due to the transmission control algorithm of RT-MAC, none of the received packets are late. Hence, IEEE 802.11 throughput for $G > 0.3$ actually represents wasted capacity or a usable throughput of 0.0. Usable throughput, S_U, is equal to the product of the throughput, S, and the failure ratio, F, or $S_U = S(1 - F)$. A graph of usable throughput is shown in Figure 6.5 for an ideal channel. Similar results are obtained for a bursty channel. Therefore in terms of usable throughput, RT-MAC clearly outperforms IEEE 802.11 for $G > 0.3$.

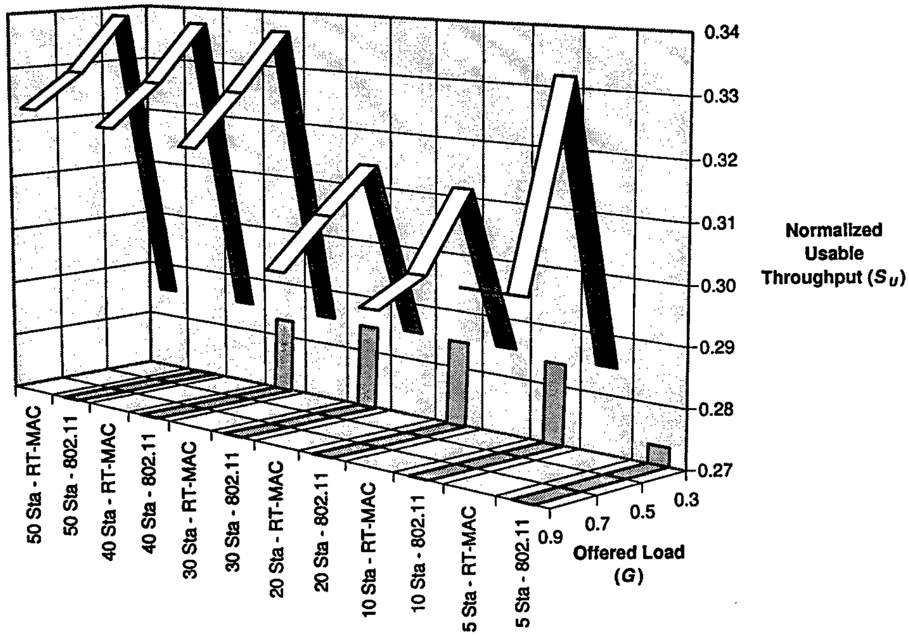


Figure 6.5: Usable Telemetry Throughput - Ideal Channel

6.1.2 Mean Delay

The mean delay of IEEE 802.11 and RT-MAC is shown in Figures 6.6 and 6.7. Mean delay is calculated as the arithmetic mean of the time difference from packet creation to successful reception of the last bit. Delay that discarded packets suffer do not contribute to mean delay since, in effect, their delay is infinite.

For every network size considered in these simulations, IEEE 802.11 delay increases rapidly as G increases. It tends to stabilize at $G \geq 0.5$. The magnitude of the maximum delay was quite large—1 to 10 seconds being typical. Due to the long delays, buffer overflow was common. The packet buffer size for this traffic model was 200 packets. Packets that arrived to a full buffer were discarded and counted as a missed deadline. The percentage of packets discarded due to a full buffer increased linearly with G with 0% being discarded at $G = 0.3$ and approximately 50% being discarded at $G = 0.9$.

RT-MAC mean delay is inversely proportional to G. This is due to both the discarding

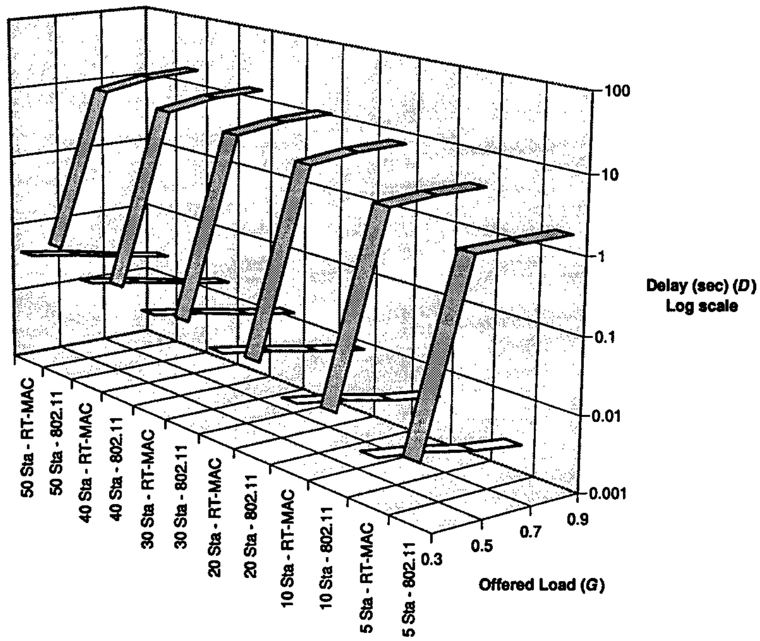


Figure 6.6: Telemetry Mean Delay - Ideal Channel

of late packets rather than transmitting them and due to the enhanced collision avoidance algorithm (cf., Chapter 5). Discarding late packets and avoiding collisions increases buffer throughput, and lowers the mean delay of packets that are transmitted. Since more and more packets are discarded as G increases (cf., Figure 6.8), the buffer throughput also increases and mean delay is decreased. No buffer overflow was experienced with RT-MAC.

In terms of a statistical comparison, RT-MAC always performed better than IEEE 802.11 except in the case of $N = 5$ and 50, $G = 0.3$ for a bursty error channel, for which the performance was not different.

6.1.3 Missed Deadlines

Simulation results for missed deadlines are shown in Figures 6.8 and 6.9. The figures indicate that IEEE 802.11 is very susceptible to missed deadlines at even moderate loading. RT-MAC is more tolerant of network load and always performs dramatically better than IEEE 802.11.

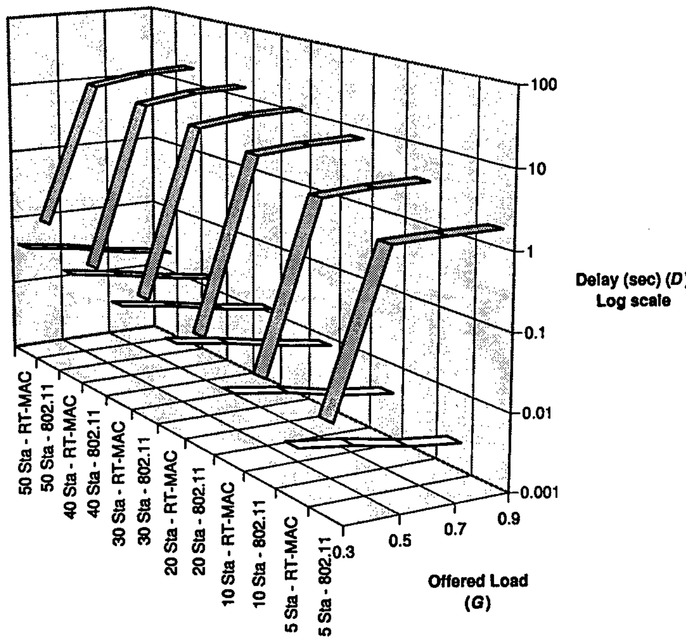


Figure 6.7: Telemetry Mean Delay - Bursty Error Channel

Even so, at higher offered loads the missed deadline ratio is large and whether or not this is acceptable depends on the underlying application. Statistically, RT-MAC always performs better than IEEE 802.11.

Consider the missed deadline ratio of IEEE 802.11 in Figure 6.8 for $G = 0.3$. As N increases from 5 to 10 stations, the missed deadline ratio decreases noticeably and does not appear to increase again until $N = 50$. That is, the missed deadline ratio for $G = 0.3$ is somewhat parabolic. This parabolic shape is shown in Figure 6.10.

This presumably occurs because the packet deadline is equal to the interarrival time. To see why this is so, consider the mean interarrival time resulting from a given G in a network with N stations, a packet size of P bits, and a channel rate of C bps. The resulting mean interarrival time is $T = \frac{NP}{CG}$ seconds. As N decreases, the interarrival time decreases and hence, the deadline decreases as well. The offered load however, remains constant. The net result is that as N decreases, a more stringent deadline requirement is presented to the stations for the same offered load.

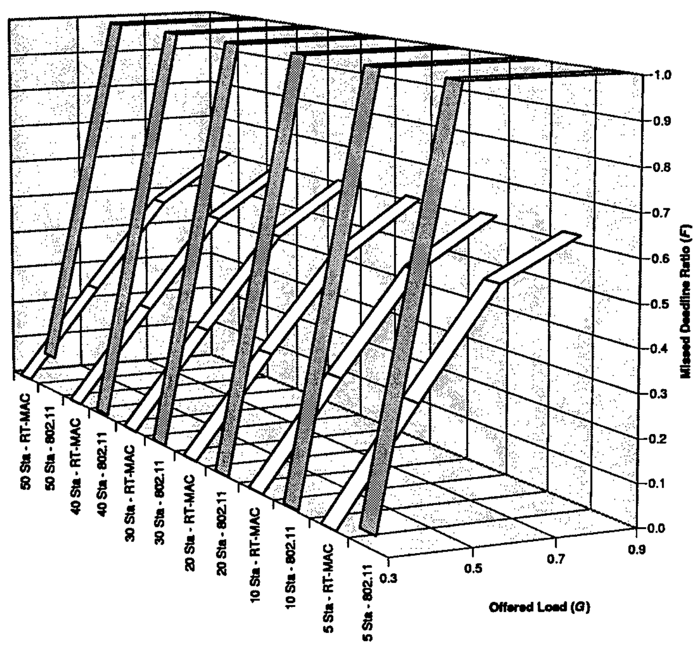


Figure 6.8: Telemetry Missed Deadline Ratio - Ideal Channel

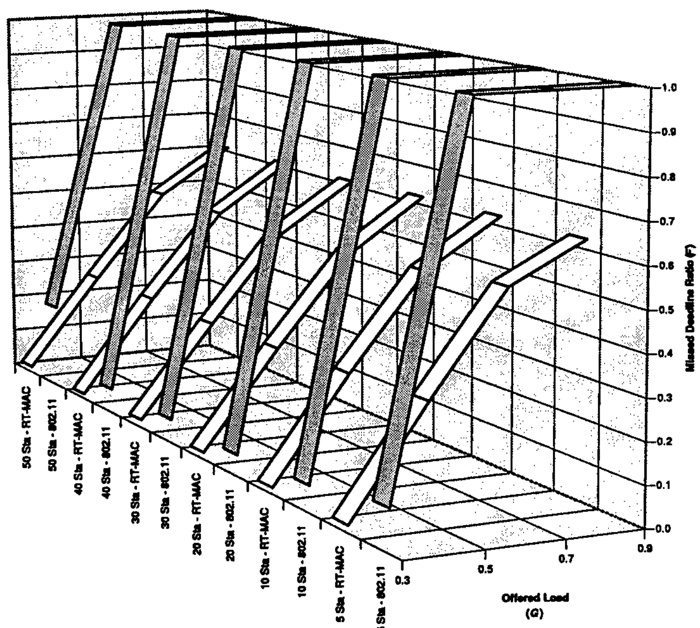


Figure 6.9: Telemetry Missed Deadline Ratio - Bursty Error Channel

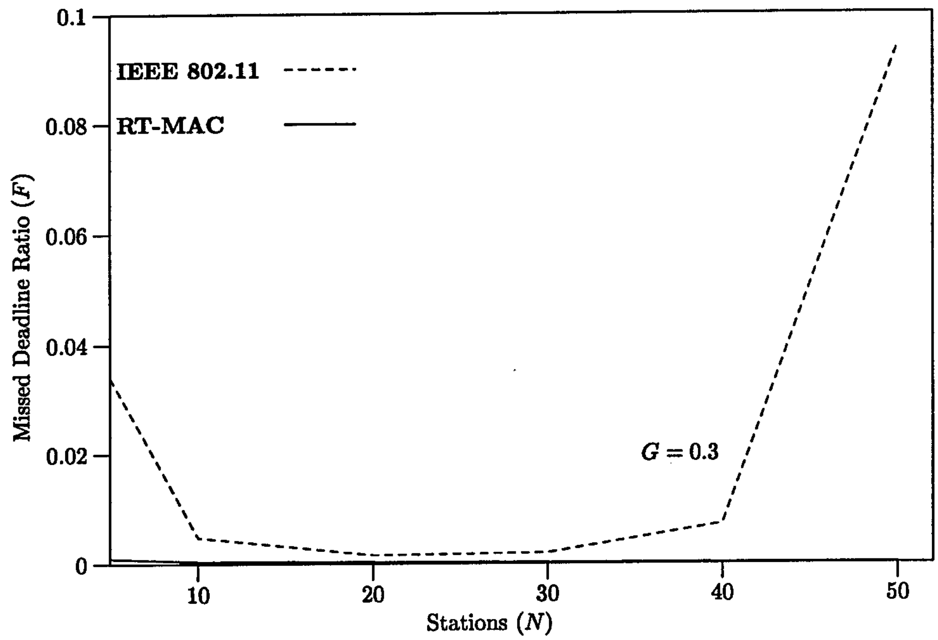


Figure 6.10: Telemetry Missed Deadline Ratio (5-50 Stations) - Ideal Channel

To confirm this hypothesis, simulations were run for networks with $N = 2$ and $N = 4$. The simulation results should show larger missed deadline ratios for networks with fewer stations. As Figure 6.11 shows, this is indeed the case. By inspecting Table B.5 in Appendix B, it can be seen that this also occurs for every G when using RT-MAC. For IEEE 802.11 with $G > 0.3$, the effect is masked since the missed deadline ratio is always 1.0 due to other factors.

6.1.4 Collisions

IEEE 802.11 and RT-MAC collision ratios are shown in Figures 6.12 and 6.13. As with IEEE 802.11 mean delay and missed deadline ratio, the collision ratio, C, increases rapidly with G and reaches a local maximum at $G = 0.5$. As G increases further the collision ratio tends to stay relatively constant. As N increases, the starting value and the maximum value of the collision ratio increase as well. Hence, IEEE 802.11 collisions are highly influenced by both G and N.

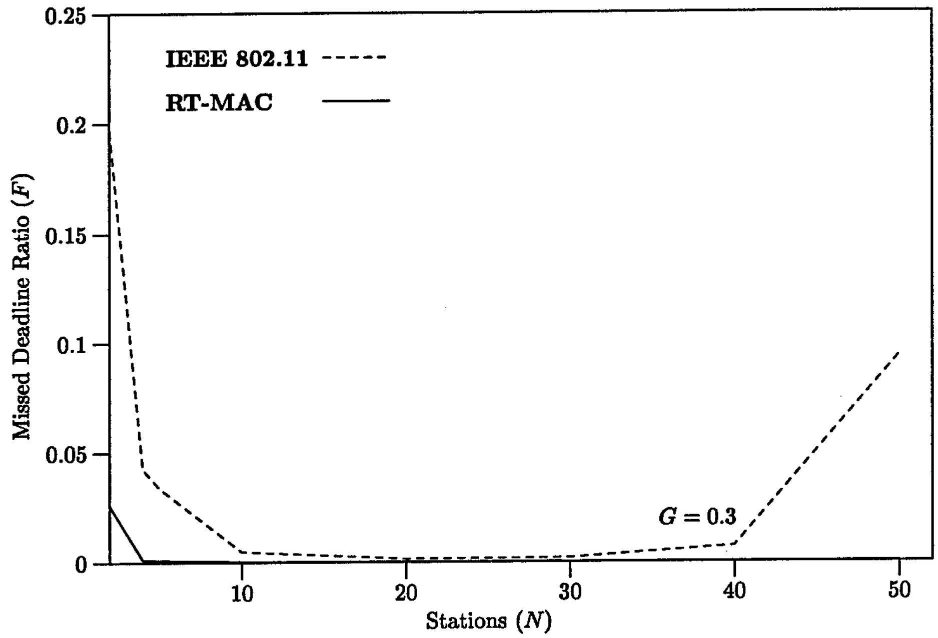


Figure 6.11: Telemetry Missed Deadline Ratio (2-50 Stations) - Ideal Channel

In contrast, RT-MAC collision ratio is very stable. Compared to IEEE 802.11, it is only slightly influenced by either G or N. Using $N = 20$ as an example, as G increases, RT-MAC collision ratio increases from about 0.033 to 0.037—an increase of about 12%. Over the same range the IEEE 802.11 collision ratio increases from about 0.148 to 0.256—an increase of over 72%. The RT-MAC enhanced collision avoidance scheme (cf., Section 5.2), therefore, is very effective in reducing network collisions. Statistically, RT-MAC always performs better than IEEE 802.11.

6.1.5 Bursty Error Channel

While the bursty error channel did have a detectable effect on the above performance metrics, it is noteworthy that its impact was not very large. The average BER varied from about 1×10^{-2} to 4×10^{-2}—poor by any standard. This lack of impact (especially at higher loads) is further confirmed by the regression models discussed later in Chapter 7. When the channel model factor (ideal or bursty) was included in a regression model, it was found to be

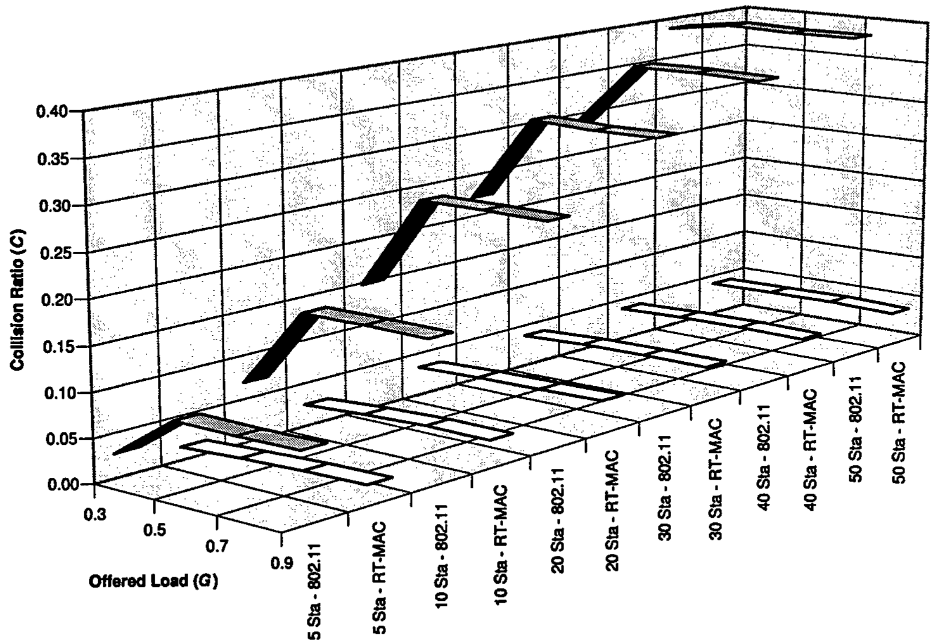


Figure 6.12: Telemetry Collision Ratio - Ideal Channel

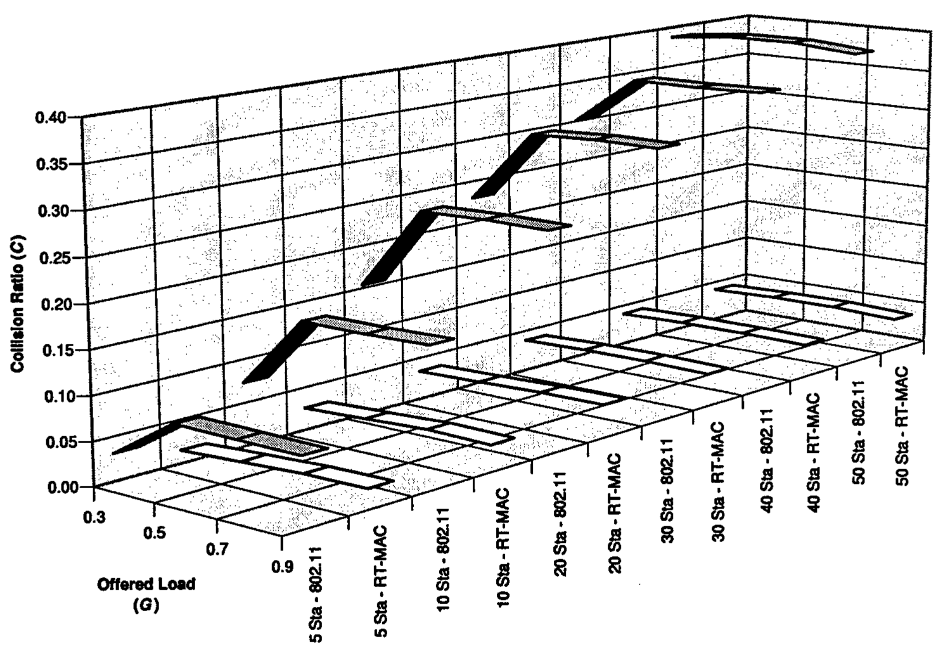


Figure 6.13: Telemetry Collision Ratio - Bursty Error Channel

statistically significant but of limited impact to the overall model. This is most probably due to the effects of other factors such as collisions and since the amount of time the channel was in a "bad" state was small compared to the "good" state (cf., Section 4.5.3). To help confirm this, the effect of a static BER on the performance metrics is examined in Section 6.4.5.

6.2 Avionics Traffic Model

The avionics traffic model parameters are discussed in Section 4.7 and summarized in Table 4.4. The avionics traffic model is characterized by fixed-length packets (775 bytes), and by more than 60 processes that access the channel with various constant packet interarrival times. These interarrival times are approximated by using a Poisson process for packet arrivals. Packets deadlines are drawn from a truncated normal distribution with a mean of 380 ms. This traffic model is serves as a representative traffic model for an avionics bus. The packet size is moderate and the deadlines are not as stringent as the telemetry traffic model.

6.2.1 Normalized Throughput

For $N = 5$ and 10, IEEE 802.11 throughput (Figures 6.14 and 6.15) tends to monotonically increase to a maximum value as G increases. For $N > 10$, the throughput increases to a local maximum at $G = 0.7$ and then decreases for $G > 0.7$. This decrease can be attributed to an increase in the number of packet collisions (cf., Figure 6.27 and 6.28). In contrast, RT-MAC throughput for all N monotonically increases with G.

6.2.1.1 Throughput Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 throughput is given in Figures 6.16 and 6.17 for the ideal and bursty error channels respectively. As before, unless

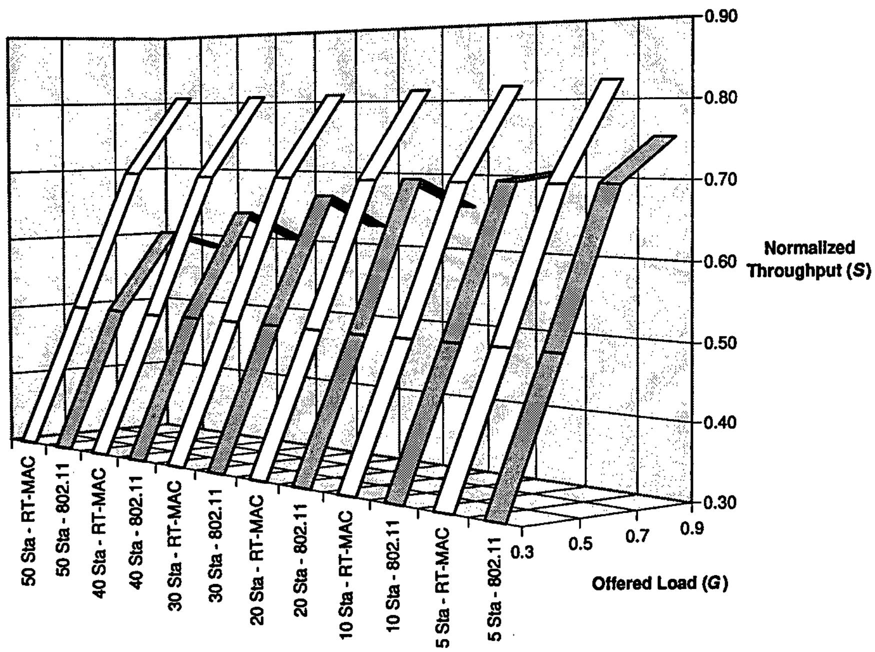


Figure 6.14: Avionics Throughput - Ideal Channel

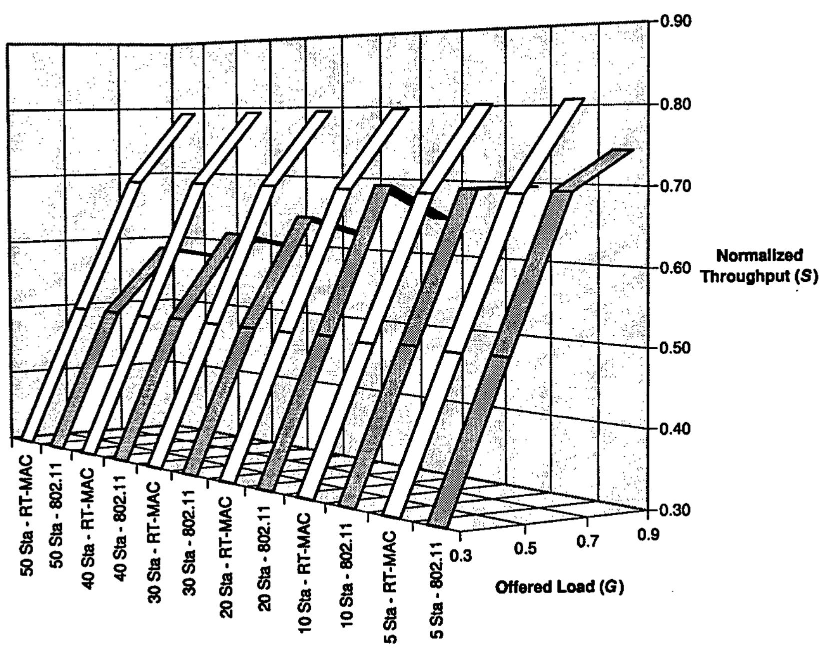


Figure 6.15: Avionics Throughput - Bursty Error Channel

Offered Load (G)						
0.9	B	B	B	B	B	B
0.7	N	N	N	N	B	B
0.5	N	N	N	N	N	N
0.3	N	N	N	N	N	N
Stations (N)	5	10	20	30	40	50

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.16: Avionics Throughput Performance Comparison - Ideal Channel

otherwise noted, the level of significance used is 0.1. The region in the figures demarcated by thick lines is where RT-MAC performance is statistically better than IEEE 802.11.

6.2.1.2 Usable Throughput

The raw throughput of IEEE 802.11 and RT-MAC is similar for $G \leq 0.7$. However, as with the telemetry traffic model, when packet deadlines are also considered, a different result is indicated. For $G > 0.7, N \leq 20$ and $G > 0.5, N > 20$, IEEE 802.11 throughput represents wasted capacity or a usable throughput, S_U, that rapidly approaches 0.0. Recall that $S_U = S(1-F)$. Usable throughput is shown in Figure 6.18 for the ideal channel. Similar results are obtained for the bursty channel. In terms of throughput that can be used by the receiver, RT-MAC outperforms IEEE 802.11 for medium to high network loads.

6.2.2 Mean Delay

The mean delay of IEEE 802.11 and RT-MAC is shown in Figures 6.19 and 6.20. Mean delay is calculated in the same manner as described in the telemetry traffic model above.

Offered Load (G)	5	10	20	30	40	50
0.9	B	B	B	B	B	B
0.7	N	W*	N	B	B	B
0.5	N	N	N	N	N	N
0.3	N	N	N	N	N	N

Stations (N)

Legend
With respect to IEEE 802.11

- B — Better
- N — Not Different
- W — Worse
- * — Determined by t-test

Figure 6.17: Avionics Throughput Performance Comparison - Bursty Error Channel

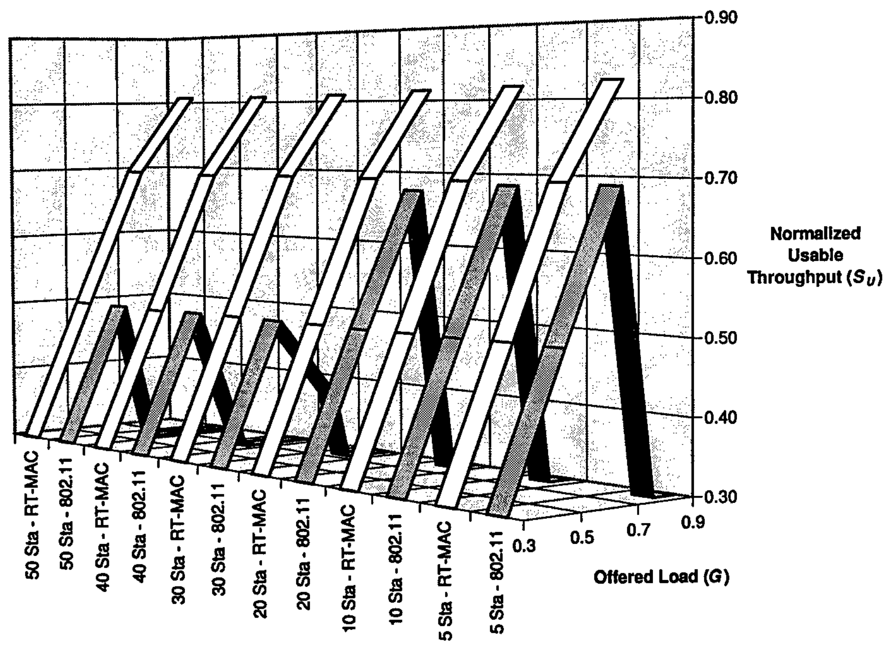


Figure 6.18: Usable Avionics Throughput - Ideal Channel

For $G \leq 0.5$, it is difficult to make any general statements about IEEE 802.11 mean delay. For the ideal channel it was generally better than RT-MAC, while for the bursty error channel, it was comparable or better than RT-MAC. For $G \geq 0.7$, IEEE 802.11 delay increases rapidly, sometimes reaching 10s of seconds. For $N > 10$, this increase began at $G = 0.5$. Due to these long delays, buffer overflow was common. The packet buffer size for this traffic model was 200 packets. The maximum percentage of packets discarded due to a full buffer was approximately 10% at $G = 0.9$.

RT-MAC mean delay increases at a roughly constant rate throughout the range of offered loads, G. For $G > 0.5$, RT-MAC generally performed better than IEEE 802.11. Compared to the telemetry traffic model, relatively few of the RT-MAC packets are discarded due to lateness (cf., Figures 6.23 and 6.24). Therefore, the primary reason for the improved mean delay for $G > 0.5$ is presumed to be the low collision rate. No buffer overflow was experienced with RT-MAC.

The reason for RT-MACs worse mean delay performance for $G \leq 0.5$ can be attributed to two factors. First, RT-MAC CW size (cf., Section 5.2) is always larger than IEEE 802.11 so the probability that RT-MAC will wait longer to access the channel is greater. Second, the "penalty" (i.e., access delay) for this larger CW size is greater due to the larger packet size. For $G > 0.5$, other factors such as collisions and retransmissions in the IEEE 802.11 network negate this penalty.

6.2.3 Mean Delay Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 throughput is given in Figures 6.21 and 6.22 for the ideal and bursty error channels respectively.

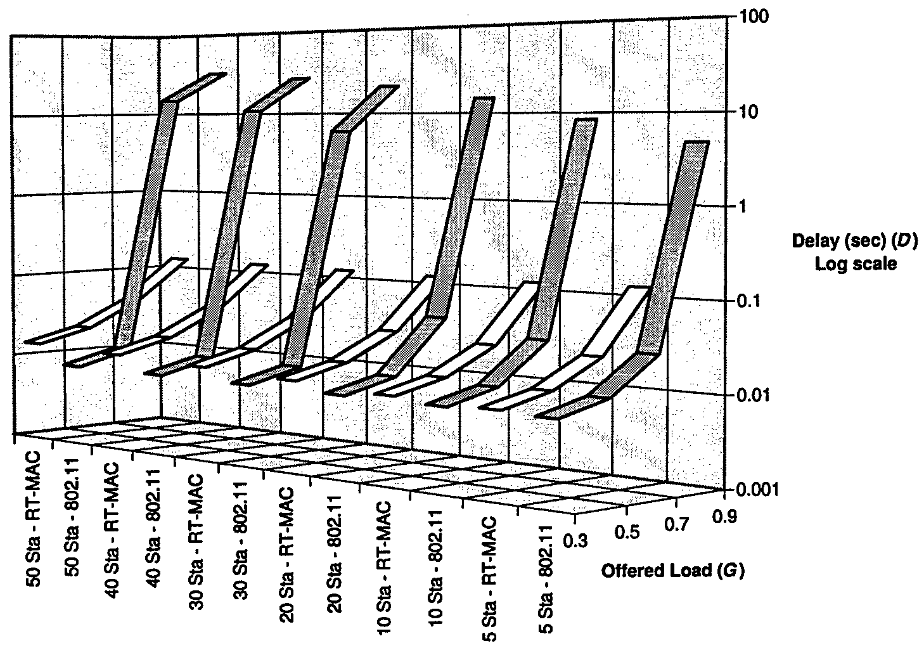


Figure 6.19: Avionics Mean Delay - Ideal Channel

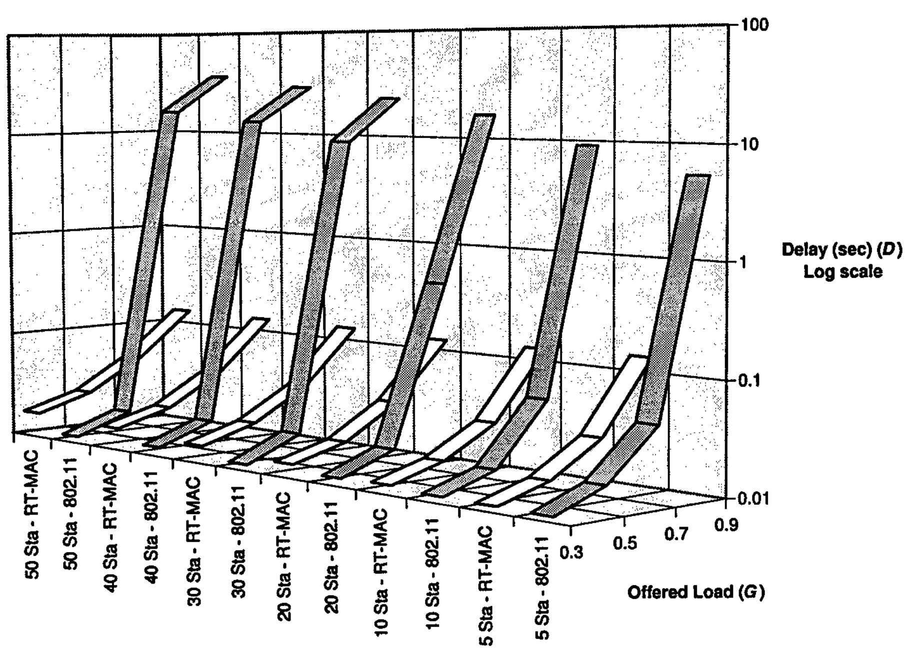


Figure 6.20: Avionics Mean Delay - Bursty Error Channel

Offered Load (G)						
0.9	B	B	B	B	B	B
0.7	B	B	B	N	B	B
0.5	W	W	W	W	W	W
0.3	W	W	W	W	W	W
Stations (N)	5	10	20	30	40	50

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.21: Avionics Mean Delay Performance Comparison - Ideal Channel

Offered Load (G)						
0.9	B	B	B	B	B	B
0.7	B	B	N	B	B	B
0.5	N*	N	N	N	N*	W
0.3	N	N	W	W	W	W
Stations (N)	5	10	20	30	40	50

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.22: Avionics Mean Delay Performance Comparison - Bursty Error Channel

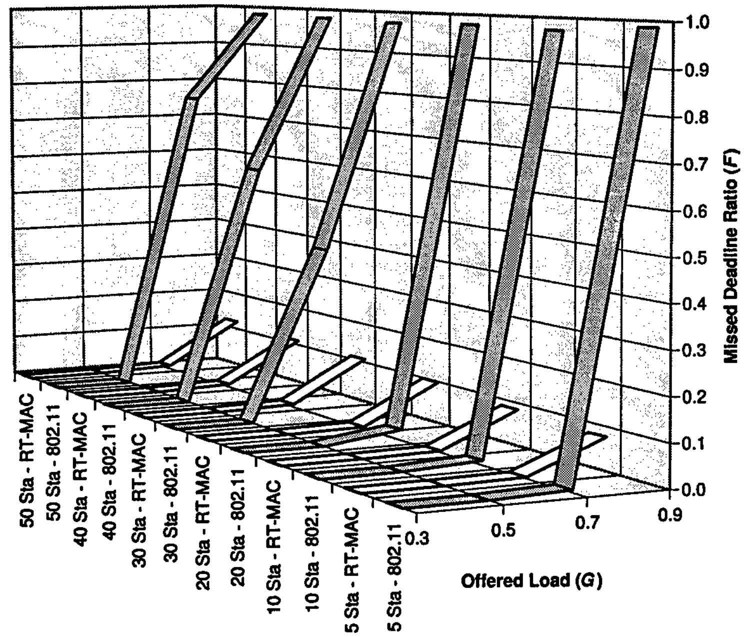


Figure 6.23: Avionics Missed Deadline Ratio - Ideal Channel

6.2.4 Missed Deadlines

Simulation results for missed deadlines are shown in Figures 6.23 and 6.24. As seen in the figures, IEEE 802.11 is susceptible to missed deadlines at moderate to heavy loading for $N \leq 20$. At lighter loads, missed deadline ratios were poor for $N > 20$. RT-MAC is more tolerant of network load and for higher offered loads, always performs dramatically better than IEEE 802.11. For the ideal channel, the missed deadline ratio never exceeded 0.12.

6.2.5 Missed Deadline Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 throughput is given in Figures 6.25 and 6.26 for the ideal and bursty error channels respectively. While the performance of RT-MAC for $G \leq 0.5$ is comparable or worse than IEEE 802.11, the magnitude of the missed deadline ratio for both protocols is much less that 0.01 and therefore not a concern. Of some interest is the better performance of RT-MAC in the bursty error channel. This

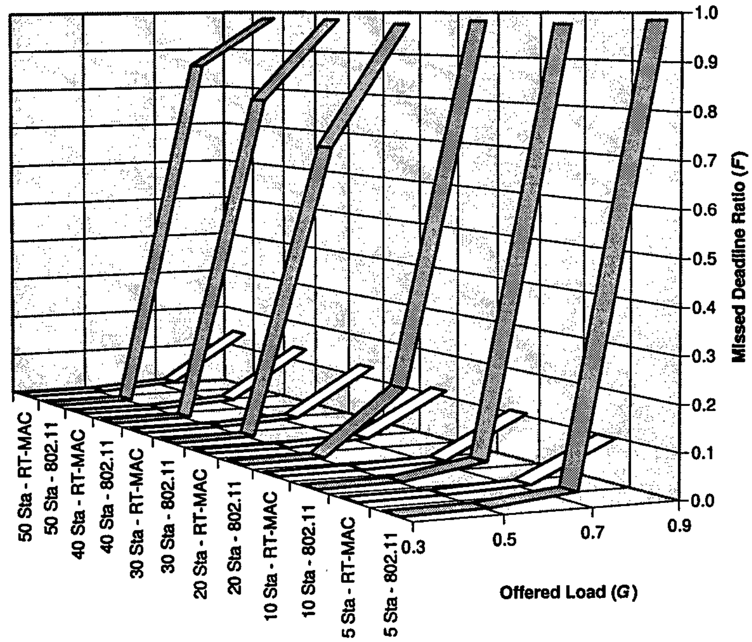


Figure 6.24: Avionics Missed Deadline Ratio - Bursty Error Channel

can be attributed to the fact that RT-MAC will discard a late packet while IEEE 802.11 will transmit until successfully received.

6.2.6 Collisions

IEEE 802.11 and RT-MAC collision ratios are shown in Figures 6.27 and 6.28. As with the IEEE 802.11 mean delay and missed deadline ratio, the IEEE 802.11 collision ratio increases with G. As N increases, the maximum value of the collision ratio increases as well. Therefore, as with the telemetry traffic model, IEEE 802.11 collisions are influenced to a large degree by both G and N.

In contrast, RT-MAC collision ratio remains quite stable. Compared to IEEE 802.11, it is only slightly influenced by either G or N. Statistically, RT-MAC always outperformed IEEE 802.11. Thus far then, the enhanced collision avoidance scheme (cf., Section 5.2) has been seen to be quite effective in reducing collisions for two disparate types of traffic

Offered Load (G)						
0.9	B	B	B	B	B	B
0.7	B	B	B	B	B	B
0.5	N	N	W	W	W	W
0.3	N	N	W*	W	W	W
Stations (N)	5	10	20	30	40	50

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.25: Avionics Missed Deadline Performance Comparison - Ideal Channel

Offered Load (G)						
0.9	B	B	B	B	B	B
0.7	B	B	B	B	B	B
0.5	B	W	B	B	B	W
0.3	W	W	W	W	W	W
Stations (N)	5	10	20	30	40	50

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.26: Avionics Missed Deadline Performance Comparison - Bursty Error Channel

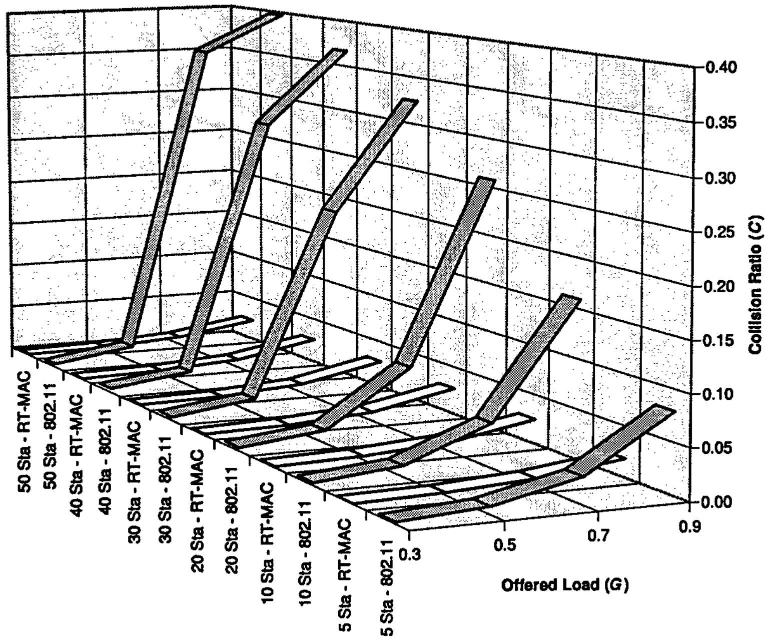


Figure 6.27: Avionics Collision Ratio - Ideal Channel

models—telemetry and avionics.

6.2.7 Bursty Error Channel

Generally, the same observations made in Section 6.1.5 about the bursty error channel also applies to the avionics traffic case. That is, while the bursty error channel did have a detectable effect on the performance metrics, it was not very large. One exception to this, was the mean delay metric. In the figure illustrating the regression model for mean delay (Figure 7.12), the bursty channel is seen to increase the mean delay by a constant factor of about 4.46 ms. This was not seen in the telemetry traffic case, most likely, due to the large difference in packet sizes—83 bytes in the telemetry model versus 775 bytes for the avionics model. That is, in the telemetry model it takes much less time to retransmit a packet. So much so, that the effect on the overall mean delay is negligible.

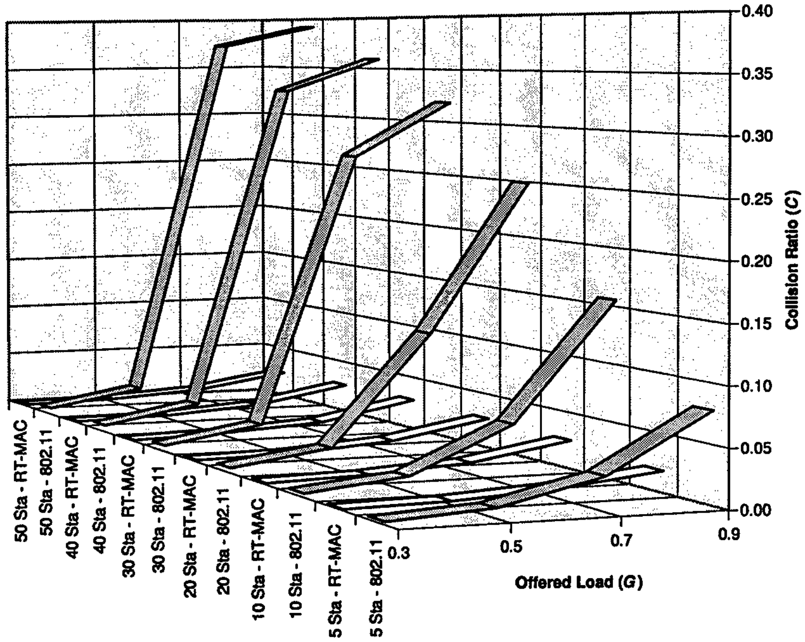


Figure 6.28: Avionics Collision Ratio - Bursty Error Channel

6.3 Voice with Non Real-time Data Traffic Model

The voice traffic model has both real-time traffic (i.e., the packetized voice data) and non real-time traffic (or data with no deadlines). This model was chosen to determine how well RT-MAC performed with the very common application of transmitting voice data as well as to determine how well RT-MAC performed with various levels of non real-time data "interfering" with the delivery of the real-time data. A discussion of this traffic model is found in Section 4.7 and summarized in Table 4.4. A non preemptive head-of-line service discipline is used. If there are any real-time packets in the queue, they are serviced first. Only when there are no real-time packets to transmit are non real-time packets serviced.

In the figures that follow, the term *Offered Data Load* refers to the normalized amount of non real-time (data) traffic that is offered *in addition* to the packetized voice traffic that each station in the network is generating. The amount of real-time traffic generated is a function of N, the number of stations in the network (cf., Section 4.5.2 and Table 4.2). Normalized

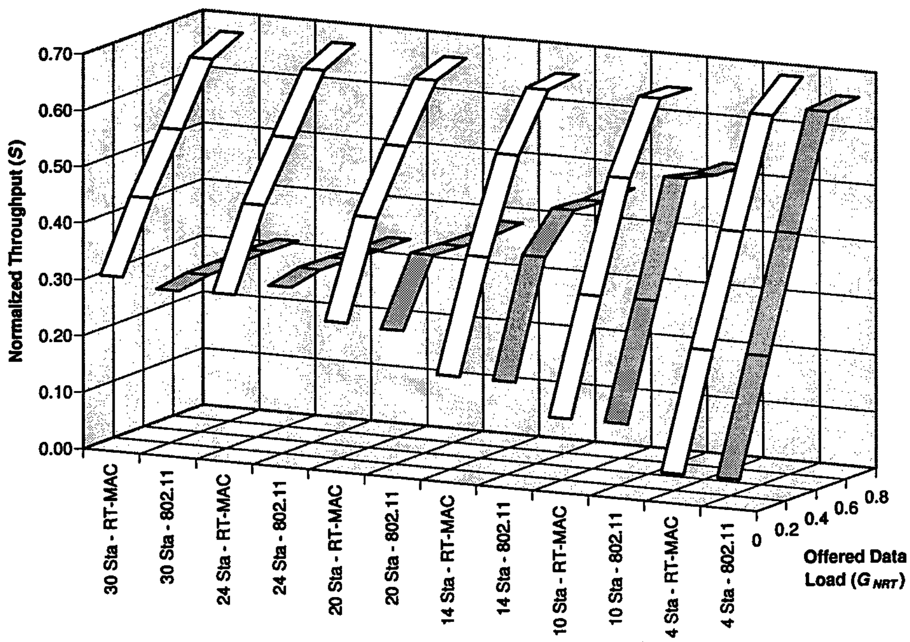


Figure 6.29: Voice Throughput - Ideal Channel (1 Mbps)

throughput, S, is the sum of the real-time and non real-time throughputs or $S = S_{RT} + S_{NRT}$. The quality of the voice channel was deemed usable if $F \leq 0.10$ (cf., Section 2.3.1).

Simulations using the voice traffic model were performed using two different channel capacities, 1 Mbps and 10 Mbps. The 1 Mbps channel is discussed first.

6.3.1 1 Mbps Data Rate

6.3.1.1 Normalized Throughput

As is evident from Figures 6.29 and 6.30, RT-MAC throughput is generally comparable to IEEE 802.11 for $N < 14$ and at modest offered data loads, G_{NRT}. Outside of these limits, RT-MAC easily outperforms IEEE 802.11. Note that the throughput of the voice traffic can be determined by inspecting the figures along the axis where the *Offered Data Load* is equal to 0.0.

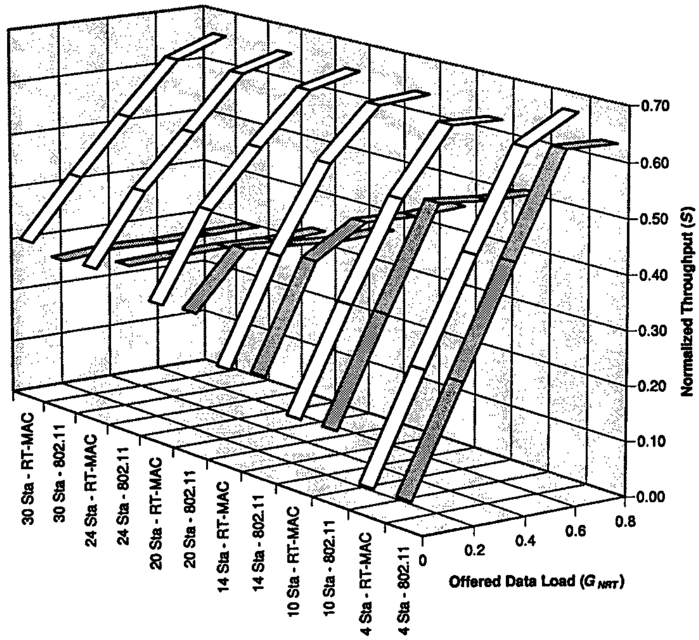


Figure 6.30: Voice Throughput - Bursty Error Channel (1 Mbps)

6.3.1.2 Throughput Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 throughput is given in Figures 6.31 and 6.32 for the ideal and bursty error channels respectively. The region where RT-MAC performed better than IEEE 802.11 was the same for both channel models.

6.3.1.3 Usable Throughput

Before discussing usable throughput, the reader needs to be made aware of a caveat with regard to the IEEE 802.11 throughput data used to construct Figure 6.33. In terms of G, a known proportion of real-time and non real-time data is offered to the channel. In terms of total throughput, S, the proportion of real-time throughput (S_{RT}) versus non real-time throughput (S_{NRT}) data was *not* gathered and is therefore unknown. This makes it impossible to accurately determine S_U since $S_U = S_{RT}(1 - F) + S_{NRT}$ where F is the missed deadline ratio. For RT-MAC throughput data this does not pose a problem since all

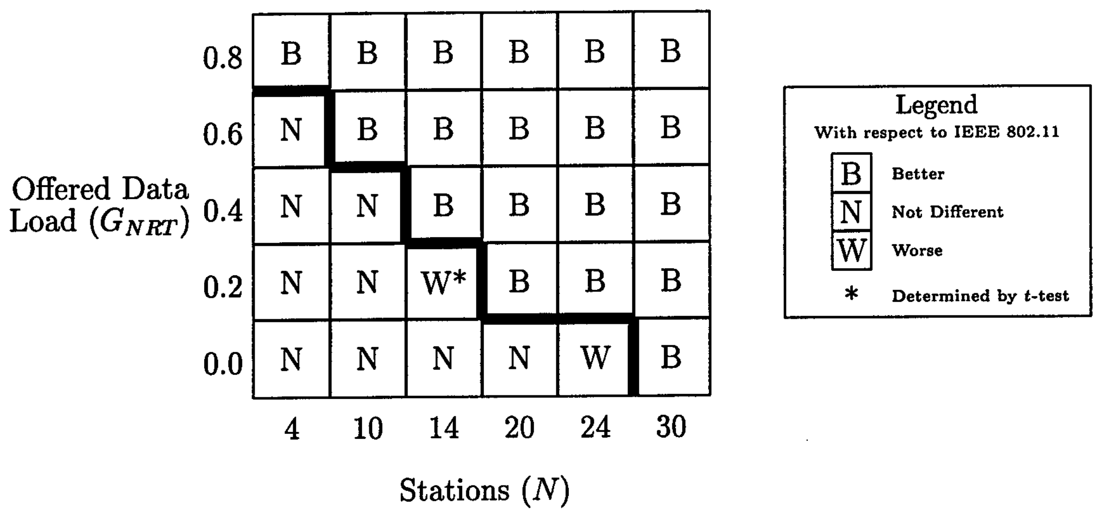


Figure 6.31: Voice Throughput Performance Comparison - Ideal Channel (1 Mbps)

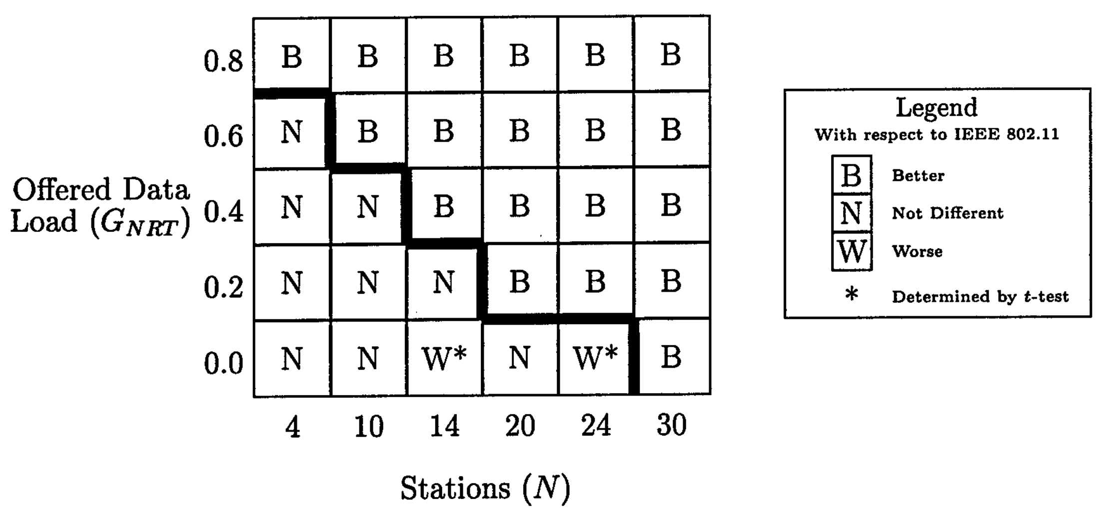


Figure 6.32: Voice Throughput Performance Comparison - Bursty Error Channel (1 Mbps)

throughput is usable due to the transmission control algorithm which will not transmit a late packet. IEEE 802.11, however, *will* attempt to transmit a late packet and therefore some IEEE 802.11 throughput may in fact be late real-time packets. Therefore, an assumption must be made with regard to this proportion. (Note that this does *not* affect the previous usable throughput data discussed for the telemetry and avionics traffic models since all of the packets were real-time.)

Usable throughput is shown in Figure 6.33. Figure 6.33 assumes that any IEEE 802.11 throughput is first due to real-time packets up to the limit of G_{RT} and any throughput greater than G_{RT} is due to non real-time packets. In effect, this changes the usable throughput equation from $S_U = S_{RT}(1 - F) + S_{NRT}$ to $S_U = S - G_{RT}F$ for $S > G_{RT}$ or $S_U = 0.0$ for $S \leq G_{RT}F$. Obviously, then, the figure should only be considered representative of the actual performance. However, due to the head-of-line service discipline used (i.e., real-time packets are serviced first), the figure does give an indication of what the actual performance might be. When compared to Figures 6.29 and 6.30 it can be seen that for $N > 4$, the performance advantage of RT-MAC is intensified.

6.3.1.4 Mean Delay

The mean delay of IEEE 802.11 and RT-MAC is shown in Figures 6.34 and 6.35. As before, mean delay is calculated as the arithmetic mean of the time difference from packet creation to successful reception of the last bit. Delay that discarded packets suffer do not contribute to mean delay.

For every network size considered, IEEE 802.11 delay increases more rapidly than the corresponding RT-MAC network. This is evident from the slope of the mean delay curves. The magnitude of the maximum delay was quite large—6 to 10 seconds being typical. Due to the long delays, buffer overflow for non real-time data was common in IEEE 802.11 networks—25% of arriving packets being discarded was a typical value. For real-time packets, up to 3% were discarded. In RT-MAC networks, discarded non real-time packets rarely occurred

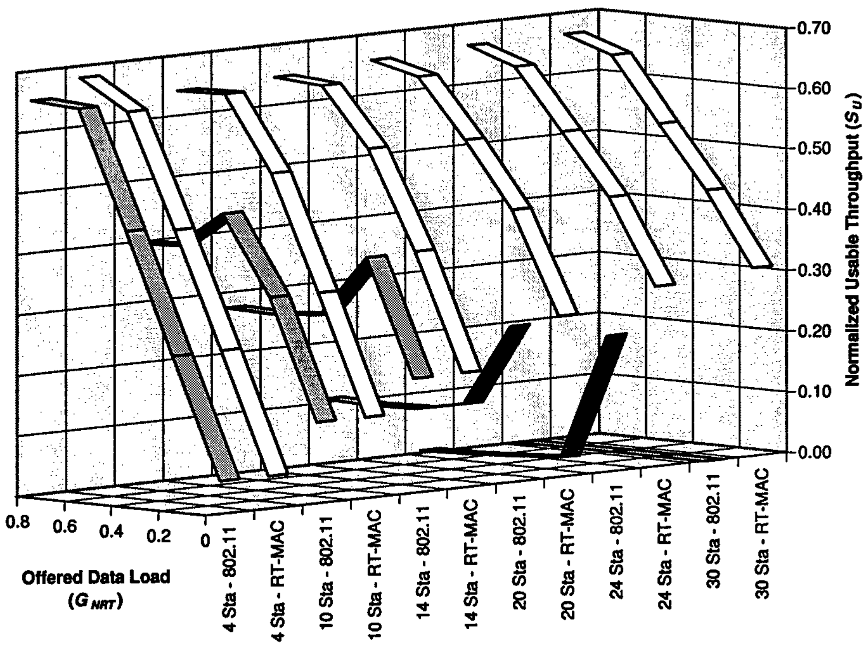


Figure 6.33: Representative Usable Voice Throughput - Ideal Channel (1 Mbps)

and never exceeded 12%. No discarding of real-time packets occurred in RT-MAC stations. The real-time and non real-time packets each had a buffer capable of holding 500 packets. Note that the mean delay is seen to decrease for $N = 4, G_{NRT} = 0.2$ from the value at $N = 4, G_{NRT} = 0.0$. The mean delay is larger with no offered data load due to the way the mean delay is calculated. Real-time and non real-time mean delay is aggregated into a single statistic. Since the volume of real-time traffic is a small portion of the overall traffic the delay suffered by the non real-time traffic will dominate. As the number of stations increase, so too does the wait for channel access and the number of collisions. This increases the non real-time delay and so the mean delay begins to increase for $G > 0.0$ rather than decrease.

RT-MAC mean delay, while typically comparable to IEEE 802.11 for smaller size networks and at low offered data loads, increased at a smaller rate. At larger network sizes and offered data loads, RT-MAC was typically better than IEEE 802.11.

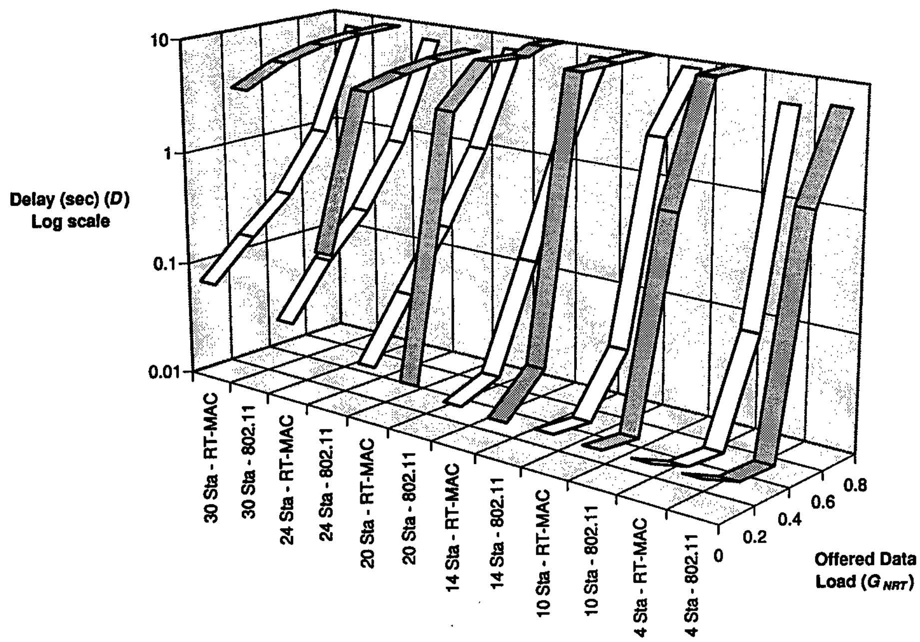


Figure 6.34: Voice Mean Delay - Ideal Channel (1 Mbps)

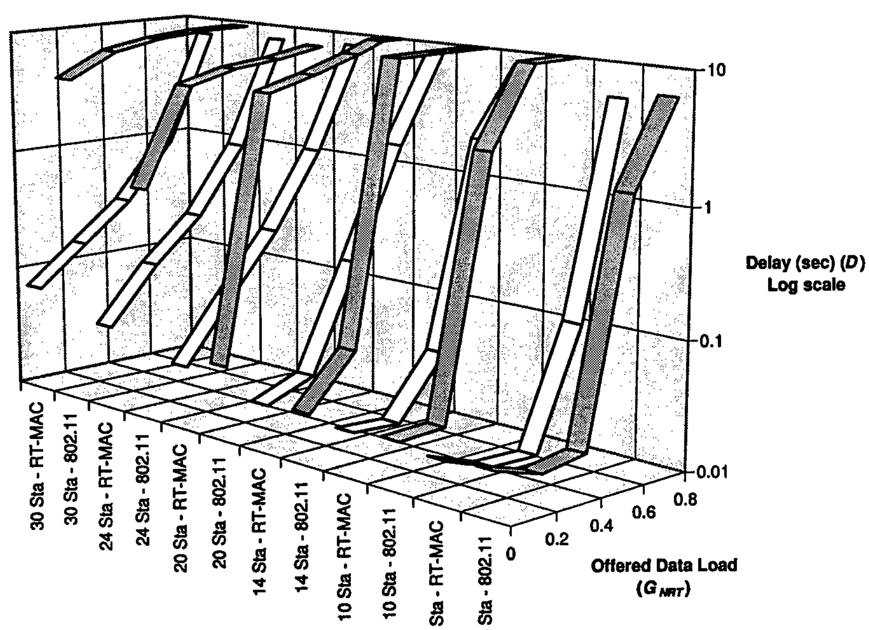


Figure 6.35: Voice Mean Delay - Bursty Error Channel (1 Mbps)

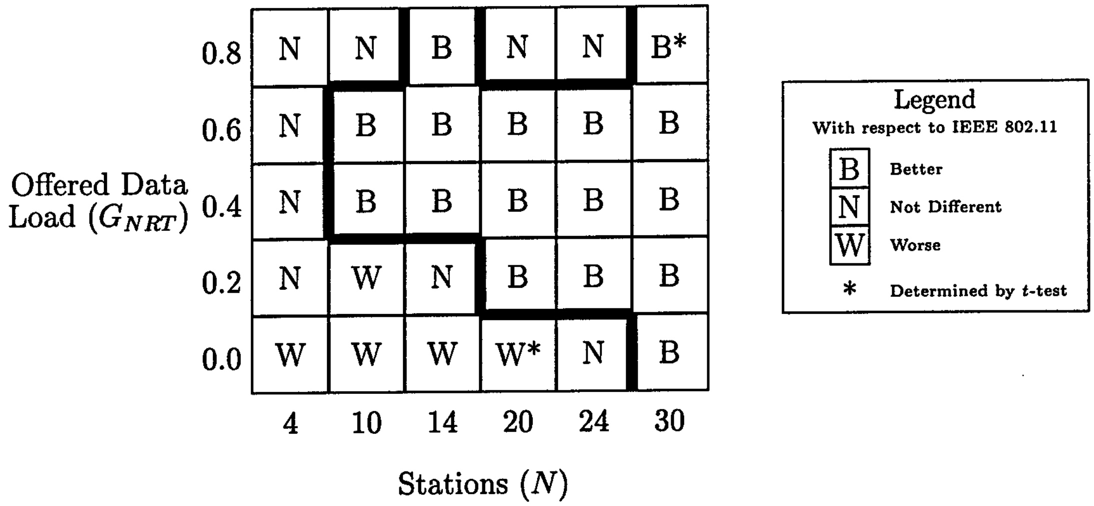


Figure 6.36: Voice Mean Delay Performance Comparison - Ideal Channel (1 Mbps)

6.3.1.5 Mean Delay Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 throughput is given in Figures 6.36 and 6.37 for the ideal and bursty error channels. In contrast to most of the previous performance summaries, the region where RT-MAC is better than IEEE 802.11 is not contiguous. That is, there does not exist a region where RT-MAC always performs better than IEEE 802.11. This can be attributed to the Pareto distribution from which the non real-time packet arrivals times are drawn. As observed in Section 2.3.1, the shape parameter, $a = 1.6$, of the Pareto distribution is in the finite mean, infinite variance region. Given the infinite variance, it is to be expected that mean delay may also widely vary.

6.3.1.6 Missed Deadlines

Simulation results for missed deadlines are shown in Figures 6.38 and 6.39. IEEE 802.11 is susceptible to missed deadlines at light network loads, especially for $N > 10$. RT-MAC is more tolerant of network load and for higher offered loads, always performs better than

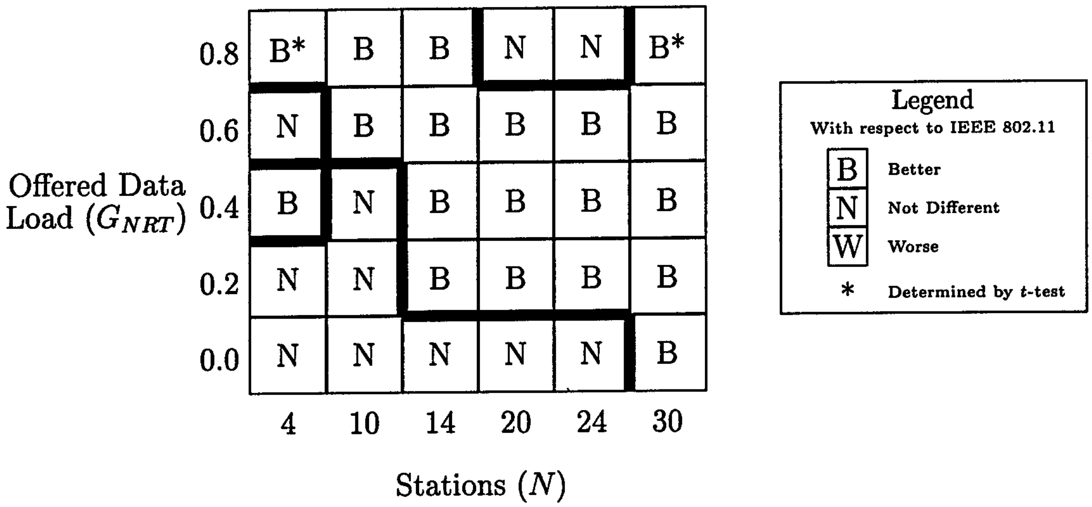


Figure 6.37: Voice Mean Delay Performance Comparison - Bursty Error Channel (1 Mbps)

IEEE 802.11. Statistically, RT-MAC was always better than IEEE 802.11 except for the following cases where it was not different. For the ideal channel RT-MAC and IEEE 802.11 were not different for $N = 4, G_{NRT} = 0.0, 0.2$ and $N = 10, G_{NRT} = 0.0$; for the bursty error channel, RT-MAC and IEEE 802.11 were not different for $N = 10, G_{NRT} = 0.0$.

6.3.1.7 1 Mbps Data Rate Missed Deadline Performance Summary

The maximum acceptable missed deadline ratio for voice traffic used in this research is $F \leq 0.10$ (cf., Section 2.3.1). Figures 6.40–6.43 summarize the ability of IEEE 802.11 and RT-MAC to meet this level of performance. In the figures, areas to the left of the heavy line indicate areas where the maximum acceptable missed deadline ratio is not exceeded. As the legend in the figures indicate, "A" denotes acceptable performance, "M" indicates marginally acceptable performance, and "U" denotes unacceptable performance. For easy comparison, Figures 6.41 and 6.43 also circle the letters where RT-MAC performs better than IEEE 802.11. In no case did RT-MAC perform worse than IEEE 802.11 in terms of

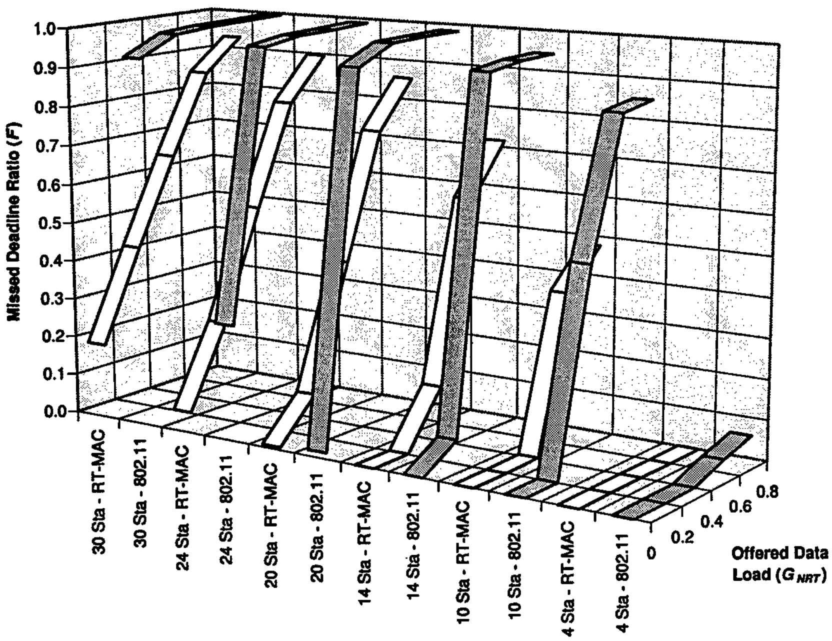


Figure 6.38: Voice Missed Deadline Ratio - Ideal Channel (1 Mbps)

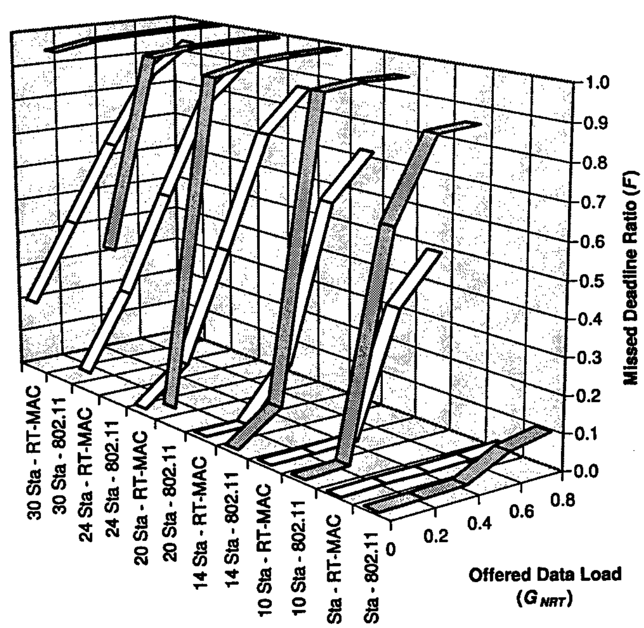


Figure 6.39: Voice Missed Deadline Ratio - Bursty Error Channel (1 Mbps)

the performance measures "A", "M", and "U".

For the ideal channel, RT-MAC was able to improve performance in two areas ($N = 4, G_{NRT} = 0.8$; $N = 14, G_{NRT} = 0.2$) and operate in two additional areas where IEEE 802.11 could not ($N = 10, G_{NRT} = 0.4$; $N = 24, G = 0.0$). For the bursty error channel, RT-MAC was able to improve performance in three areas ($N = 4, G_{NRT} = 0.6, 0.8$; $N = 20, G_{NRT} = 0.0$) and operate in three additional areas where IEEE 802.11 could not ($N = 10, G_{NRT} = 0.4$; $N = 20, G_{NRT} = 0.2$; $N = 24, G = 0.0$).

While the performance of RT-MAC compared to IEEE 802.11 indicates an improvement, the maximum number of stations than could be supported (irrespective of non real-time data load) only increased from $N = 20$ to $N = 24$. Given the sometimes large performance improvements seen in the telemetry and avionics traffic models in RT-MAC networks, it seems plausible that a limit is being reached with respect to some other resource. The most likely resource limit being reached is the 1 Mbps channel data rate.

To determine a theoretic maximum number of stations that can be supported using a 1 Mbps data rate, we use the simplifying assumptions of perfect scheduling, an ideal channel, and a deadline equal to the packet interarrival time. Voice traffic is generated by an ON/OFF source. When ON, packets arrive every $20ms$ and contain 80 bytes of data. A source is ON for an average of 1.0s and OFF for an average of 1.35s. To each packet, additional bits are added at the physical layer, therefore each 80 byte packet is expanded to 132 bytes or 1056 bits. In addition, an ACK packet must be received for each transmission which means an additional 308 bits must be transmitted. Further, each packet suffers at least a DIFS and SIFS (cf., Section 2.2.3.1) which totals 30 μs. Therefore, it takes each packet at least

$$\frac{(1056 + 308) bits}{1 \times 10^6 bps} + 30\mu s = 1.4ms \tag{6.1}$$

to complete transmission. On average there are $\frac{N}{1.0+1.35}$ stations generating voice packets. Therefore, under the assumption of deadlines prior to the next packet arrival, perfect schedul-

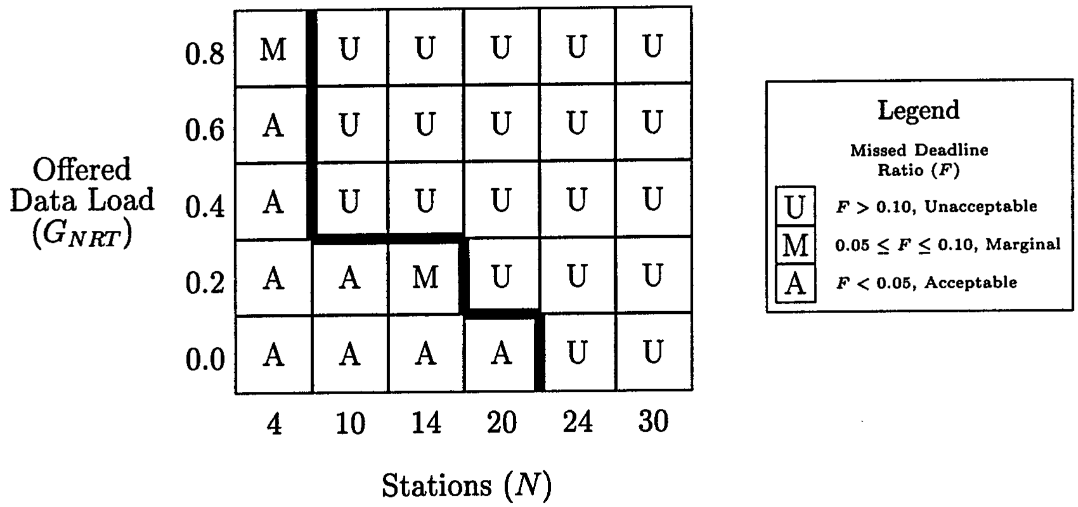


Figure 6.40: Voice Missed Deadline Ratio Summary - Ideal Channel (IEEE 802.11, 1 Mbps)

ing (as well as immediate access to the channel), the maximum number of stations that can be supported is $N_{max} = \lfloor \frac{20ms}{1.4ms} \times 2.35 \rfloor$ or $N_{max} = 33$.

Using the same reasoning but substituting a 10 Mbps data rate, $N_{max} = 282$. Since it appears that the channel data rate *is* a limiting factor, a data rate of 10 Mbps is investigated in Section 6.3.2.

6.3.1.8 Collisions

IEEE 802.11 and RT-MAC collision ratios are shown in Figures 6.44 and 6.45. As with the other traffic models, IEEE 802.11 collision ratio, C, increases rapidly with G and reaches a local maximum. As G increases further the collision ratio tends to stay relatively constant. As N increases, the starting value and the maximum value of the collision ratio increase as well. Hence, IEEE 802.11 collisions are highly influenced by both G and N.

The RT-MAC collision ratio is very stable. As before, compared to IEEE 802.11, it is only slightly influenced by either G or N. Statistically, RT-MAC performed better than

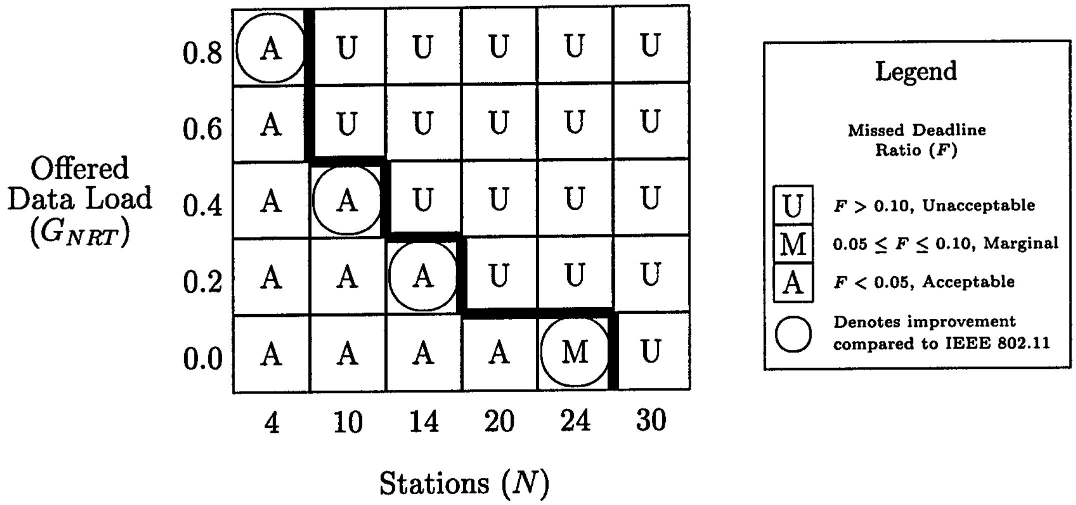


Figure 6.41: Voice Missed Deadline Ratio Summary - Ideal Channel (RT-MAC, 1 Mbps)

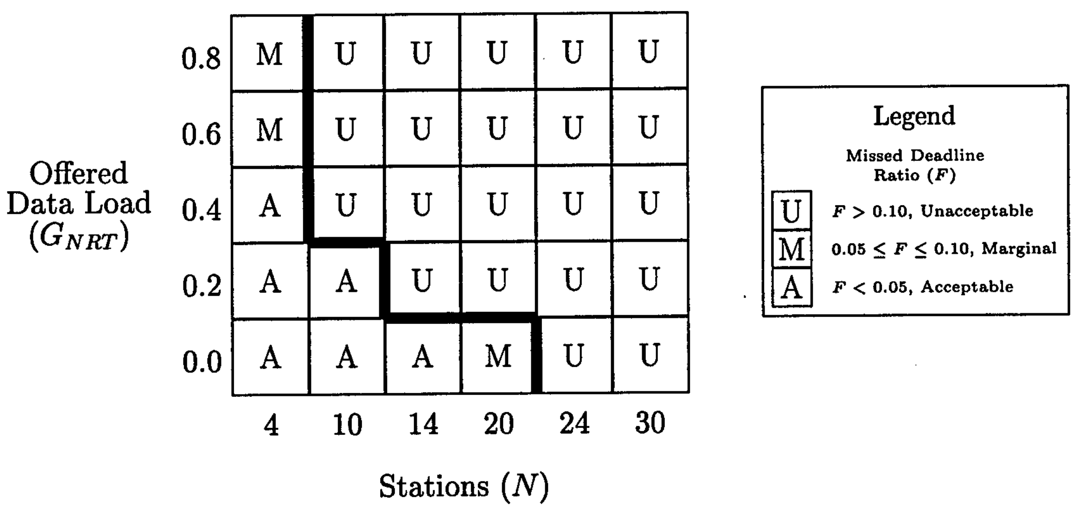


Figure 6.42: Voice Missed Deadline Ratio Summary - Bursty Error Channel (IEEE 802.11, 1 Mbps)

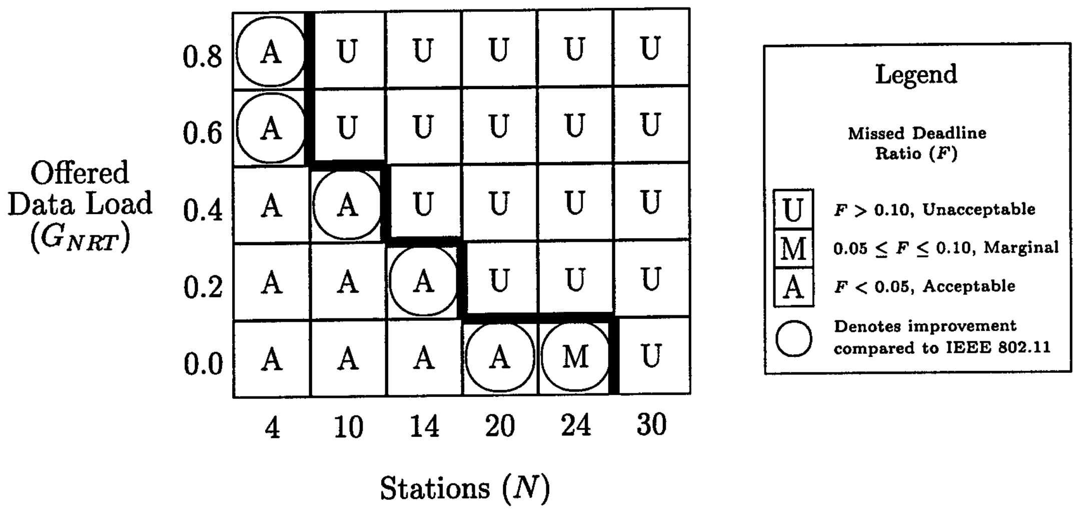


Figure 6.43: Voice Missed Deadline Ratio Summary - Bursty Error Channel (RT-MAC, 1 Mbps)

IEEE 802.11 with only one exception, $N = 10, G_{NRT} = 0.0$, where it performed worse. The reason for this exception has not been determined.

6.3.2 10 Mbps Data Rate

6.3.2.1 Normalized Throughput

As with the 1 Mbps channel, in the figures that follow, the term *Offered Data Load* refers to the normalized amount of non real-time (data) traffic that is offered *in addition* to the packetized voice traffic that each station in the network is generating. The amount of real-time traffic generated is a function of N, the number of stations in the network (cf., Section 4.5.2 and Table 4.3). Normalized throughput, S, is the sum of the real-time and non real-time throughputs or $S = S_{RT} + S_{NRT}$. The quality of the voice channel was deemed usable if $F \le 0.10$ (cf., Section 2.3.1).

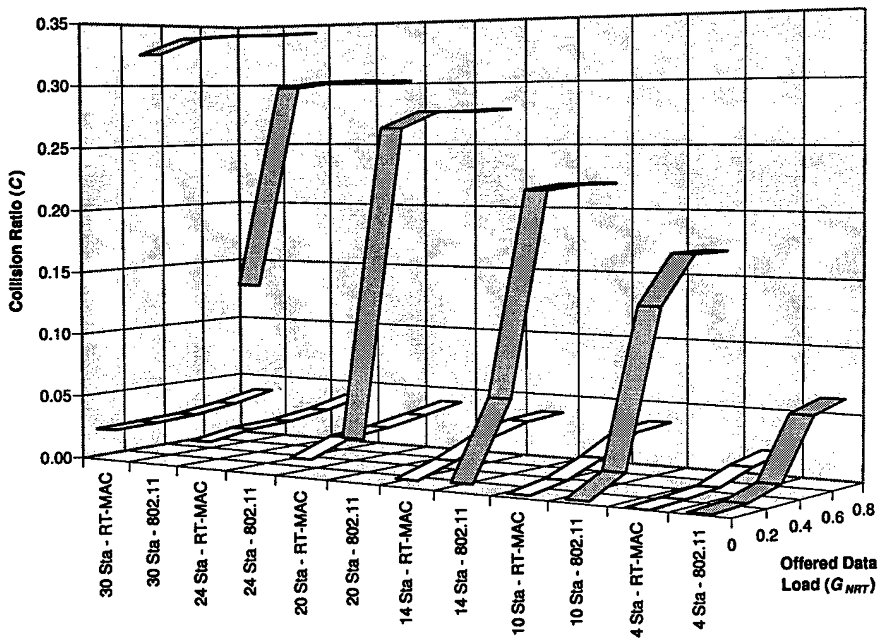


Figure 6.44: Voice Collision Ratio - Ideal Channel (1 Mbps)

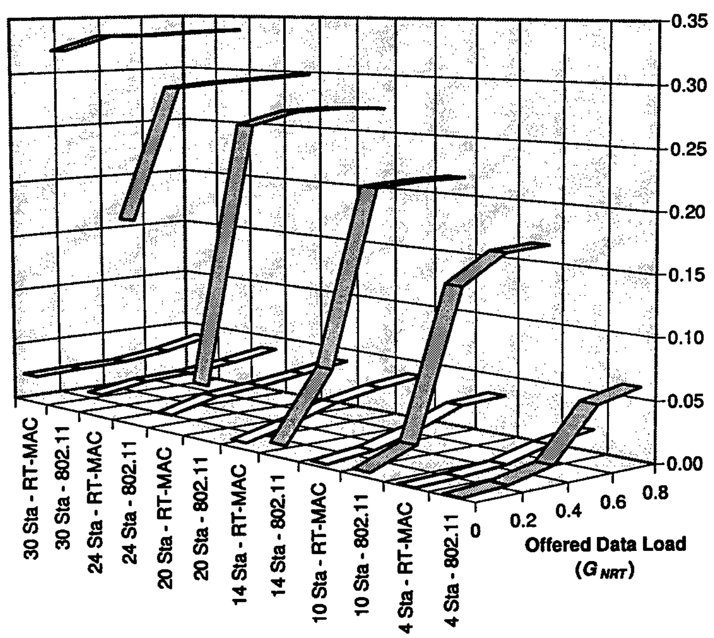


Figure 6.45: Voice Collision Ratio - Bursty Error Channel (1 Mbps)

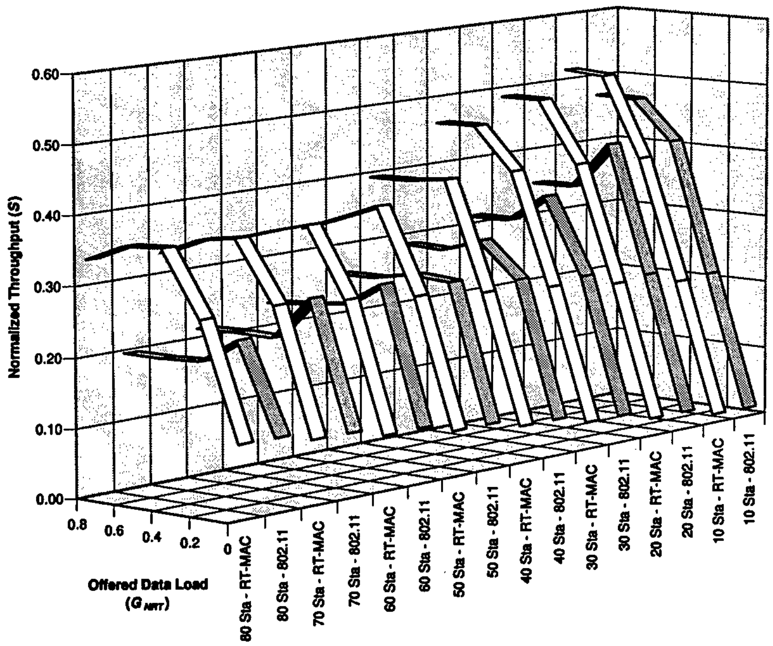


Figure 6.46: Voice Throughput - Ideal Channel (10 Mbps)

Figures 6.46 and 6.47 show that RT-MAC throughput is generally comparable to IEEE 802.11 at modest offered data loads, G_{NRT}. In the cases where RT-MAC performed worse than IEEE 802.11, RT-MACs mean throughput was typically within 10% of the IEEE 802.11 mean throughput. For $G_{NRT} > 0.4$, RT-MAC easily outperformed IEEE 802.11 in almost all cases.

6.3.2.2 Throughput Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 throughput is given in Figures 6.48 and 6.49 for the ideal and bursty error channels respectively. The region where RT-MAC performed better than IEEE 802.11 was the same for both channel models except for the bursty channel where at $G_{NRT} = 0.2, N = 80$ RT-MAC outperformed IEEE 802.11 as well.

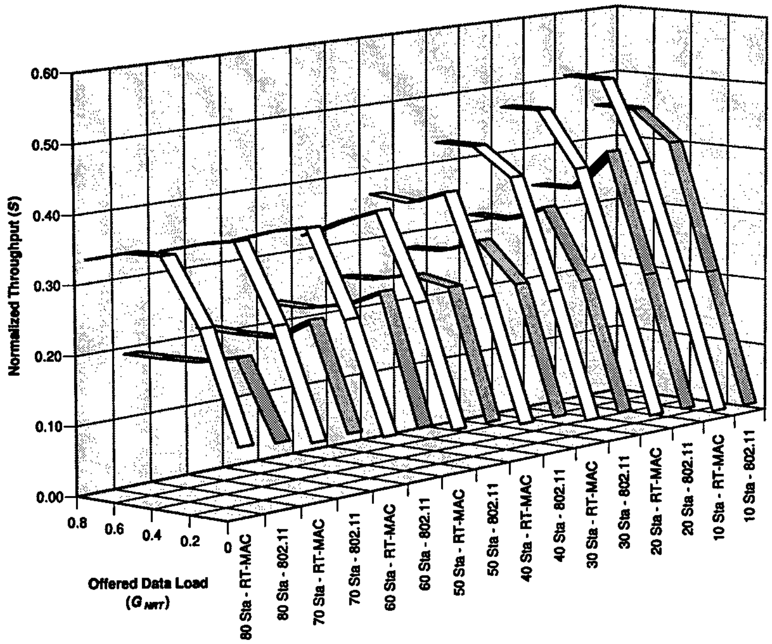


Figure 6.47: Voice Throughput - Bursty Error Channel (10 Mbps)

Offered Data Load (G_{NRT})								
0.8	B	B	B	B	B	B	B	B
0.6	B	B	B	B	B	B	B	B
0.4	W	W	B	B	B	B	B	B
0.2	W*	W	W	W	W	W	N	N
0.0	N	N	N	N	N	N	N	N
Stations (N)	10	20	30	40	50	60	70	80

Legend
With respect to IEEE 802.11

- B: Better
- N: Not Different
- W: Worse
- *: Determined by t-test

Figure 6.48: Voice Throughput Performance Comparison - Ideal Channel (10 Mbps)

Offered Data Load (G_{NRT})	10	20	30	40	50	60	70	80
0.8	B	B	B	B	B	B	B	B
0.6	B	B	B	B	B	B	B	B
0.4	W	N	B	B	B	B	B	B
0.2	W*	W*	W*	W	W*	N	N	B
0.0	N	N	W	N	N	N	N	N

Stations (N)

Legend
With respect to IEEE 802.11
- B Better
- N Not Different
- W Worse
- * Determined by *t*-test

Figure 6.49: Voice Throughput Performance Comparison - Bursty Error Channel (10 Mbps)

6.3.2.3 Mean Delay

The mean delay of IEEE 802.11 and RT-MAC is shown in Figures 6.50 and 6.51. Mean delay is calculated as the arithmetic mean of the time difference from packet creation to successful reception of the last bit. Delay that discarded packets suffer do not contribute to mean delay.

Many of the observations made for the mean delay of the 1 Mbps channel (Section 6.3.1.4) can also be made about the 10 Mbps channel. In general, IEEE 802.11 delay increases more rapidly than the corresponding RT-MAC network. Due to the long delays, buffer overflow for non real-time data was common—as much as 35% of arriving packets were discarded in IEEE 802.11 networks, 27% in RT-MAC networks. In contrast to the 1 Mbps channel, no real-time packets were discarded. This is most likely due to the faster channel speed. As with the 1 Mbps channel, the mean delay is seen to decrease in many cases as G_{NRT} increased from 0.0 to 0.2. This is due to the way the mean delay is calculated. Real-time and non real-time mean delay is aggregated into a single statistic. Since the volume of real-

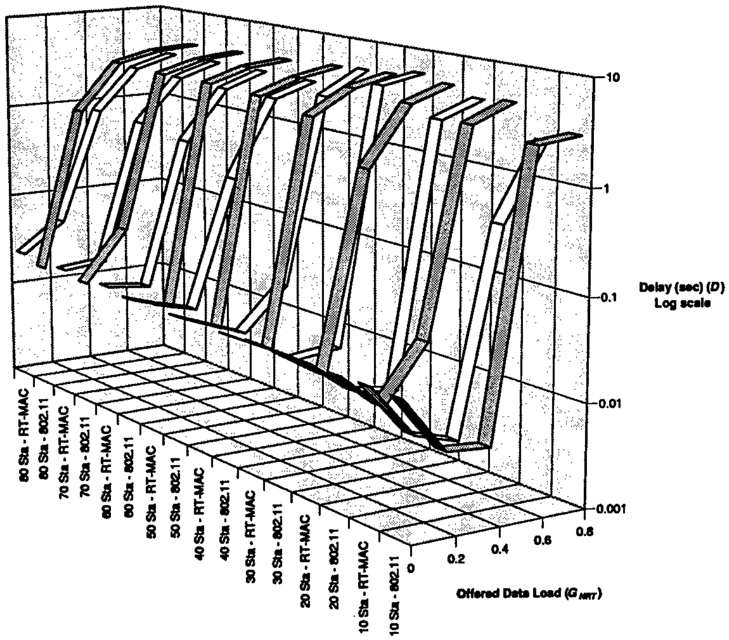


Figure 6.50: Voice Mean Delay - Ideal Channel (10 Mbps)

time traffic is a small portion of the overall traffic, the delay suffered by the non real-time traffic will dominate. The proportion of non real-time packets to real-time packets is quite high even when $G_{NRT} = 0.2$. The proportion ranges from about 15 to 1 for $N = 10$ down to about 2 to 1 for $N = 80$. Therefore, the mean delay experienced by the non real-time traffic quickly masks the effect of the delay experienced by the real-time packets. Data for the delay suffered by real-time packets and non real-time packets separately was not collected.

6.3.2.4 Mean Delay Performance Summary

A summary of the performance of RT-MAC versus IEEE 802.11 mean delay is given in Figures 6.52 and 6.53 for the ideal and bursty error channels. As in the 1 Mbps case, the region where RT-MAC is better than IEEE 802.11 is not contiguous. That is, there does not exist a region where RT-MAC always performs better than IEEE 802.11. This can be attributed to the Pareto distribution from which the non real-time packet arrivals times are drawn. As observed in Section 2.3.1, the shape parameter, $a = 1.6$, of the Pareto distribution

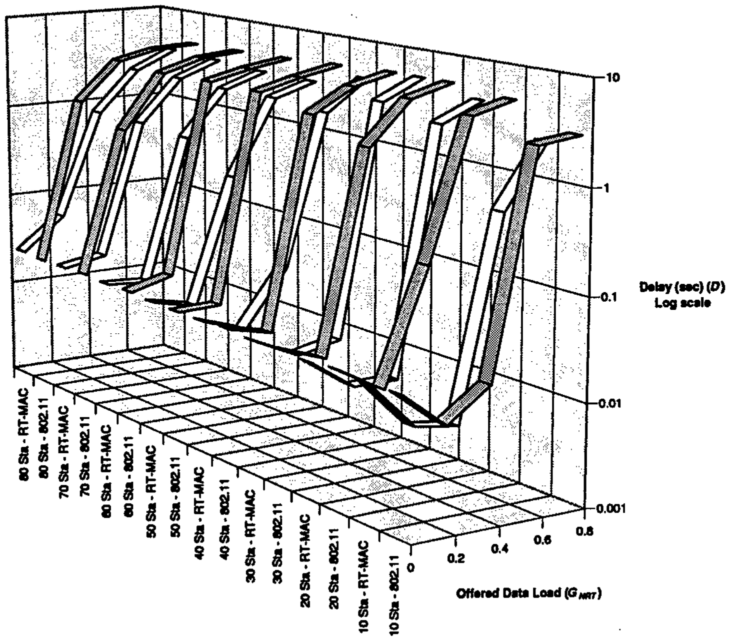


Figure 6.51: Voice Mean Delay - Bursty Error Channel (10 Mbps)

is in the finite mean, infinite variance region. Given the infinite variance, it is to be expected that mean delay may also widely vary.

6.3.2.5 Missed Deadlines

Simulation results for missed deadlines are shown in Figures 6.54 and 6.55. While obviously benefiting from the higher channel rate, IEEE 802.11 is still susceptible to missed deadlines at light network loads, especially for $N > 20$. RT-MAC is more tolerant of network load and for higher offered loads, always performs better than IEEE 802.11. There were a few instances where RT-MAC performed worse than IEEE 802.11 in terms of missed deadlines (cf., Tables B.30 and B.31). However, in these cases the ratio of missed deadlines for RT-MAC was typically on the order of 0.00001 and therefore not significant. In the case of a bursty error channel, RT-MAC always performed better than IEEE 802.11 except for three cases where it was not different.

Offered Data Load (G_{NRT})								
0.8	B	N	W	N	B	B	B	B
0.6	B	N	W	B	B	B	B	B
0.4	B	N	B	B	B	B	B	B
0.2	W*	W	W	W	W	W	N	B
0.0	W	W	W	W	W	W	W	W
Stations (N)	10	20	30	40	50	60	70	80

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.52: Voice Mean Delay Performance Comparison - Ideal Channel (10 Mbps)

Offered Data Load (G_{NRT})								
0.8	B	B	N	N	B	B	B	B
0.6	B	B*	N	B	B	B	B	B
0.4	B*	N	B	B	B	B	B	B
0.2	N	N	N	N	N	N	B	B
0.0	B*	N	N	N	N	N	N	N
Stations (N)	10	20	30	40	50	60	70	80

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.53: Voice Mean Delay Performance Comparison - Bursty Error Channel (10 Mbps)

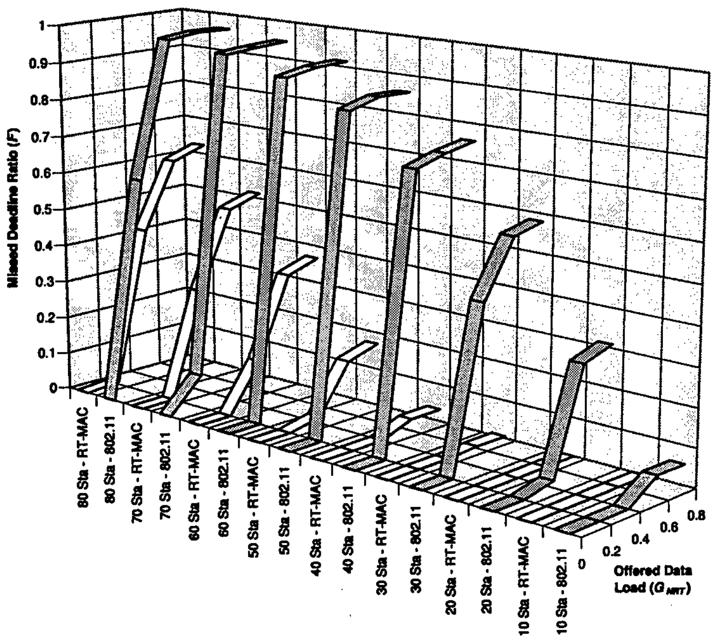


Figure 6.54: Voice Missed Deadline Ratio - Ideal Channel (10 Mbps)

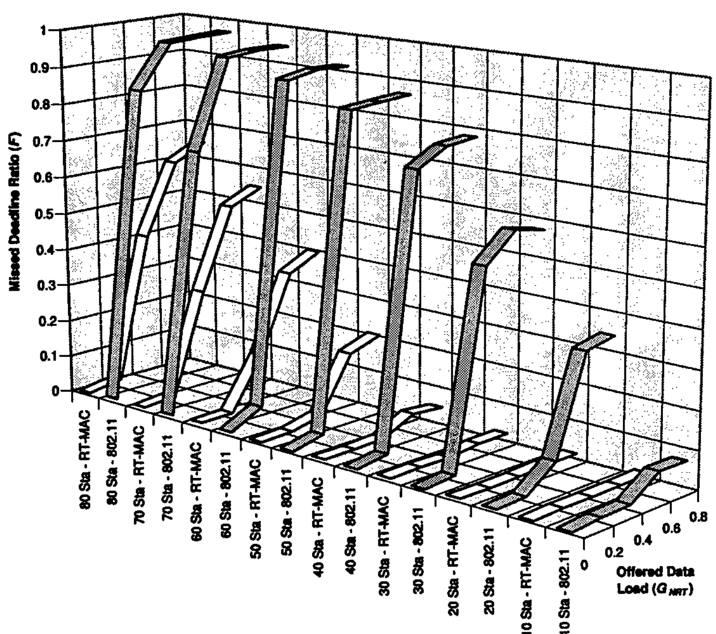


Figure 6.55: Voice Missed Deadline Ratio - Bursty Error Channel (10 Mbps)

6.3.2.6 10 Mbps Data Rate Missed Deadline Performance Summary

The maximum acceptable missed deadline ratio for voice traffic used in this research is $F \leq 0.10$ (cf., Section 2.3.1). Figures 6.56–6.59 summarize the ability of IEEE 802.11 and RT-MAC to meet this level of performance using a 10 Mbps channel. In the figures, areas to the left of the heavy line indicate areas where the maximum acceptable missed deadline ratio is not exceeded. As the legend in the figures indicate, "A" denotes acceptable performance, "M" indicates marginally acceptable performance, and "U" denotes unacceptable performance. For easy comparison, Figures 6.57 and 6.59 also circle the letters where RT-MAC performs better than IEEE 802.11. In no case did RT-MAC perform worse than IEEE 802.11 in terms of the summary performance measures "A", "M", or "U".

In Section 6.3.1.6, we speculated that the reason RT-MAC did not improve performance more when compared to IEEE 802.11 was due to the 1 Mbps channel data rate. The data obtained for the 10 Mbps channel seems to confirm this, especially considering the amount of G_{NRT} that can be transmitted compared to IEEE 802.11.

As a separate study, we discuss the maximum number of stations that can be supported using a 10 Mbps channel in Section 6.4.5.1.

6.3.2.7 Collisions

IEEE 802.11 and RT-MAC collision ratios are shown in Figures 6.60 and 6.61. As with the other traffic models, IEEE 802.11 collision ratio, C, increases rapidly with G and reaches a local maximum. As G increases further the collision ratio tends to stay relatively constant. As N increases, the starting value and the maximum value of the collision ratio increase as well. Hence, IEEE 802.11 collisions are highly influenced by both G and N.

The RT-MAC collision ratio is very stable. As before, compared to IEEE 802.11, it is only slightly influenced by either G or N. In contrast to previous traffic models, however, RT-MAC performs worse than IEEE 802.11 for $N = 10 - 80; G = 0.0$ and $N = 10 - 50; G = 0.2$

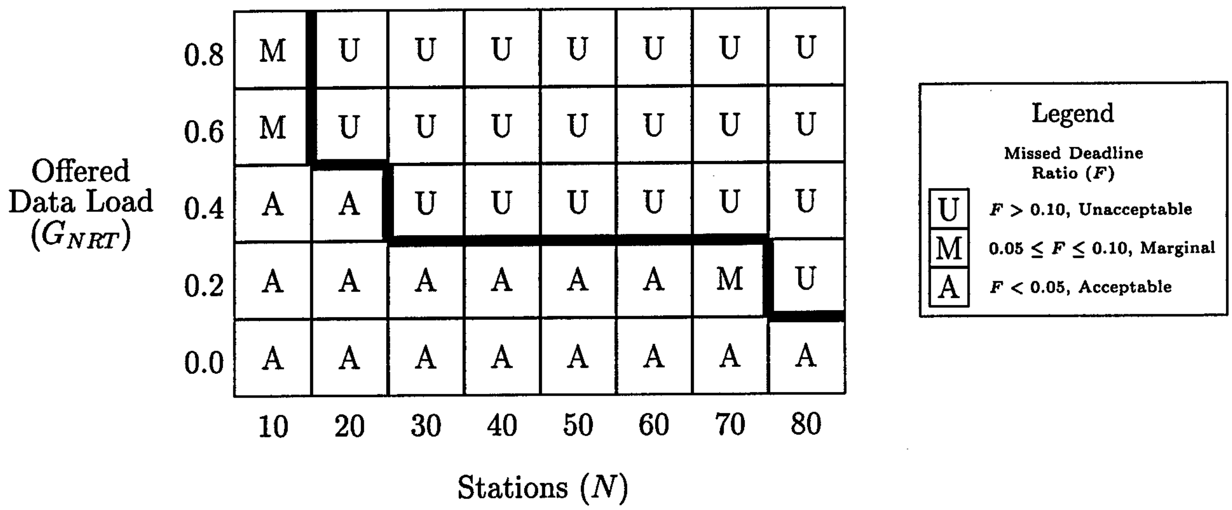


Figure 6.56: Voice Missed Deadline Ratio Summary - Ideal Channel (IEEE 802.11, 10 Mbps)

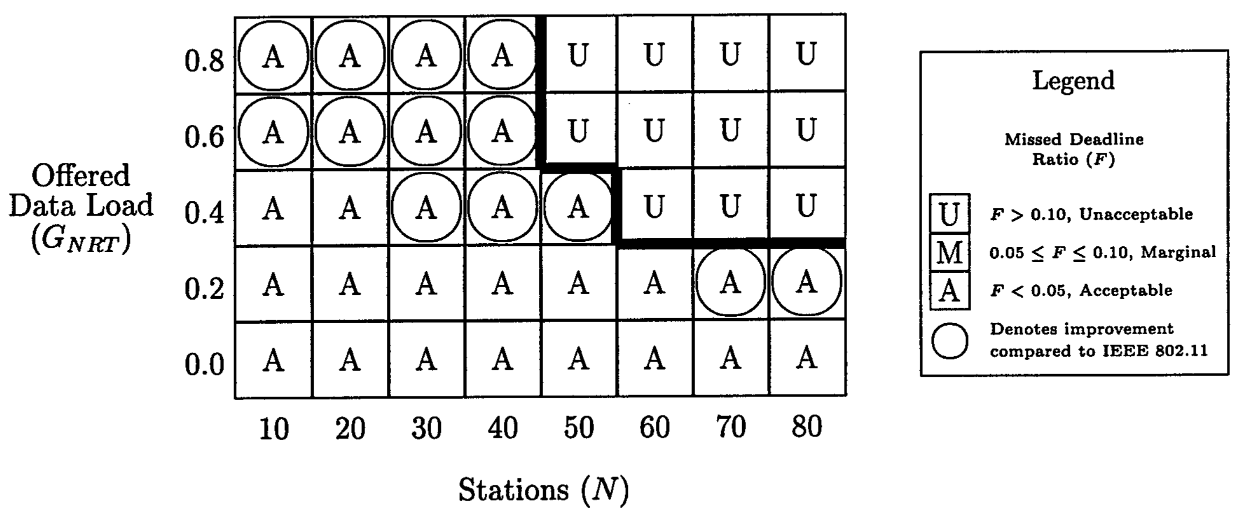


Figure 6.57: Voice Missed Deadline Ratio Summary - Ideal Channel (RT-MAC, 10 Mbps)

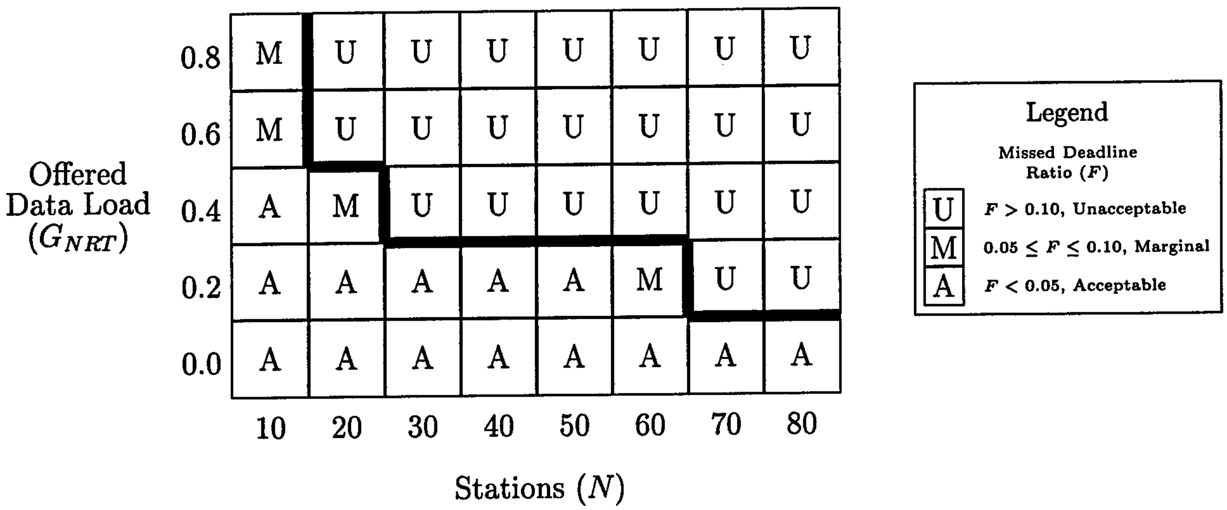


Figure 6.58: Voice Missed Deadline Ratio Summary - Bursty Error Channel (IEEE 802.11, 10 Mbps)

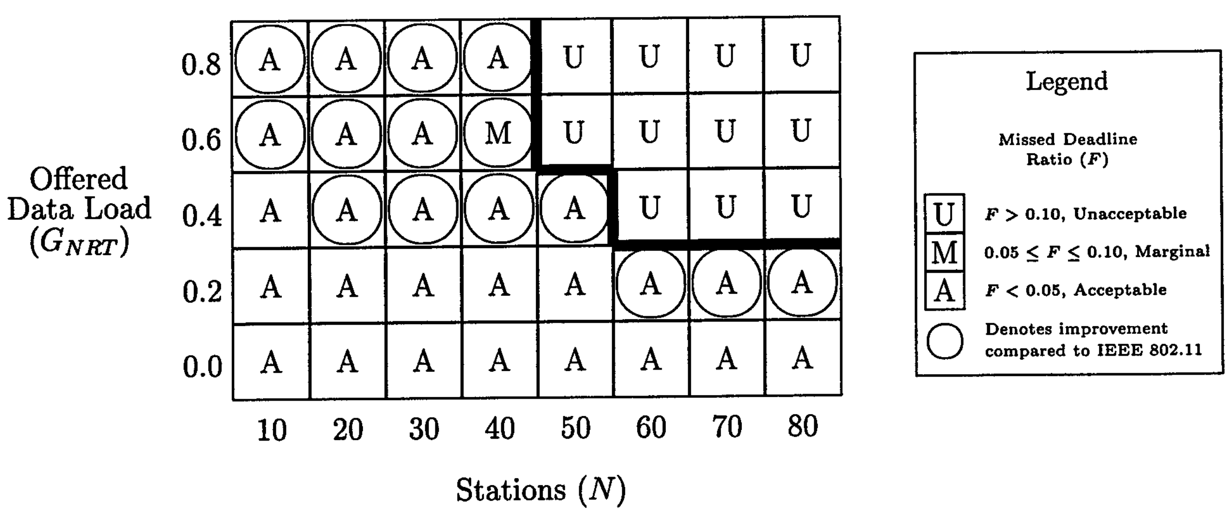


Figure 6.59: Voice Missed Deadline Ratio Summary - Bursty Error Channel (RT-MAC, 10 Mbps)

for the ideal channel and with $N = 10 - 80; G = 0.0$ and $N = 10; G = 0.2$ for the bursty channel. This is shown in summary form in Figures 6.62 and 6.63. In terms of the magnitude of the collision ratio, IEEE 802.11 tends to range between 0.01 and 0.02 with RT-MAC being roughly twice that (i.e., 0.02 to 0.04). Given the previous performance of the RT-MAC enhanced collision avoidance algorithm (ECA), this change is curious.

Before discussing the areas investigated to determine the cause for this collision performance, we list some aspects of IEEE 802.11 and RT-MAC collision behavior that have been previously noted.

- A reduction in collisions was noted for a given IEEE 802.11 or RT-MAC network when the channel rate was increased from 1 Mbps to 10 Mbps.
- IEEE 802.11 collisions were less that RT-MAC as noted in Figures 6.62 and 6.63
- Using the data collected in Section 6.4.5.1 to determine the maximum N that can be supported it was found that for $N = 130, G_{NRT} = 0.0$ the collision ratios of IEEE 802.11 and RT-MAC were comparable.
- For $N = 130, G_{NRT} = 0.2$ and $N = 140, G_{NRT} = 0.0$ the collision ratio of IEEE 802.11 was about 0.53 while RT-MAC was about 0.08.

Three areas were investigated to determine the cause for this collision performance: (1) differences in the way RT-MAC and IEEE 802.11 treat packets that arrive to an idle channel, (2) the range of backoff values used for the next backoff value (BV), and (3) the data being transported and the nature of its arrival including queueing behavior.

If an IEEE 802.11 station is not in backoff (cf., Section 2.2.3.1) and a packet arrives to an empty queue it will be transmitted immediately (assuming an idle channel). In order to reduce to possibility of collisions among stations with simultaneous arrivals, RT-MAC will, in this situation, choose a backoff value rather than immediately transmit the packet (cf., Section 5.2). This behavior was changed to reflect the IEEE 802.11 algorithm with negligible effect.

To investigate the second area, rather than choose the next BV from the range [0, CWmin], RT-MAC was modified to choose from [0, $3N$]. The supposition being that perhaps the advertisement of the backoff values for the voice data was ineffective (due to the rapid packet transmission of the 10 Mbps channel) and that a wider contention window would reduce collisions. This, too, had a negligible effect on RT-MAC performance.

For the third area investigated, note that the voice packets arrive every 20 ms when the voice source is on and transmission time for a voice packet is about 0.17 ms. No instance of more than one voice packet awaiting transmission was observed for either an IEEE 802.11 or RT-MAC network. That is, the current voice packet was always transmitted prior to the next packet arriving. Therefore, queued packets could not be a cause of the behavior. Additionally, simulations were run using Poisson arrivals as also used in the avionics traffic model. In those simulations, RT-MAC had a higher collision ratio at low offered loads as well. Therefore, it appears that the increase in collisions is not sensitive to the arrival patterns tested.

Another rather obvious source for this increase in collisions is an implementation error in the protocol algorithm. This possibility was diligently investigated and while it cannot be ruled out, seems unlikely.

Hence, we note the behavior and must leave it as an area for further investigation.

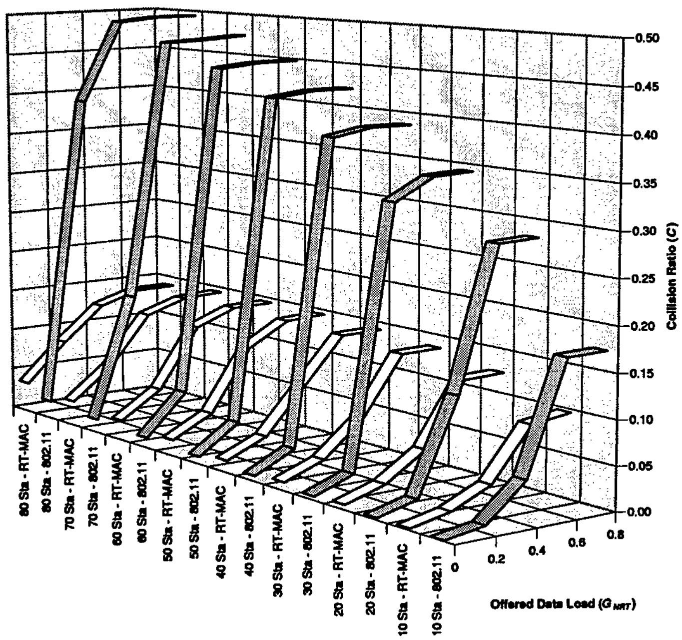


Figure 6.60: Voice Collision Ratio - Ideal Channel (10 Mbps)

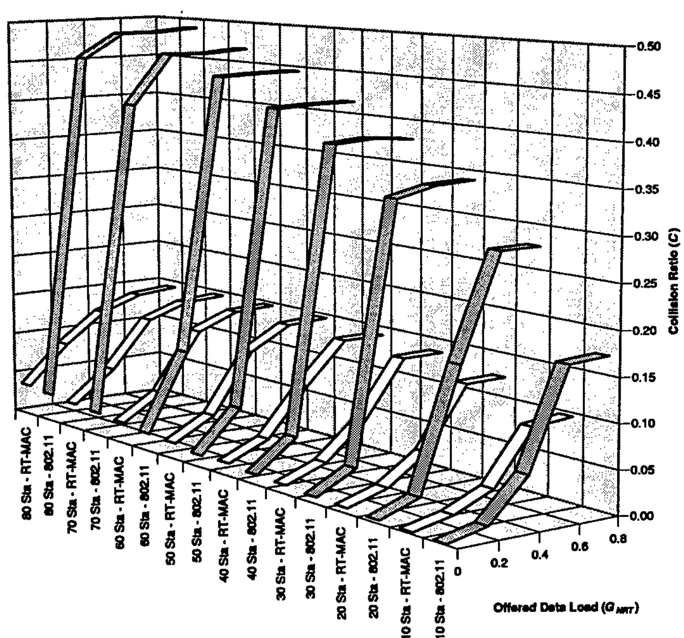


Figure 6.61: Voice Collision Ratio - Bursty Error Channel (10 Mbps)

Offered Data Load (G_{NRT})	10	20	30	40	50	60	70	80
0.8	B	B	B	B	B	B	B	B
0.6	B	B	B	B	B	B	B	B
0.4	B	B	B	B	B	B	B	B
0.2	W	W	W	W	W	B	B	B
0.0	W	W	W	W	W	W	W	W

Stations (N)

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

Figure 6.62: Voice Collision Ratio Performance Comparison - Ideal Channel (10 Mbps)

Offered Data Load (G_{NRT})	10	20	30	40	50	60	70	80
0.8	B	B	B	B	B	B	B	B
0.6	B	B	B	B	B	B	B	B
0.4	B	B	B	B	B	B	B	B
0.2	W	N	B	B	B	B	B	B
0.0	W	W	W	W	W	W	W	W

Stations (N)

Legend
With respect to IEEE 802.11
B Better
N Not Different
W Worse
* Determined by t-test

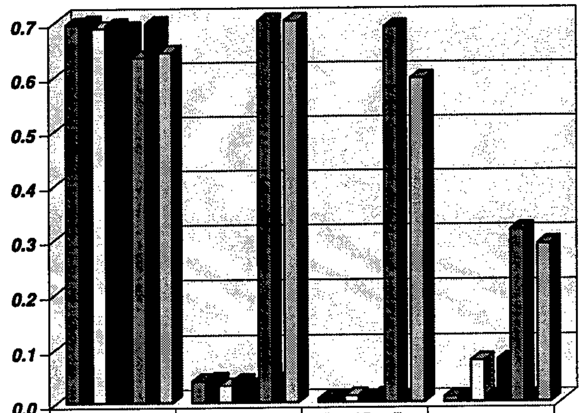
Figure 6.63: Voice Collision Ratio Performance Comparison - Bursty Error Channel (10 Mbps)

6.4 Other Simulations Studies

6.4.1 RT-MAC Enhancements Study

Originally, three enhancements were proposed to IEEE 802.11 (cf., Section 4.1.1)—an EDF service discipline, a transmission control (TC) algorithm, and an enhanced collision avoidance (ECA) algorithm. The purpose of this simulation study was to establish the relative effect on the performance metrics of these enhancements in isolation and in all possible combinations. The question this simulation study seeks to answer is whether one enhancement alone provides the best improvement in a particular performance metric, or whether a combination of the three enhancements provides the best improvement. For instance, it may be found that collisions are reduced the most when both the ECA and the TC algorithms are enabled, rather than when the ECA alone is enabled. We may then conclude that the TC control algorithm helps to reduce collisions as well (presumably by a reduction in packet transmissions). Conversely, it may be found that enhancements in combination degrade performance. The network employed throughout this study uses an ideal channel with the avionics traffic model and $N = 40, G = 0.7$. This network was chosen since it provided a traffic model with deadlines which are drawn from a normal distribution and therefore might benefit from an EDF service discipline, as well as having a large number of stations to induce collisions.

Figure 6.64 shows the mean results obtained by this study. As with the previous simulations, five replications were performed. Each combination of enhancements are compared to three "reference" networks: IEEE 802.11, RT-MAC, and the enhancement plus an EDF service discipline. For example, if the network is simulated with only the ECA algorithm running, those results are compared to an IEEE 802.11 network, an RT-MAC network, and a network with ECA and the EDF service discipline.



	Normalized Throughput (S)	Mean Delay (sec) (D)	Missed Deadline Ratio (F)	Collision Ratio (C)
TC/ECA/EDF	0.6937	0.0388	0.0062	0.0091
ECA/EDF	0.6977	0.0415	0.0074	0.0092
TC/EDF	0.6868	0.0310	0.0120	0.0756
TC/ECA (RT-MAC)	0.6918	0.0384	0.0069	0.0091
Transmission Control (TC) only	0.6858	0.0313	0.0127	0.0774
Earliest-Deadline-First (EDF) only	0.6325	11.2508	0.6878	0.3136
Enhanced Collision Avoidance (ECA) only	0.6948	0.0410	0.0079	0.0096
NONE (IEEE 802.11)	0.6421	10.8162	0.5928	0.2879

Figure 6.64: RT-MAC Enhancements Study Mean Results

6.4.1.1 Throughput

Figure 6.65 shows the results in terms of the throughput performance metric. As with previous simulations, the means and corresponding CIs were used to arrive at a statistical comparison of the reference systems (cf., Section C.1). Any combination of the proposed enhancements performed better than IEEE 802.11 in terms of throughput except for EDF which was not different. When compared to a network using the proposed enhancement and the EDF service discipline, no difference in terms of throughput was found. With respect to an RT-MAC network, any combination of enhancements either performed worse or were not different. One exception was the ECA/EDF network which had a higher throughput than RT-MAC. By inspecting the mean throughput, however, it can be seen that the performance advantage was not exceptional (0.6977 vs. 0.6918).

Enhancements Enabled	IEEE 802.11	Enhancement w/EDF	RT-MAC
TC/ECA/EDF	B	—	N
ECA/EDF	B	—	B*
TC/EDF	B	—	W*
TC/ECA (RT-MAC)	B	N	—
TC	B	N*	W*
EDF	N	—	W
ECA	B	N	N
NONE (IEEE 802.11)	—	N	W

Reference Network

Legend
With respect to Reference Network

- B Better
- N Not Different
- W Worse
- * Determined by t-test
- TC Transmission Control
- ECA Enhanced Collision Avoidance
- EDF Earliest-Deadline-First
- — Not Applicable

Figure 6.65: RT-MAC Enhancements Study Throughput Performance Comparison

6.4.1.2 Mean Delay

Mean delay performance is shown in Figure 6.66. As with throughput, any combination of the proposed enhancements performed better than IEEE 802.11 in terms of mean delay except for EDF which was not different. When compared to a network using the proposed enhancement and the EDF service discipline, no difference in terms of mean delay was found. For an RT-MAC network, the results varied. The TC/EDF and the TC network were better than RT-MAC. All others were either not different or worse. Thus far, then, we see that the EDF service discipline does not provide any advantage with respect to throughput or mean delay. Given that EDF is only a reordering of packets, this is not unexpected. Note also that the TC algorithm alone (or with EDF) provides a better mean delay than RT-MAC. This too could have been predicted given that the ECA algorithm works by delaying pending transmissions. Evidently, the resulting increase in collisions is not of such a magnitude that it greatly affects the mean delay.

6.4.1.3 Missed Deadline

Missed deadline performance is shown in Figure 6.67. Again, any combination of the proposed enhancements performed better than IEEE 802.11 in terms of missed deadline except for EDF which was worse. This worse performance of EDF may be due to the retransmission scheme of IEEE 802.11. With a FCFS discipline, a packet with a deadline far in the future might possibly meet its deadline even when retransmitted. And while packets behind it may be late due to this, the currently transmitted packet, at least, was on time. With a EDF discipline, it is conceivable that the packet being retransmitting (say, Packet A) has already missed its deadline and during the retransmission Packet B (whose deadline is next) also misses its deadline. When Packet B is being transmitted, it may cause the next packet to miss its deadline and so on. Since the packets are in an EDF order, it may be a while before a packet that has not missed its deadline is reached. Therefore, a purely EDF service discipline may be a disadvantage in a multiple access network. Obviously, the preceding

Enhancements Enabled	IEEE 802.11	Enhancement w/EDF	RT-MAC
TC/ECA/EDF	B	—	N
ECA/EDF	B	—	W
TC/EDF	B	—	B
TC/ECA (RT-MAC)	B	N	—
TC	B	N	B
EDF	N	—	W
ECA	B	N	W
NONE (IEEE 802.11)	—	N	W

Reference Network

Legend
With respect to Reference Network

B	Better
N	Not Different
W	Worse
*	Determined by t-test
TC	Transmission Control
ECA	Enhanced Collision Avoidance
EDF	Earliest-Deadline-First
—	Not Applicable

Figure 6.66: RT-MAC Enhancements Study Mean Delay Performance Comparison

conjecture needs to be studied further before a firm conclusion on the observed behavior can be reached.

The RT-MAC network was better than all of the combinations except for the RT-MAC network with EDF (i.e., TC/ECA/EDF). As with the throughput metric, the magnitude of this improvement was not exceptional (0.0062 vs. 0.0068).

6.4.1.4 Collisions

Figure 6.68 shows the collision performance. Any combination of the proposed enhancements performed better than IEEE 802.11 except for EDF. Given that EDF only involves a reordering of the packets, it is not clear why EDF performance was worse in this area. With respect to an EDF service discipline, performance was either not different or in the case of a TC, performance was worse. The RT-MAC network was better than all of the combinations or in the case of ECA/EDF and TC/ECA/EDF, RT-MAC was not different.

6.4.1.5 Summary

Based on the above results, the EDF service discipline was not included in RT-MAC in favor of a FCFS discipline. There were several reasons for this. First, on each station in the network, a single application is assumed to be providing the entire offered load. Most applications require either an in-order delivery or a reordering on the receiving station. Second, the performance advantage gained by using the EDF service discipline was only evident in the missed deadline case—and it was not an exceptional improvement. Third, FCFS is easier to realize in an actual implementation.

This being said, it still remains to be determined whether a significant performance improvement in terms of missed deadlines could be achieved by using a service discipline other than FCFS for stations with *multiple* applications. In this scenario, the relative ordering of the packets within an particular application would remain the same, but one application might

Enhancements Enabled	IEEE 802.11	Enhancement w/EDF	RT-MAC
TC/ECA/EDF	B	—	B
ECA/EDF	B	—	W
TC/EDF	B	—	W
TC/ECA (RT-MAC)	B	W	—
TC	B	W	W
EDF	W	—	W
ECA	B	W	W
NONE (IEEE 802.11)	—	B	W

Reference Network

Legend
With respect to Reference Network

- B Better
- N Not Different
- W Worse
- * Determined by t-test
- TC Transmission Control
- ECA Enhanced Collision Avoidance
- EDF Earliest-Deadline-First
- — Not Applicable

Figure 6.67: RT-MAC Enhancements Study Missed Deadline Performance Comparison

Enhancements Enabled	IEEE 802.11	Enhancement w/EDF	RT-MAC
TC/ECA/EDF	B	—	N
ECA/EDF	B	—	N
TC/EDF	B	—	W
TC/ECA (RT-MAC)	B	N	—
TC	B	W	W
EDF	W	—	W
ECA	B	N*	W
NONE (IEEE 802.11)	—	B	W

Reference Network

Legend
With respect to Reference Network

- B — Better
- N — Not Different
- W — Worse
- * — Determined by *t*-test
- TC — Transmission Control
- ECA — Enhanced Collision Avoidance
- EDF — Earliest-Deadline-First
- — — Not Applicable

Figure 6.68: RT-MAC Enhancements Study Collision Performance Comparison

get priority service over another application because it meets the service discipline criteria (i.e., earliest deadline, shortest job, etc.). In Section 6.4.3, different service disciplines were studied for stations running a *single* application where out of order delivery was permitted. Stations with multiple applications which require in-order delivery is left for future study.

Given that FCFS has been adopted, we conclude that the combination of TC and ECA provides the best overall performance. Further, TC and ECA do not interfere with each other, rather, in all areas except mean delay, they perform better in when used together. The reason why mean delay performance is worse is probably due to the static contention window expansion used in the ECA algorithm. The static CW has been discussed above in Sections 6.1 and 6.2. It will be explored further in Section 6.4.4.

6.4.2 Contention Window Expansion Study

As discussed in Section 5.2, the enhanced collision algorithm (ECA) has two components: (1) a expansion of the contention window (CW), and (2) transmitting a station's next backoff value. The purpose of this study was to establish that both components contributed to a reduction in collisions. This is similar in purpose to the study in Section 6.4.1. For this study, the network employed uses an ideal channel with the telemetry traffic model and $N = 10, 50; G = 0.7$. This network was chosen since it would have a large number of collisions. Since the contention window expansion is a function of N, two values of N were selected to observe the behavior for a small and a large station network. The contention window is also a function of the channel data rate and therefore the simulations were performed for both a 1 and 10 Mbps data rate.

Figure 6.69 shows the collision ratios for a 10 and 50 station network with CW expansion only and CW expansion in addition to transmitting the next backoff value for the 1 Mbps channel. For reference, the IEEE 802.11 values are also shown. The results and statistical analysis clearly show that both the CW expansion and transmission of a station's next backoff values contribute to the collision reduction. The results for the 10 Mbps channel were statistically

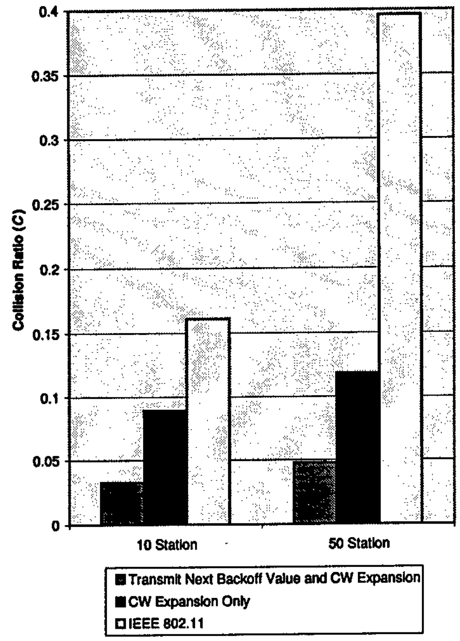


Figure 6.69: Contention Window Study Results - Collision Ratio

not different when compared to the 1 Mbps channel and therefore the same conclusion holds for the 10 Mbps channel collision ratios as well.

6.4.3 Service Disciplines Study

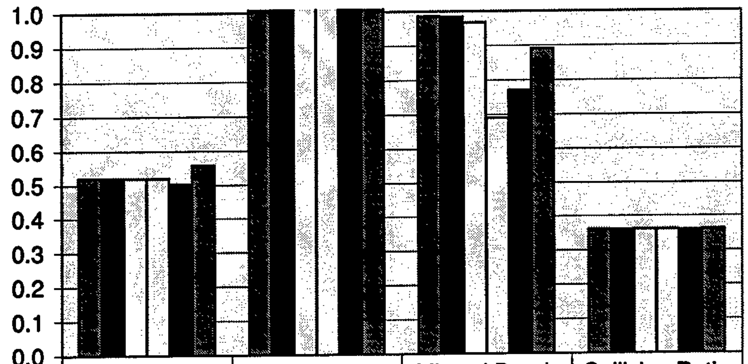
As discussed in Section 6.4.1.5, the purpose of this study was to determine the effect of different service disciplines for stations transmitting data from a *single* application where out-of-order delivery was permitted. The service disciplines used were: earliest-deadline-first (EDF), first-come-first-served (FCFS), random, last-come-first-served (LCFS), shortest-job-first (SJF), and longest-job-first (LJF). The network parameters used in this study are the same as the IEEE 802.11 avionics traffic model using an ideal channel (cf., Table 4.4) with the following exceptions: $N = 40, G = 0.95$, 0% of late packets were resubmitted for later transmission, and the packet size was drawn from a geometric distribution with a mean of 775 bytes. The packet size was varied so that the SJF and LJF service discipline could be studied and a high offered load was chosen to help ensure the stations transmission buffers always had packets to transmit.

Figure 6.70 shows the mean results of the simulations. Note that the y-axis stops at 1.0. Since all the mean delays were greater than 1.0, refer to the table below the graph for those values. As would be expected, there were no significant differences in the collision ratio for the different service disciplines. Throughput was generally no different except that it was better for a LJF discipline and worse for a SJF discipline. This is because if a packet is transmitted successfully, the longer packets would tend to result in a higher throughput due to the lower overhead. Conversely, short packets have a higher overhead.

The best performance in terms of mean delay and missed deadlines is clearly LCFS with SJF being next. In terms of missed deadlines only, LJF was next in terms of performance. Interestingly, for this network EDF was statistically worse than any other service discipline in terms of missed deadlines. Thus, our initial premise that an EDF service discipline would reduce the number of missed deadlines (cf., Section 4.1.1) is not supported by this data. Therefore, while it has long been known that the EDF service discipline is optimal with respect to meeting *computing* deadlines [LL73], this does not seem to hold with multiple access communications systems. We speculate that this is because with computing tasks, the computer system will always successfully perform the computation (though not necessarily on time), while in a multiple access communication system, the "task" (i.e., packet transmission) may need to be repeated due to failures from collisions or bit errors. Further, these errors can greatly reduce the utilization of the transmission channel which further degrades the ability of the communication system to meet deadlines.

6.4.4 Networks with RT-MAC and IEEE 802.11 Stations

The purpose of this study was to investigate how RT-MAC performs within mixed networks; those with both RT-MAC and IEEE 802.11 stations. In this study, the telemetry and avionics traffic models were used (cf., Table 4.4). Each simulation looked at six different network configurations: (1) a network with 100% RT-MAC stations, (2) a 20/80% IEEE 802.11/RT-



	Normalized Throughput (S)	Mean Delay (sec) (D)	Missed Dead-line Ratio (F)	Collision Ratio (C)
EDF	0.520	32.164	0.985	0.361
FCFS	0.519	31.749	0.984	0.361
Random	0.518	25.506	0.967	0.362
LCFS	0.518	3.172	0.690	0.362
SJF	0.503	6.587	0.771	0.359
LJF	0.557	26.495	0.890	0.363

Figure 6.70: Service Disciplines Study Results

MAC station network, (3) a 40/60% IEEE 802.11/RT-MAC station network, (4) a 60/40% IEEE 802.11/RT-MAC station network, (5) a 80/20% IEEE 802.11/RT-MAC station network, and (6) a 100% IEEE 802.11 station network. These configurations were chosen on the supposition that there may be a point where RT-MAC provided no useful benefit due to a large proportion of IEEE 802.11 stations. The data (including confidence intervals) upon which the following figures were based may be found in Section B.4.

6.4.4.1 Telemetry Traffic Model

Recall that the telemetry traffic model was used to stress the network due to the high overhead that it induced (Section 6.1). Using this traffic model, offered loads of $G = 0.3, 0.9$ (with $N = 20$) were simulated to see if the amount of traffic on the channel might also be a factor which affects performance. Figure 6.71 shows the results of the simulation for $G = 0.9$. In the figure, the four performance metrics are shown: throughput, mean delay, missed deadline ratio, and collision ratio. For reference, the left-most side of a graph shows

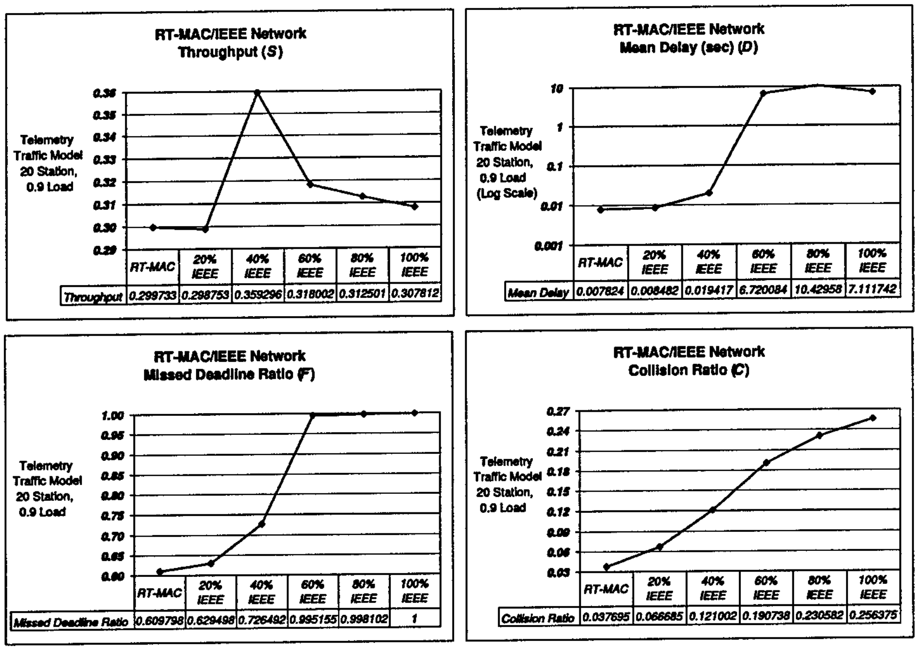


Figure 6.71: Mixed RT-MAC/IEEE 802.11 Network, $G = 0.9$

the 100% RT-MAC network performance while the right-most side of a graph shows the 100% IEEE 802.11 network performance. In the cases of throughput, mean delay and missed deadline ratios, the 40/60% network is the point at which the benefit provided by RT-MAC is overcome by the population of IEEE 802.11 stations. Significantly though, in terms of collisions, RT-MAC reduced collisions even when the mix was as high as 80/20%. The large increase in throughput at the 40/60% point is due to the IEEE 802.11 stations using a CW range of [0-31] for their BVs while the RT-MAC stations are using a CW range of [0-159]. Thus, the channel is being utilized more often by the IEEE 802.11 stations. Beyond this point, the throughput decreases due to an increase in collisions.

The same network was tested with $G = 0.3$. Using this load, even the IEEE 802.11 network was able to meet almost all deadlines. Figure 6.72 shows the results of this simulation. As before, the four performance metrics are shown. The conclusion to draw from these graphs is that even with a low offered load, using RT-MAC shows an improvement in the performance metrics. Further, the degradation in the performance metrics as the ratio of IEEE 802.11

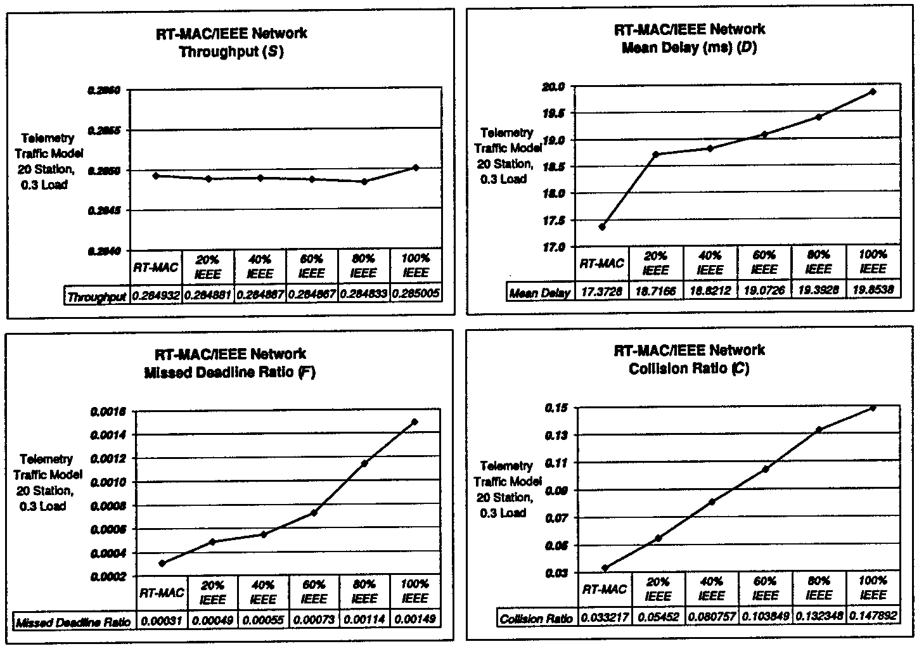


Figure 6.72: Mixed RT-MAC/IEEE 802.11 Network, $G = 0.3$

stations increase is quite linear. So virtually any amount of RT-MAC stations in the network provides a benefit.

6.4.4.2 Avionics Traffic Model

As a further test for mixed networks the avionics traffic model was used with $G = 0.9$ and $N = 40$. Those results are shown below in Figure 6.73. The same observations made about the simulations using the telemetry traffic model above can be made here. Note that with the avionics model, though, the network does not begin to degrade significantly until the percentage of IEEE 802.11 stations is 60%. Note also that the mean delay actually improved as IEEE 802.11 stations were added. Further, the missed deadline ratio improved slightly as well. These improvements are most likely due to the CW expansion in RT-MAC (cf., Section 5.2). For this size network, the initial IEEE 802.11 CW ranges from [0-31], where the initial CW for an RT-MAC station ranges from [0-319]. This expanded CW would likely lead to a longer delay for packets. To confirm this, the same load and traffic model were

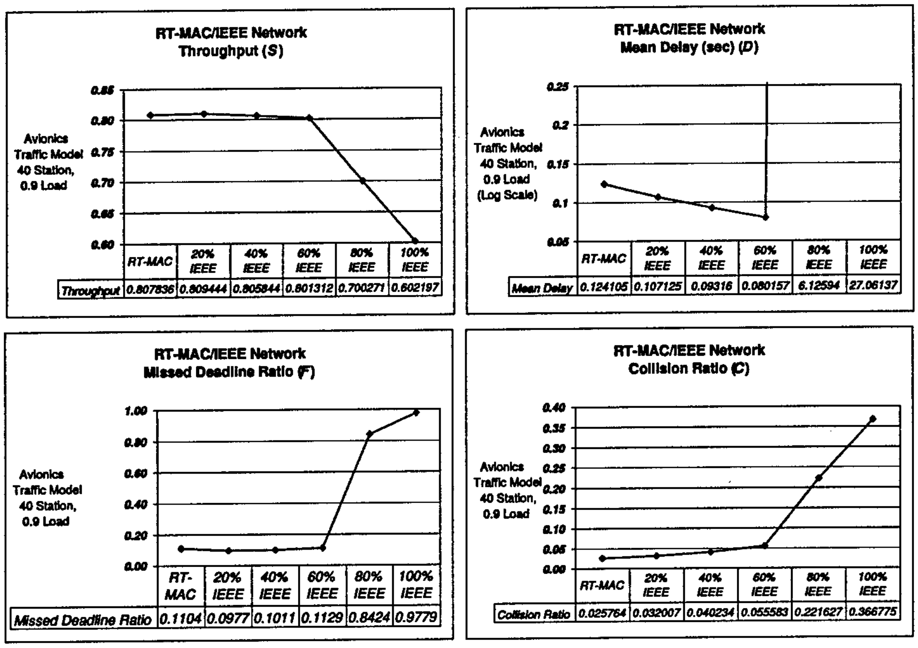


Figure 6.73: Mixed RT-MAC/IEEE 802.11 Network, Avionics Traffic Model

simulated with $N = 5$. Using this network, the RT-MAC CW would be [0-39], very close to the IEEE 802.11 CW of [0-31].

Figure 6.74 seems to confirm this. Note that the magnitude of the slope of the mean delay, while still negative (i.e., improving), is less than before. The missed deadline ratio slope has changed from a slightly negative slope, indicating better performance as IEEE 802.11 stations are added, to a positive slope, indicating worse performance as IEEE 802.11 stations are added.

These simulation results also highlight that the static initial CW expansion algorithm used is less than optimum. That is, the initial CW value used, $(2 + \lfloor\frac{6}{\sqrt{R}}\rfloor)\hat{N}$, should likely be changed to a dynamically varying CW depending on the number of stations as well as the load (e.g., [BFO96]). Further indications that the fixed initial CW expansion fails to provide optimum performance can be seen in Section 6.3.2 above where the channel data rate is increased to 10 Mbps.

Overall, however, these simulations show that RT-MAC is very robust. It will improve most

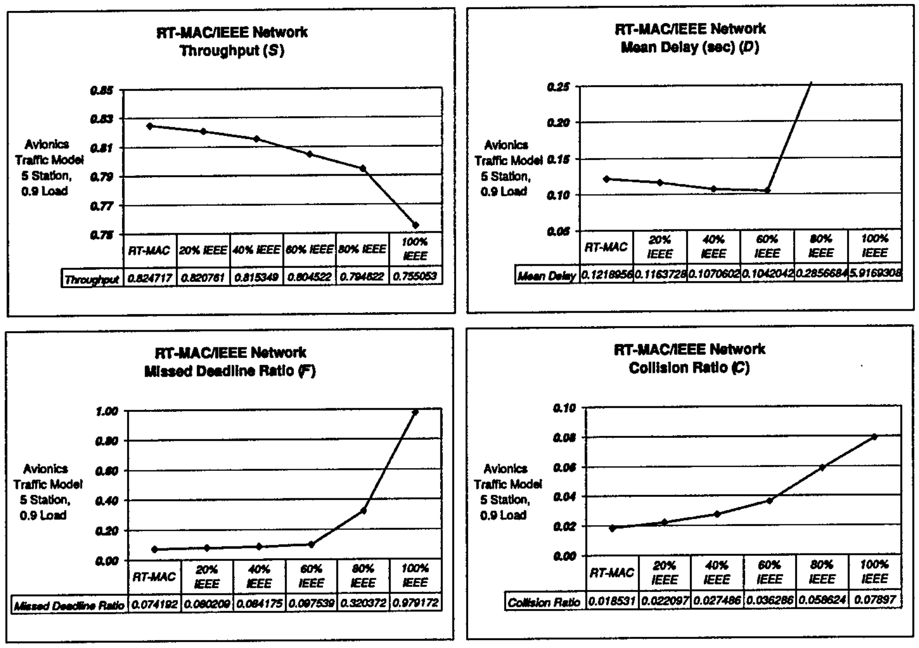
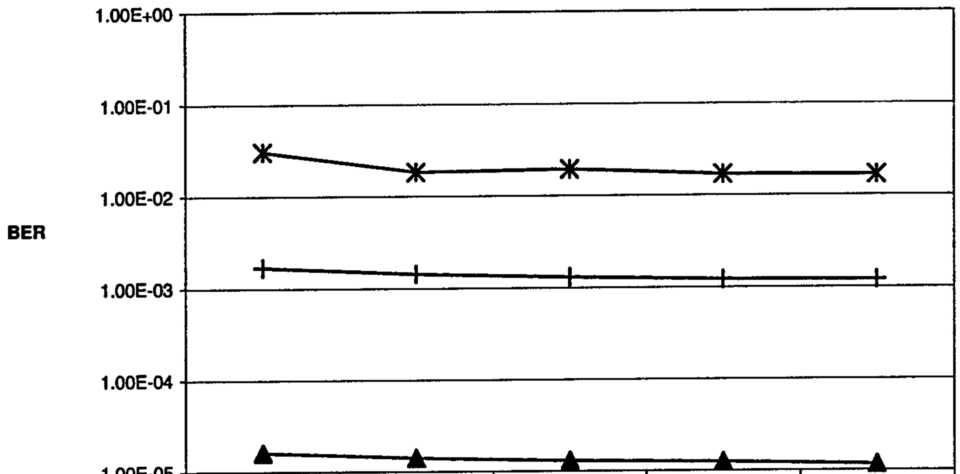


Figure 6.74: Mixed RT-MAC/IEEE 802.11 Network, Avionics Traffic Model, 5 Stations

performance metrics even when a significant portion of the network is not using the RT-MAC protocol.

6.4.5 Static BER Study

The purpose of this study was to observe how a network performs in a static BER environment as well provide a basis of comparison (however informal) between static and bursty BER models. In this study, the voice with non real-time data traffic model (cf., Section 6.3) with $N = 14, G_{NRT} = 0.0, 0.2, 0.4, 0.6, 0.8$ and a 1 Mbps data rate is used. Three channel error models were investigated: (a) a static model with BER 1×10^{-5}, (b) a static model with BER 1×10^{-3}, and (c) the bursty error model (cf., Section 4.5.3). Simulations were run for both the IEEE 802.11 and RT-MAC networks. While there were differences between the IEEE 802.11 and RT-MAC networks performance, the effect of the different error models on the networks was similar. Therefore, for the sake of clarity in discussion and the figures, only the results of the RT-MAC simulations will be presented. Simulation data for both



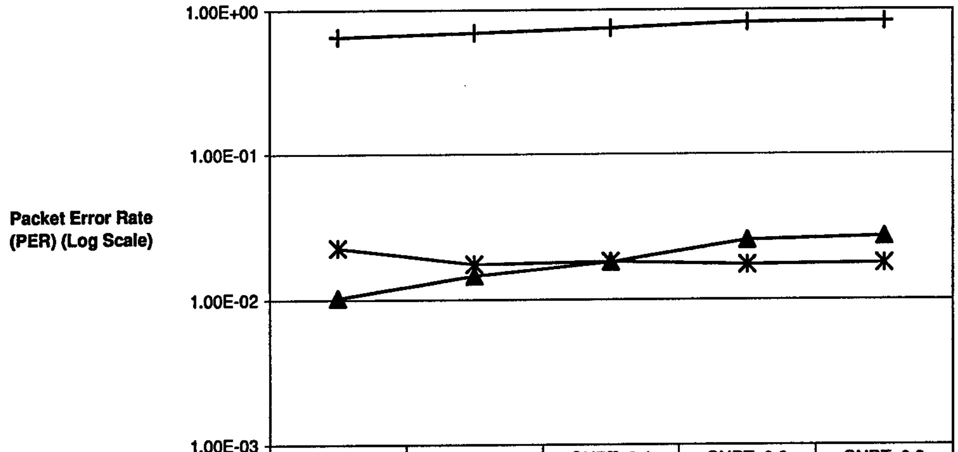
	GNRT=0.0	GNRT=0.2	GNRT=0.4	GNRT=0.6	GNRT=0.8
BER=1E-3	1.68E-03	1.42E-03	1.28E-03	1.20E-03	1.19E-03
BER=1E-5	1.62E-05	1.40E-05	1.30E-05	1.24E-05	1.16E-05
Bursty	3.05E-02	1.84E-02	1.93E-02	1.68E-02	1.67E-02

Figure 6.75: Static BERs

RT-MAC and IEEE 802.11 networks can be found in Appendix B.

Figure 6.75 shows the BERs for the three different error models. The largest BER in terms of magnitude is the bursty error model. This model is described in Sections 2.3.2 and 4.5.3. While Figure 6.75 shows the raw BER, it is the packet error rate (PER) which has a larger influence on the performance of the network. This is because whether there is a single bit error in a packet or one hundred, the packet is discarded. The PER of the three different error models are shown in Figure 6.76. Note the similarity in PERs for the 1×10^{-5} model and the bursty model. This similarity will be seen to carry over to the different performance metrics as well.

Figures 6.77–6.80 show the throughput, mean delay, missed deadline ratio, and collision ratio performance metrics for the three different error models. In terms of throughput and missed deadlines performance, the 1×10^{-3} model is clearly the worst as would be expected. In terms of mean delay and collision, however, it often performs better than the other two models. This is easily explained by the way in which these performance metrics are counted. Mean delay is determined by the aggregate delay of *successfully* transmitted packets. Packets



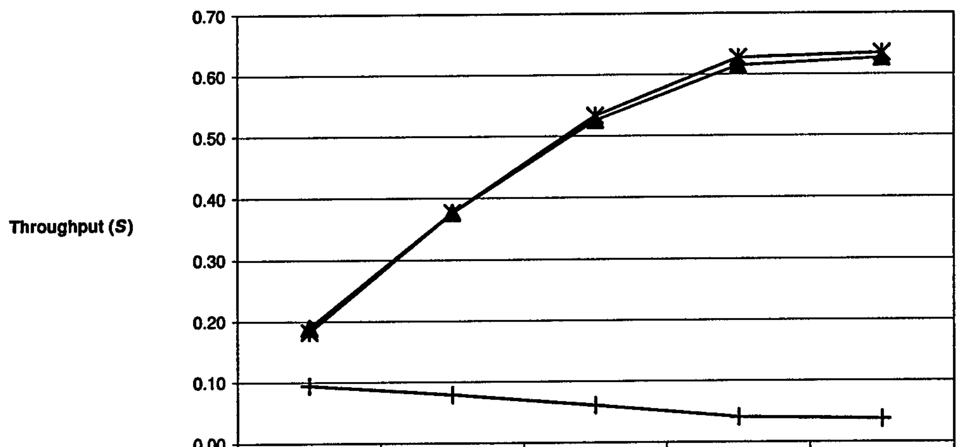
	GNRT=0.0	GNRT=0.2	GNRT=0.4	GNRT=0.6	GNRT=0.8
BER=1E-3	6.51E-01	6.97E-01	7.52E-01	8.23E-01	8.37E-01
BER=1E-5	1.02E-02	1.45E-02	1.80E-02	2.54E-02	2.68E-02
Bursty	2.25E-02	1.74E-02	1.81E-02	1.73E-02	1.77E-02

Figure 6.76: Static BER, Packet Error Rate

that are *never* successfully transmitted due to errors do not contribute to mean delay since their delay is infinite. The performance in terms of the collision ratio is similar (though the 1×10^{-3} model is statistically better in most cases). This is due to the transmission control algorithm in RT-MAC which discards late packets rather than transmit them. Since many of the packets in a high BER environment will need to be retransmitted, it is probable that many will be discarded due to a missed deadline rather than retransmitted.

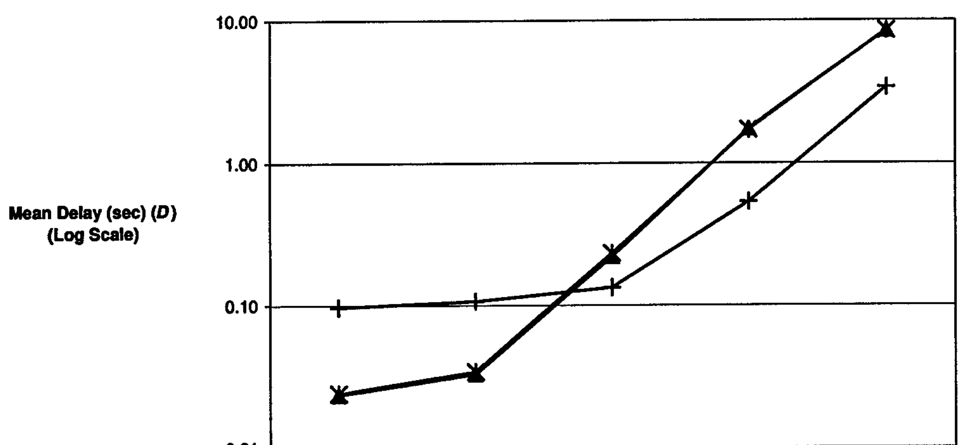
More interesting is the almost identical performance of the 1×10^{-5} model and the bursty error model across all performance metrics. The data seems to indicate that the bursty error model and the static model are almost identical *in terms of the measured metrics.* If, however, the error models were compared on the basis of metrics that were not measured such as mean queue length, channel access delay, transmission queue throughput and others, differences would undoubtedly be manifest. With respect to simulation efficiency, the bursty error model is more desirable since large blocks of error-free periods occur where error calculations do not need to be made, thus reducing simulation time.

In light of these simulations, therefore, we conclude that: (1) RT-MAC performance in a



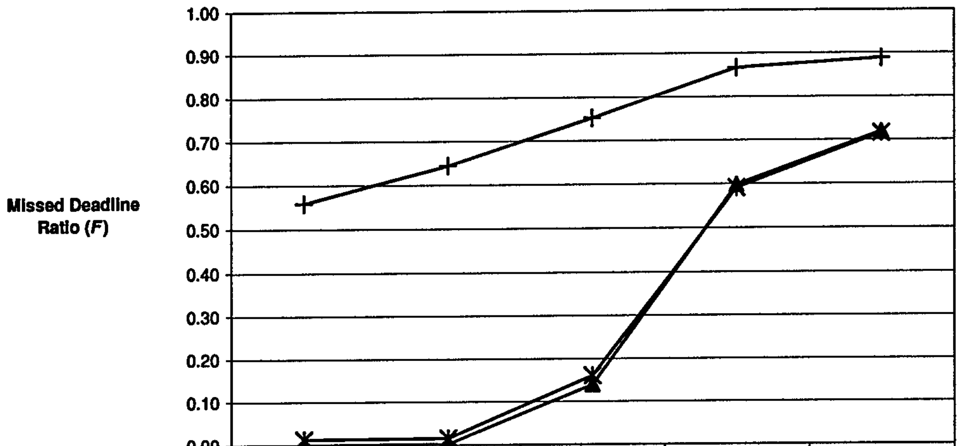
	GNRT=0.0	GNRT=0.2	GNRT=0.4	GNRT=0.6	GNRT=0.8
BER=1E-3	0.0944	0.0787	0.0609	0.0408	0.0375
BER=1E-5	0.1887	0.3770	0.5264	0.6153	0.6271
Bursty	0.1819	0.3770	0.5339	0.6275	0.6351

Figure 6.77: Static BER, Throughput



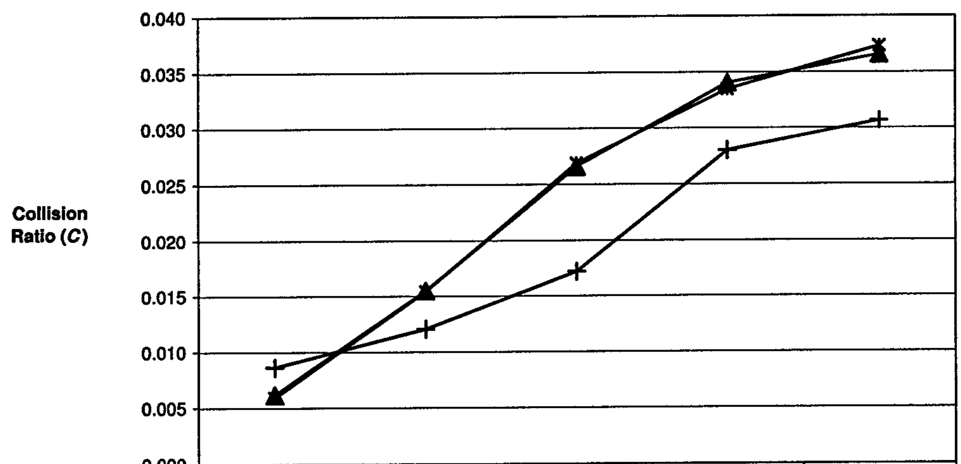
	GNRT=0.0	GNRT=0.2	GNRT=0.4	GNRT=0.6	GNRT=0.8
BER=1E-3	0.10	0.11	0.13	0.54	3.39
BER=1E-5	0.02	0.03	0.22	1.75	8.45
Bursty	0.02	0.03	0.23	1.71	8.48

Figure 6.78: Static BER, Mean Delay



	GNRT=0.0	GNRT=0.2	GNRT=0.4	GNRT=0.6	GNRT=0.8
BER=1E-3	0.559	0.644	0.752	0.867	0.889
BER=1E-5	0.000	0.002	0.139	0.598	0.719
Bursty	0.013	0.015	0.160	0.592	0.716

Figure 6.79: Static BER, Missed Deadline Ratio



	GNRT=0.0	GNRT=0.2	GNRT=0.4	GNRT=0.6	GNRT=0.8
BER=1E-3	0.009	0.012	0.017	0.028	0.031
BER=1E-5	0.006	0.015	0.027	0.034	0.037
Bursty	0.006	0.015	0.027	0.033	0.037

Figure 6.80: Static BER, Collision Ratio

static BER environment is comparable to that in an equivalent bursty error environment, and (2) the bursty error model is roughly analogous *in its effect* to a static BER of 1×10^{-5} with respect to the performance metrics being measured. Namely, throughput, mean delay, missed deadline ratio, and collision ratio.

6.4.5.1 10 Mbps Maximum Capacity Study

In Section 6.3.1.7, it was determined that the 1 Mbps data rate was a factor limiting the effectiveness of RT-MAC with voice traffic. In Section 6.3.2, a 10 Mbps data rate was investigated but the time required to run the 400 simulations prevented the determination of a maximum number of stations that could be supported. However, since the 10 Mbps data rate effectively removed the only known limiting factor with regard to RT-MAC performance, it became interesting to consider the maximum number of stations that could be supported by an RT-MAC network.

In Section 6.3.1.7, we derived a theoretic maximum of $N = 282$ at 10 Mbps to justify investigating a higher data rate channel. However, the simplifying assumptions used in that analysis left the actual performance of a 10 Mbps channel using RT-MAC or IEEE 802.11 an open question. Therefore, further simulations were performed to determine the maximum number of voice stations that could be supported. Due to the increasingly large amount of simulation time required to study these larger networks, multiple replications were not performed. Therefore, the results presented below should be considered preliminary or indicative in nature.

In this study, we continue to use the criteria that $F \leq 0.10$ constitutes usable voice quality. The maximum number of stations that could be supported was found to be (for $G_{NRT} = 0.0$) $130 \leq N < 140$ for both an RT-MAC and an IEEE 802.11 network. That is, at $N = 130, F \leq 0.10$ and at $N = 140, F > 0.10$. Having found the maximum N, we set $G_{NRT} = 0.2$ and found that the failure ratio was greater than 0.10 for both RT-MAC and IEEE 802.11. Table 6.1 summarizes the performance metrics of this study.

Performance Metric	$N = 130, G_{NRT} = 0.0$ RT-MAC	$N = 130, G_{NRT} = 0.0$ IEEE 802.11	$N = 130, G_{NRT} = 0.2$ RT-MAC	$N = 130, G_{NRT} = 0.2$ IEEE 802.11	$N = 140, G_{NRT} = 0.0$ RT-MAC	$N = 140, G_{NRT} = 0.0$ IEEE 802.11
Throughput (S)	1.21E-01	1.32E-01	2.16E-01	1.36E-01	1.22E-01	1.26E-01
Mean Delay (D)	5.57E-02	2.15E-02	2.23E-01	3.17E+00	6.91E-02	7.35E-01
Failure Ratio (F)	5.39E-02	4.74E-02	4.01E-01	9.80E-01	1.36E-01	7.97E-01
Collision Ratio (C)	7.44E-02	8.58E-02	8.72E-02	5.64E-01	7.53E-02	5.07E-01

Table 6.1: Maximum Capacity Study Results

The data in the table indicates that while RT-MAC in most cases improves performance metrics, since F must be less than 0.10 to be useful, the improvement is of no benefit. For the case $N = 130, G_{NRT} = 0.0$, F is slightly higher for RT-MAC due to the increased delay caused by contention window expansion (cf., Section 5.2). For $N = 130, G_{NRT} = 0.2$ and $N = 140, G_{NRT} = 0.0$ F is reduced from 0.98 to 0.40 and 0.80 to 0.14 respectively. We note that the collision reduction algorithm is still quite effective at reducing collisions. Further, no packets were lost due to a full transmission queue. Therefore, the ability of the channel to support more voice traffic using either the RT-MAC or IEEE 802.11 protocol has simply been reached. This limit is probably close to the maximum number of stations that could be support using any random access MAC algorithm. To approach the theoretical limit of $N = 282$ discussed above, some type of scheduled access to the channel will need to be employed.

6.5 Summary

In this chapter, RT-MAC performance was compared to IEEE 802.11 for several different traffic models. Other simulations to investigate particular aspects of RT-MAC performance were performed. In Section 6.1, RT-MAC performance was investigated using a telemetry traffic model. Using the telemetry model, RT-MAC outperformed IEEE 802.11 in almost every area. Section 6.2, used an avionics traffic model to test RT-MAC. At higher data loads, RT-MAC outperformed IEEE 802.11 in every performance metric. Section 6.3 addresses the application of packetized voice data with increasing levels of non real-time data. It was found that while RT-MAC performed better in many instances, the channel data rate seemed to be a limiting factor. Therefore, a 10 Mbps channel was also investigated. Using the 10 Mbps channel, RT-MAC was able to transmit significantly more non real-time data than IEEE 802.11 while still meeting the performance requirements of the voice data. Section 6.4 explores other aspects of RT-MAC such as how different components of the RT-MAC algorithm performs individually, how RT-MAC performs in mixed RT-MAC/IEEE 802.11 networks, and performance under a static BER model along with several other simulation studies. It was found that RT-MAC is quite robust—scoring performance improvements even when up to 60% of the stations in the network were not RT-MAC stations. Further, RT-MAC performed equally well in a static and bursty BER environment. Overall, it was demonstrated that RT-MAC significantly improves the real-time performance of wireless networks.

Chapter 7

Regression Models

In this chapter, the regression models developed from the simulation data are presented. Section 7.1 discusses the assumptions that must be satisfied for the linear regression to be valid. Section 7.2 presents the regression models themselves. In Section 7.3, the models are used to predict the behavior of networks using factors not previously simulated. These predictions are then compared with simulations of the same network. Section 7.4 summarizes the results presented in this chapter.

7.1 Linear Regression Assumptions

The models described in this chapter were developed using linear regression. This type of regression is probably the most common regression performed in data analysis. A complete description of it can be found in most texts on statistics or regression analysis including [Jai91], [All90], and [DS81]. Linear regressions make several assumptions which must be satisfied in order for the regression model to be valid. They are [Jai91]: (1) the true relationship between the response variable (e.g., throughput) and the predictor variables (e.g., offered load, stations) are linear, (2) the predictor variables are not stochastic and are specified without error, (3) model errors are statistically independent, and (4) errors are normally distributed.

Each of the regression models presented in this chapter were tested against the assumptions listed above. In some cases, the relationship between the response variable and the predictor variables was not linear. In these cases, a suitable transformation of the response variable was performed in order to make the response as linear as possible. The requirement for non-stochastic predictor values was satisfied due to the nature of the predictors. That is, the number of stations, N, the offered load, G, and the channel model, bursty or ideal, can all be specified exactly.

To verify that model errors were statistically independent, a visual test was employed. In this visual test, a scatter plot of the predicted response (i.e., the regression model) versus the residuals (i.e., errors) should contain no visible trends. Figure 7.1 shows an example of this. The figure shows the scatter plot for the IEEE 802.11 (telemetry traffic) throughput regression model predicted response and residuals. Data points are vertically stacked due to the five replications of each experiment. No trends are evident in the figure.

To verify that errors are normally distributed, a quantile-quantile plot of model error versus the normal quantile is constructed for each model. If the normality assumption holds, a quantile-quantile plot should be quite linear. If the assumption does not hold, this means that the residuals contain some systematic effect not accounted for by the model. Figure 7.2 shows the quantile-quantile plot for the IEEE 802.11 (telemetry traffic) throughput model. It is quite linear. The solid line drawn through the data points is itself a regression line to determine just how linear the data points are. The high R^2 value indicates that the assumption of normality is verified.

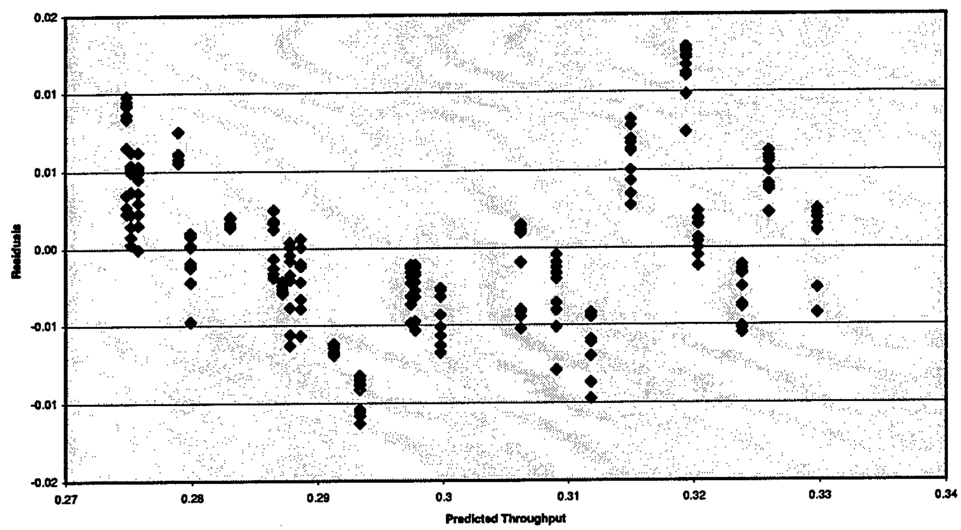


Figure 7.1: Residuals versus Predicted Response for IEEE 802.11 Telemetry Throughput Model

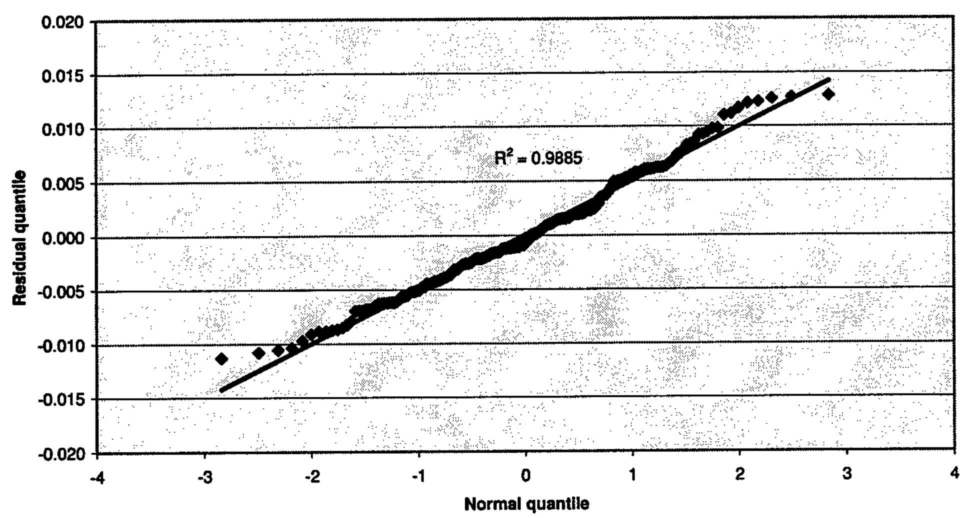


Figure 7.2: Normal Quantile-Quantile Plot for Residuals of IEEE 802.11 Telemetry Throughput Data

7.2 Regression Model Tables and Figures

Tables 7.1–7.4 were constructed, in part, from the output of SAS [SAS] (cf., Appendix C). The tables contain the following items: the regression model itself, the model R^2 value, the R^2 value of the quantile-quantile plot, and the 90% confidence intervals for the mean predicted response for m future experiments. The confidence interval used herein is given by [DS81], [Jai91] as $\hat{y} \mp t_{[0.95;120]} s_{\hat{y}_m}$ where $\hat{y}$ is the mean response, $t_{[0.95;120]}$ is the t-value, and $s_{\hat{y}_m}$ is the standard deviation of the sample mean for m experiments. This standard deviation is

$$s_{\hat{y}_m} = s_e \left(\frac{1}{n_{eff}} + \frac{1}{m} \right)^{\frac{1}{2}} \tag{7.1}$$

where s_e is the standard deviation of model error, n_{eff} is the effective number of degrees of freedom in the model, and m is the number of future experiments performed. The term n_{eff} is given by [Jai91]

$$n_{eff} = \frac{\text{total number of simulation runs}}{\text{1+sum of DFs of parameters used in } \hat{y}}. \tag{7.2}$$

For the t-value, $t_{[p;n]}$, $n = 120$ is used, where n is the total number of simulation runs used in the model. In most cases, the value for n exceeds 120. However, the tables used for t-values only extend to $n = 120$ and then jump to $n = \infty$. Since the difference between the t-value for $n = 120$ and $n = \infty$ is small, $n = 120$ is used as an approximation when the number of simulation runs exceeds 120.

In the following tables, two transformations were utilized to help meet the assumptions of the linear regression: the power transformation and the arcsin transformation. The power transformation consists in raising the response variable, y, to a power, a, (i.e., y^a). This transformation was used for some IEEE 802.11 and RT-MAC delay models. In these models, the delays may range from 1×10^{-6} to 100.0 seconds. By applying the power transformation with $a = 0.05$ the range is reduced to $(1 \times 10^{-6})^{0.05} = 0.501$ to $(100.0)^{0.05} = 1.26$. This latter range is much easier to accurately build a model for than the former. After the regression model is constructed, the inverse transformation is performed on the model (i.e., the model is raised to the power $\frac{1}{a}$).

The arcsin transformation, $\arcsin(\sqrt{y})$, is used in some of the regression models that involve ratios such as missed deadlines and collisions. Since the data involves ratios that range from 0.0 to 1.0, the arcsin transformation helps to linearize the response variable. The inverse transformation is $\sin^2(y)$.

The channel simulation factor, E, is conspicuous in the regression models by its absence. Indeed, it appears in only a few of thirty-three models presented. It was found that, while statistically significant, the effect of an errored channel was usually masked by the effects of either G, N, or both in high load situations. With respect to mean delay, this can be attributed to two causes. First, the mean amount of time in which errors can occur is quite small compared to the error-free time (cf., Section 4.5.3). Second, especially in the case of the telemetry traffic model, the amount of data that must be retransmitted when an error does occur is relatively small and much of the time in the errored state is spent waiting for an acknowledgement. By the time the next transmission occurs, much of the time in the errored state has past. In low and medium load situations, E was found to significantly affect the missed deadline statistic, F.

Even though the simulation factor E does not appear in most models, it should not be concluded that bit errors do not have a discernible effect on network performance—the simulation data indicates they do. Rather, for the channel model employed, most of the regression models were influenced to a higher degree by the factors N and G.

7.2.1 Telemetry Traffic Model

Table 7.1 shows the regression models for the IEEE 802.11 and RT-MAC networks with telemetry traffic. Model R^2 is generally quite high (> 0.9), and the residual quantiles are linear. Following each regression model table are figures that show how the model behaves over the range of the predictor values. Figures 7.3–7.8 show the regression models behavior for throughput, mean delay, missed deadlines, and collisions for telemetry traffic respectively.

In Section 6.5 we stated that RT-MAC stabilized the behavior of the response variables. The regression models in this chapter support this claim. Note that RT-MAC models, in general, requires fewer terms and those terms have fewer $G^x N^y$ interactions than the corresponding IEEE 802.11 models. Specifically, observe that in Table 7.1, F_{RT} contains no N factor and C_{RT} has no G factor.

Table 7.1: Regression Model — Telemetry Traffic

Response Variable		Regression Model	Model R^2	Residual Quantile-Quantile R^2	90% Confidence Interval for Predicted Response for m Future Experiments		
					$m = 1$	$m = 10$	$m = \infty$
Throughput (IEEE 802.11)	$S_{80211} =$	$5.292 \times 10^{-3} G^3 N - 6.156 \times 10^{-3} G^2 N$ $-0.204 G^2 + 0.305 G + 0.222$	0.922	0.989	±8.47E-03	±2.91E-03	±1.21E-03
Throughput (RT-MAC)	$S_{RT} =$	$-2.215 \times 10^{-6} G N^3 + 1.782 \times 10^{-4} G N^2$ $-3.091 \times 10^{-3} G N + 1.394 G^3 - 2.821 G^2$ $+1.796 G - 0.0406$	0.910	0.996	± 9.81E-03	± 3.48E-03	± 1.65E-03
Delay (sec) (IEEE 802.11)	$D_{80211} =$	$(-5.005 \times 10^{-3} G^2 N + 2.810 \times 10^{-6} G N^3$ $-3.117 \times 10^{-4} G N^2 + 1.682 \times 10^{-2} G N$ $+4.870 G^3 - 10.187 G^2 + 6.866 G - 0.499)^{20}$	0.995	0.891	± 1.43E-02	± 5.14E-03	± 2.57E-03
Delay (sec) (RT-MAC)	$D_{RT} =$	$-8.048 \times 10^{-4} G N + 1.080 \times 10^{-3} N$ $+3.002 \times 10^{-4}$	0.996	0.940	± 1.12E-03	± 3.73E-04	± 1.24E-04
Missed Deadline Ratio (IEEE 802.11)	$F_{80211} =$	$\sin^2(27.574 G^3 - 58.055 G^2 + 39.670 G$ $+1.180 \times 10^{-6} N^3 - 2.625 \times 10^{-3} N$ $-7.186)$	0.989	0.833	± 1.07E-01	± 3.75E-02	± 1.68E-02
Missed Deadline Ratio (RT-MAC)	$F_{RT} =$	$-0.807 G^2 + 1.993 G - 0.521$	0.995	0.949	± 2.76E-02	± 9.19E-03	± 3.06E-03
Collision Ratio (IEEE 802.11)	$C_{80211} =$	$-0.437 G^2 + 0.628 G - 1.015 \times 10^{-4} N^2$ $+0.0126 N - 0.184$	0.978	0.970	± 2.97E-02	± 1.02E-02	± 4.25E-03
Collision Ratio (RT-MAC)	$C_{RT} =$	$5.445 \times 10^{-7} N^3 - 6.258 \times 10^{-5} N^2$ $+2.378 \times 10^{-3} N + 9.898 \times 10^{-3}$	0.905	0.993	± 4.10E-03	± 1.39E-03	± 5.24E-04

In Figure 7.3, the model predicts that throughput for IEEE 802.11 decreases as N increases.

In Figure 7.4 a curious cyclic behavior of the throughput for RT-MAC is observed. In Section 6.1.1 we proposed that this behavior was due to an interaction between the expansion of the contention window and the transmission control algorithm in RT-MAC.

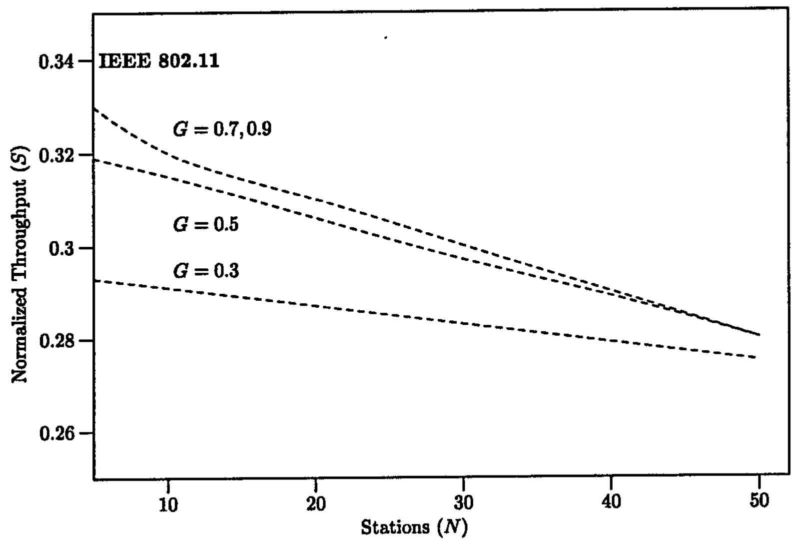


Figure 7.3: Normalized Throughput – Telemetry Traffic Model (1 of 2)

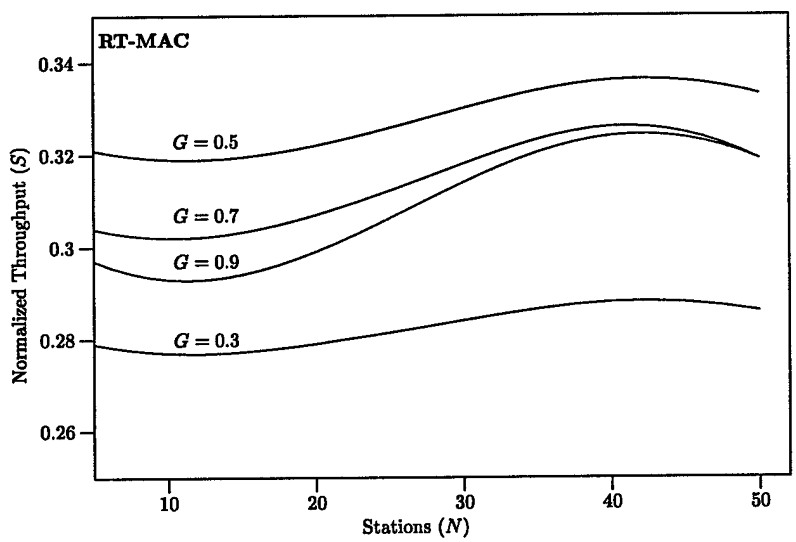


Figure 7.4: Normalized Throughput – Telemetry Traffic Model (2 of 2)

Figures 7.5 and 7.6 show the mean delay for the telemetry traffic model. The figures show that RT-MAC easily outperforms IEEE 802.11 in terms of mean delay. Figure 7.6 also shows that while RT-MAC mean delay increases with N, it decreases with G (cf., Section 6.1.2).

Figures 7.7 and 7.8 show the models for missed deadlines and collisions respectively. RT-MAC collision can be seen to be virtually independent of G and only slightly influenced by N.

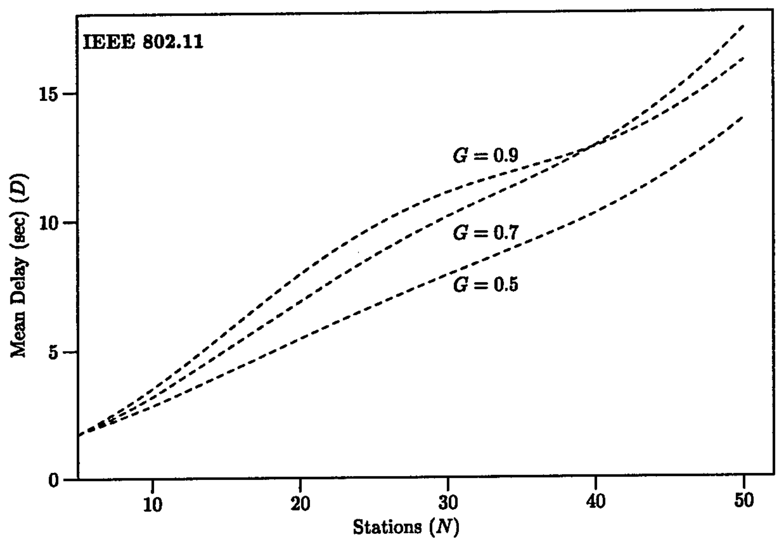


Figure 7.5: Mean Delay – Telemetry Traffic Model (1 of 2)

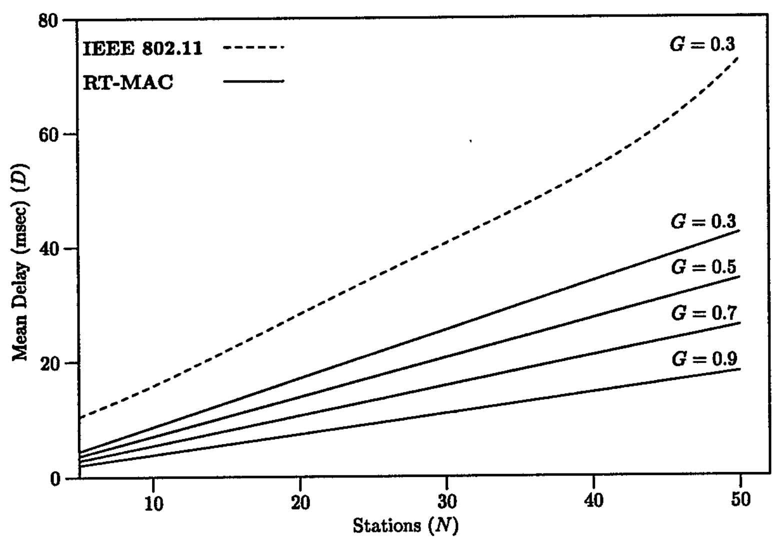


Figure 7.6: Mean Delay – Telemetry Traffic Model (2 of 2)

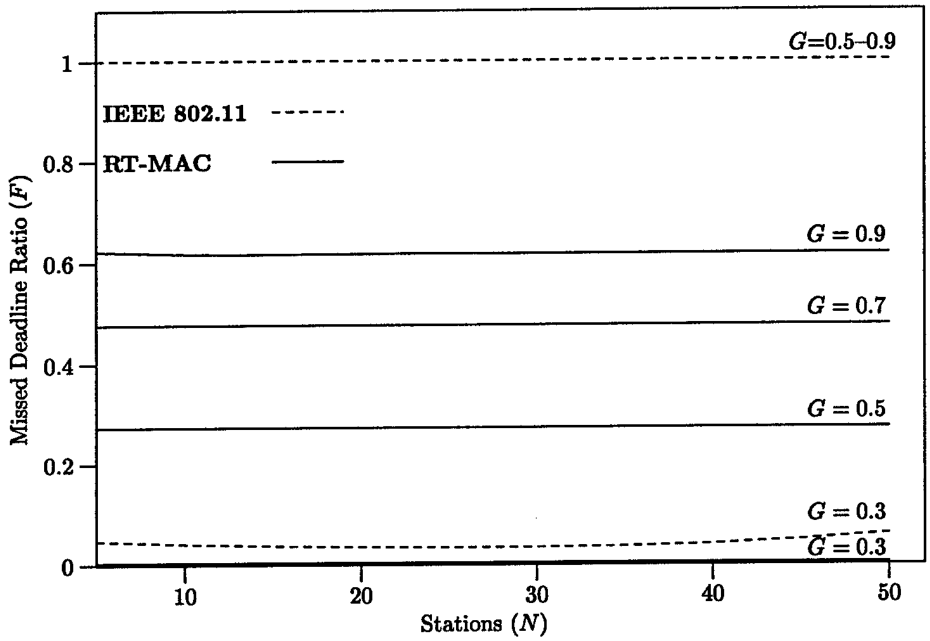


Figure 7.7: Missed Deadlines – Telemetry Traffic Model

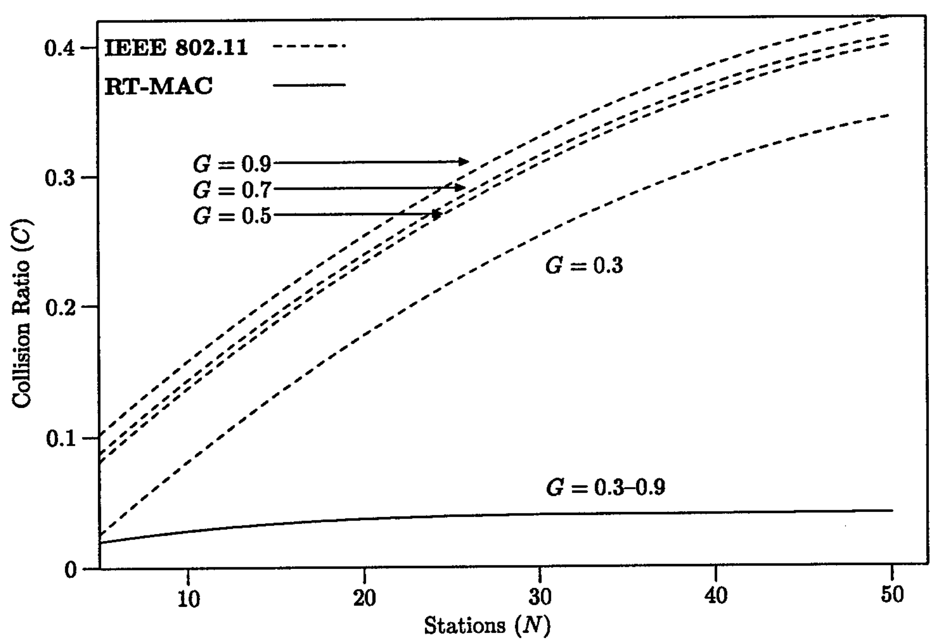


Figure 7.8: Collisions – Telemetry Traffic Model

7.2.2 Avionics Traffic Model

Table 7.2 shows the regression models for the IEEE 802.11 and RT-MAC networks with avionics traffic. Model R^2 is generally quite high (> 0.94), and the residual quantiles are linear. Figures 7.9–7.16 show the regression models behavior for throughput, mean delay, missed deadlines, and collisions.

As with the telemetry traffic models above, we note that when using the avionics traffic model RT-MAC stabilized the behavior of the response variables. In Table 7.2, S_{RT} and D_{RT} are virtually independent of N. In contrast to IEEE 802.11, RT-MAC provides both better performance and a graceful degradation of performance in high network demand situations.

Table 7.2: Regression Model — Avionics Traffic

Response Variable	Regression Model		Model R^2	Residual Quantile-Quantile R^2	90% Confidence Interval for Predicted Response for m Future Experiments		
					$m=1$	$m=10$	$m=\infty$
Throughput (IEEE 802.11)	$S_{80211} =$	$-5.072 \times 10^{-3} G^3 N - 2.088 G^3 + 2.658 G^2 + 0.116$	0.992	0.825	± 2.24E-02	± 7.57E-03	± 2.86E-03
Throughput (RT-MAC)	$S_{RT} =$	$-1.496 G^3 + 2.165 G^2 + 0.143$	0.999	0.886	± 9.37E-03	± 3.12E-03	± 1.04E-03
Delay (sec) (IEEE 802.11)	$D_{80211} =$	$(-0.444 G^3 N + 0.763 G^2 N - 0.393 GN + 7.192 G^3 - 11.184 G^2 + 5.497 G + 0.061 N - 0.043)^{20}$	0.974	0.825	± 4.48E-02	± 1.61E-02	± 8.05E-03
Delay (sec) (RT-MAC)	$D_{RT} =$	$1.239 G^3 - 1.699 G^2 + 0.778 G + 4.459 \times 10^{-3} E - 0.103$	0.991	0.992	± 7.35E-03	± 2.53E-03	± 1.05E-03
Missed Deadline Ratio (IEEE 802.11)	$F_{80211} =$ $(G \leq 0.5)$	$\sin^2(0.103 G^3 + 9.967 \times 10^{-1} GE + 2.369 \times 10^{-4} NE + 7.927 \times 10^{-3})$	0.945	0.939	± 1.09E-02	± 4.32E-03	± 2.73E-03
	$F_{80211} =$ $(G > 0.5)$	$\sin^2(-0.916 G^3 N + 1.282 G^2 N - 0.411 GN + 9.507 G^3 - 10.888 G + 4.300)$	0.974	0.832	± 1.73E-01	± 6.23E-02	± 3.12E-02
Missed Deadline Ratio (RT-MAC)	$F_{RT} =$	$8.616 \times 10^{-4} G^2 N + 1.810 G^3 - 2.666 G^2 + 1.235 G - 0.180$	0.976	0.963	± 1.21E-02	± 4.16E-03	± 1.73E-03
Collision Ratio (IEEE 802.11)	$C_{80211} =$	$\sin^2(-0.376 G^3 N + 0.661 G^2 N - 0.341 GN + 0.357 G^3 + 0.0535 N + 0.0336)$	0.973	0.968	± 6.33E-02	± 2.21E-02	± 9.89E-03
Collision Ratio (RT-MAC)	$C_{RT} =$	$5.995 \times 10^{-2} G^3 - 2.626 \times 10^{-2} G^2 - 5.150 \times 10^{-8} N^3 + 1.527 \times 10^{-4} N + 2.013 \times 10^{-4}$	0.974	0.921	± 2.56E-03	± 8.81E-04	± 3.66E-04

Throughput is shown in Figure 7.9. RT-MAC throughput is constant as N increases, whereas IEEE 802.11 throughput decreases with N. IEEE 802.11 mean delay is shown in Figures 7.10—7.11. It is highly influenced by both G and N for $G \geq 0.7$ and has a maximum delay of about 35 secs. In contrast, RT-MAC mean delay (Figure 7.12) has a maximum of about 120 ms and is independent of N and only slightly influenced by the channel model, E.

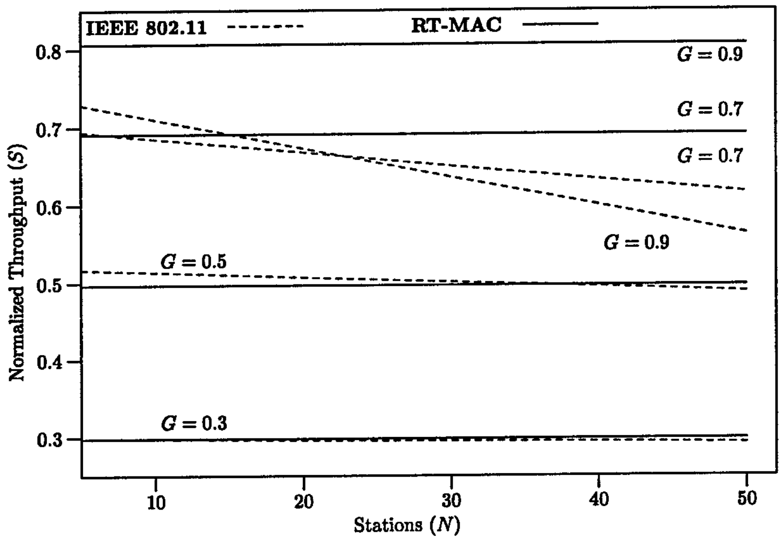


Figure 7.9: Normalized Throughput – Avionics Traffic Model

The model for the IEEE 802.11 missed deadline ratio shown in Figure 7.13 is an instance where the effect of the channel factor E was significant enough to be included in the model. Given the small magnitude of F, one may wonder why it was not included in a single overall model. This approach was attempted but it was found that the model overestimated the actual missed deadline ratio by several orders of magnitude for $G \leq 0.5$ when the simulation data for the entire range of G was included. Further, a single model resulted in F decreasing as N increased from 5 to 30—contrary to an increase in failures indicated by the simulation data. This behavior was caused by the fact that even though the model errors for F were large for $G \leq 0.5$ with respect to orders of magnitude, they were insignificant when compared to the model errors in the overall model, especially for $G \geq 0.7$. Therefore, the model for the IEEE 802.11 missed deadline ratio was split into two separate models. One model for the low/medium load case, and another for the high load case. The model for the high load IEEE 802.11 missed deadline ratio and the model for the RT-MAC missed deadline ratio is shown in Figure 7.14.

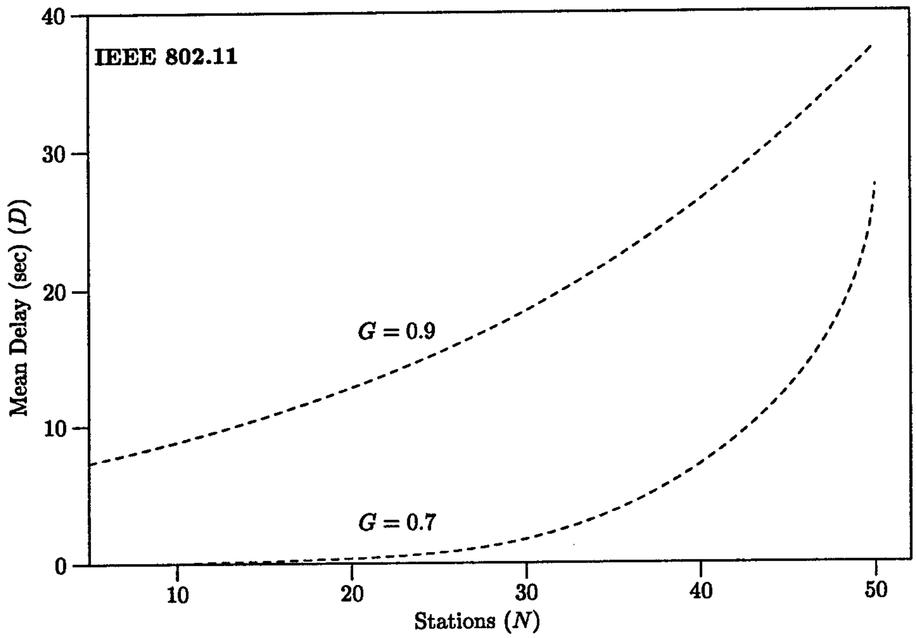


Figure 7.10: Mean Delay – Avionics Traffic Model (1 of 3)

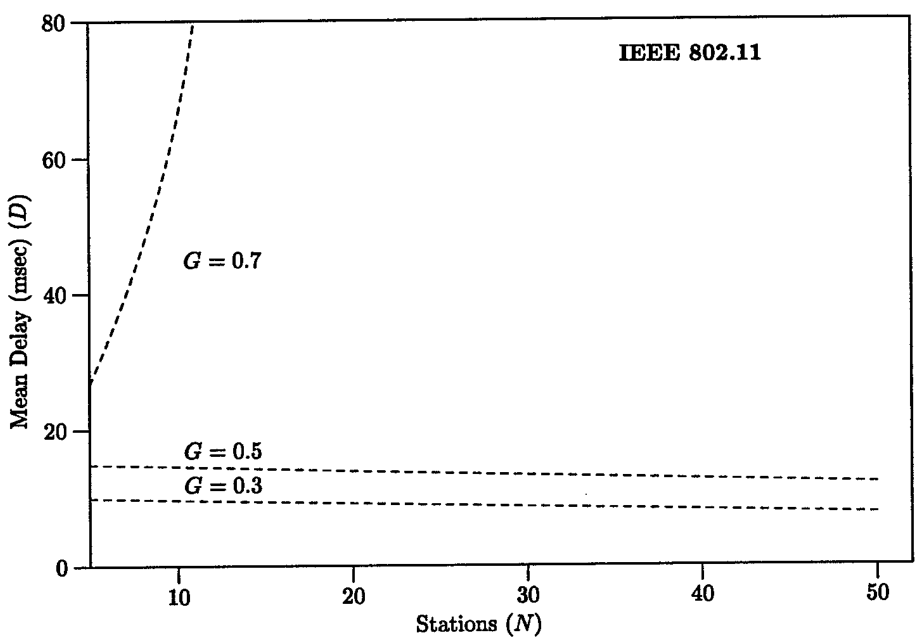


Figure 7.11: Mean Delay – Avionics Traffic Model (2 of 3)

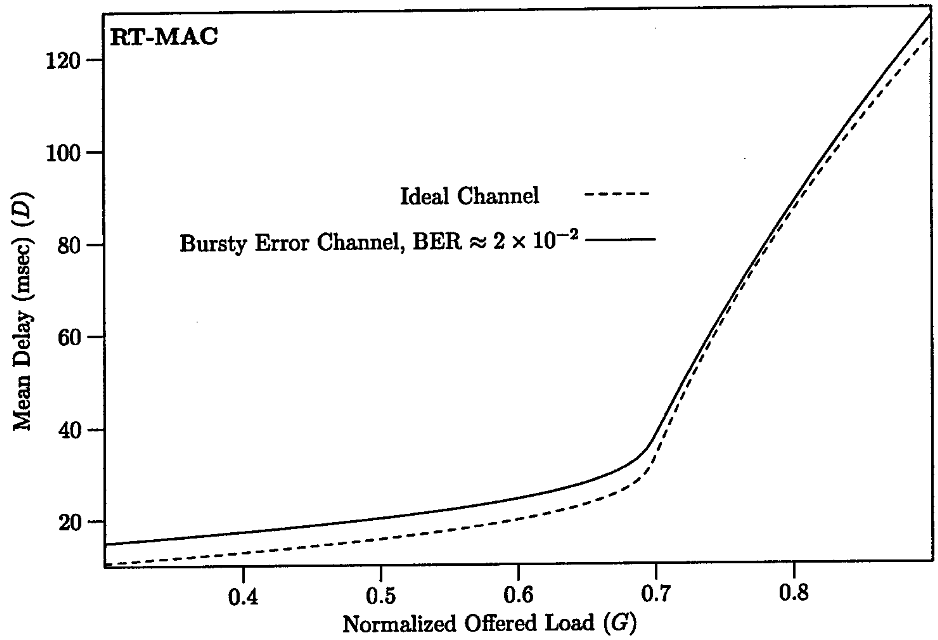


Figure 7.12: Mean Delay – Avionics Traffic Model (3 of 3)

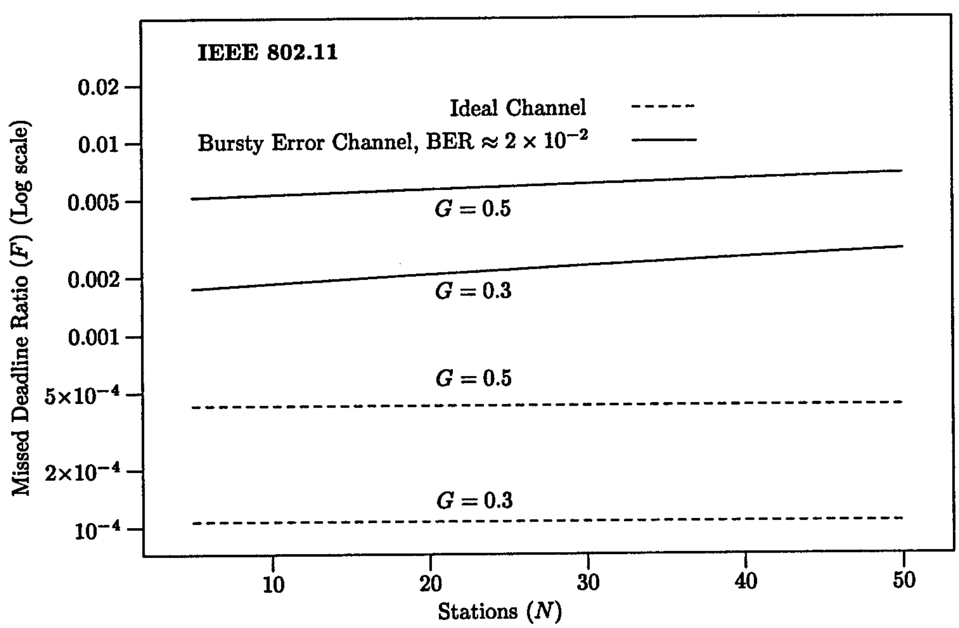


Figure 7.13: Missed Deadlines – Avionics Traffic Model (1 of 2)

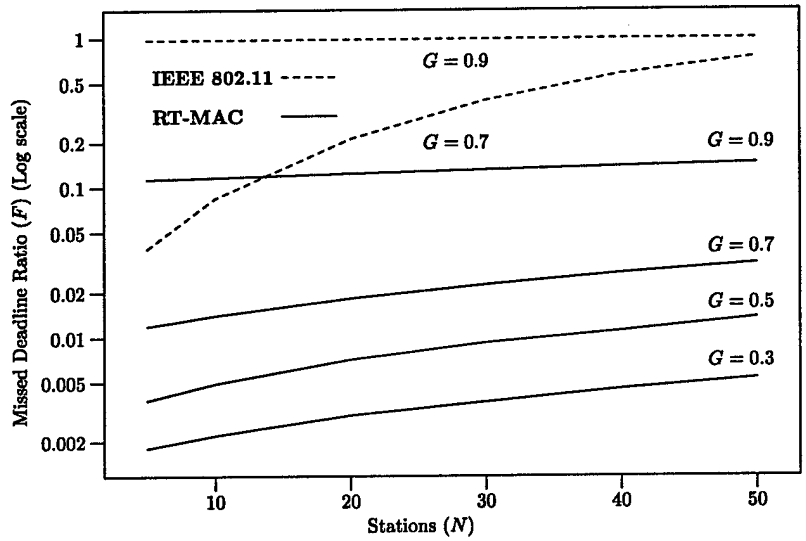


Figure 7.14: Missed Deadlines – Avionics Traffic Model (2 of 2)

The collision ratio for IEEE 802.11 is shown in Figure 7.15. It is strongly influenced by N for $G \geq 0.7$. RT-MAC collision ratio is shown in Figure 7.16. It is virtually independent of N and quite small compared to IEEE 802.11.

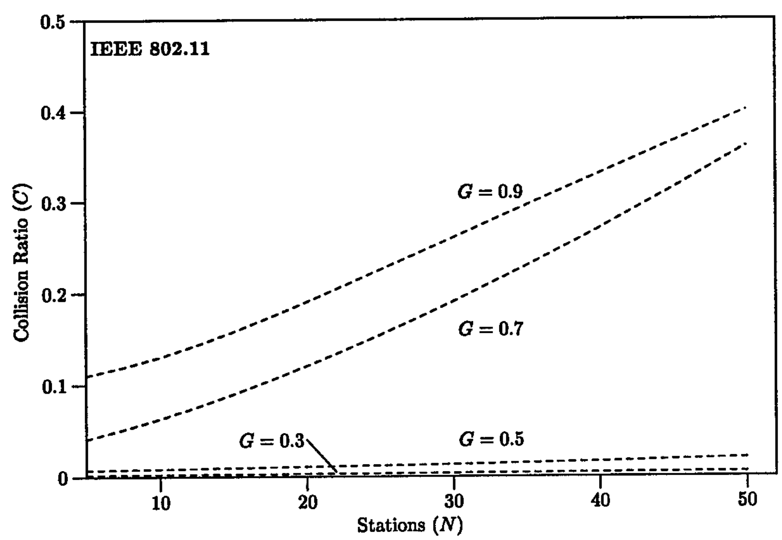


Figure 7.15: Collisions – Avionics Traffic Model (1 of 2)

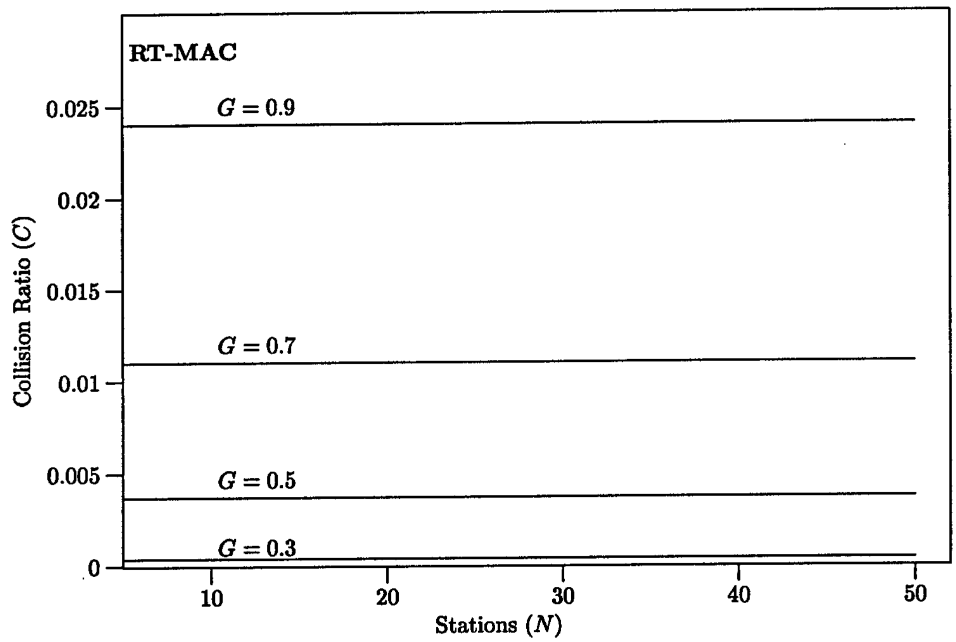


Figure 7.16: Collisions – Avionics Traffic Model (2 of 2)

7.2.3 Voice Traffic Model

7.2.3.1 1 Mbps

Table 7.3 shows the regression models for the IEEE 802.11 and RT-MAC networks with 1 Mbps voice traffic. Model $R^2 > 0.90$, and the residual quantiles are linear. In this table, the offered load, G, is understood to be the non real-time offered load G_{NRT}. Figures 7.17–7.24 show the regression models behavior for throughput, mean delay, missed deadlines, and collisions.

Figure 7.17 shows that with IEEE 802.11, as N increases the throughput converges to approximately 0.3 for any G_{NRT}. Since this is also the case for $G_{NRT} = 0.0$, this strongly suggests that almost no non real-time traffic is transmitted as N approaches 30. In contrast, consider Figure 7.18 where throughput increases linearly with N except for $G_{NRT} = 0.8$.

Mean delay is shown in Figures 7.19–7.21. In Figure 7.20, IEEE 802.11 mean delay decreases slightly (although the magnitude is large at about 10 sec). This is due to the fact that, as noted above, non real-time traffic is virtually zero therefore most of that traffic is being blocked, hence not being counted in the mean delay calculation. RT-MAC mean delay is also increasing as seen in Figure 7.21 but we note that the throughput is also increasing meaning that at least some of the non real-time traffic is being transmitted as well.

Table 7.3: Regression Model — Voice Traffic (1 Mbps)

Response Variable	Regression Model		Model R^2	Residual Quantile-Quantile R^2	90% Confidence Interval for Predicted Response for m Future Experiments		
					$m = 1$	$m = 10$	$m = \infty$
Throughput (IEEE 802.11)	$S_{80211} =$	$3.311 \times 10^{-5}G^2N^3 - 5.698 \times 10^{-2}GN$ $-4.894 \times 10^{-4}N^2 + 2.694 \times 10^{-2}N$ $-0.794G^2 + 1.647G - 0.0691$	0.964	0.956	± 4.09E-02	± 1.42E-02	± 6.17E-03
Throughput (RT-MAC)	$S_{RT} =$	$-2.075 \times 10^{-2}G^3N + 7.271 \times 10^{-3}N$ $+0.791G + 0.0918$	0.962	0.968	± 5.70E-02	± 1.91E-02	± 6.54E-03
Delay (sec) (IEEE 802.11)	$D_{80211} =$	$(7.309 \times 10^{-5}G^3N^3 - 0.117G^2N$ $-3.240 \times 10^{-3}GN^2 + 0.144GN + 1.003G^2$ $-0.572G + 9.880 \times 10^{-6}N^3 + 0.794)^{20}$	0.906	0.978	± 6.45E-02	± 2.26E-02	± 1.04E-02
Delay (sec) (RT-MAC)	$D_{RT} =$	$(0.408G^2 + 2.795 \times 10^{-3}N + 0.798)^{20}$	0.924	0.967	± 4.77E-02	± 1.57E-02	± 4.75E-03
Missed Dead-line Ratio (IEEE 802.11)	$F_{80211} =$ $[G \leq 0.2]$	$\sin^2(-6.712 \times 10^{-2}G^3N^3 + 2.966G^3N^2$ $-1.244GN + 9.381 \times 10^{-5}N^3$ $-1.345 \times 10^{-3}N^2 + 3.264G$ $+8.646 \times 10^{-2}E + 0.0235)$	0.969	0.879	± 1.87E-01	± 7.39E-02	± 4.67E-02
	$F_{80211} =$ $[G > 0.2]$	$\sin^2(9.979 \times 10^{-4}GN^3 - 5.515 \times 10^{-2}GN^2$ $+0.828GN - 4.697 \times 10^{-4}N^3 + 0.0235N^2$ $-0.255N - 2.0224G^2 + 0.192)$	0.944	0.985	± 2.18E-01	± 7.84E-02	± 3.92E-02
Missed Dead-line Ratio (RT-MAC)	$F_{RT} =$ $[G \leq 0.2]$	$\sin^2(9.248 \times 10^{-3}G^2N^2 + 1.522 \times 10^{-5}N^3$ $+5.965 \times 10^{-2}E - 3.234 \times 10^{-3})$	0.954	0.988	± 8.22E-02	± 2.95E-02	± 1.48E-02
	$F_{RT} =$ $[G > 0.2]$	$\sin^2(-5.519 \times 10^{-3}G^3N^2 + 0.168G^2N$ $+6.925 \times 10^{-4}N^2 - 7.407 \times 10^{-2})$	0.942	0.982	± 1.77E-01	± 6.00E-02	± 2.27E-02
Collision Ratio (IEEE 802.11)	$C_{80211} =$	$\sin^2(-2.670 \times 10^{-2}G^2N - 2.274 \times 10^{-3}GN^2$ $+8.747 \times 10^{-2}GN + 6.189 \times 10^{-4}N^2$ $+2.322 \times 10^{-2})$	0.930	0.960	± 8.98E-02	± 3.04E-02	± 1.15E-02
Collision Ratio (RT-MAC)	$C_{RT} =$	$\sin^2(-1.462 \times 10^{-4}GN^2 - 1.603 \times 10^{-4}N^2$ $+1.096 \times 10^{-2}N + 0.165G - 2.886 \times 10^{-2})$	0.955	0.976	± 1.75E-02	± 5.94E-03	± 2.25E-03

The $G_{NRT} = 0.0$ curves in Figures 7.22 and 7.23 exhibit a similar behavior as discussed above in Section 7.2.2 for the IEEE 802.11 avionics failure model. That is, even though the magnitude of the model error was small for $G_{NRT} \leq 0.2$, when compared to the model error for $G_{NRT} > 0.2$, when the data for $G_{NRT} \leq 0.2$ was included in an overall model, the prediction for missed deadline ratios for $G \leq 0.2$ was off by several orders of magnitude. Further, the channel model used (ideal or bursty) had a significant effect on the models for

$G_{NRT} \leq 0.2$. Therefore, the missed deadline ratio model was split into two separate models for both IEEE 802.11 and RT-MAC.

In Figure 7.24, RT-MAC has fewer collisions than IEEE 802.11 in every case.

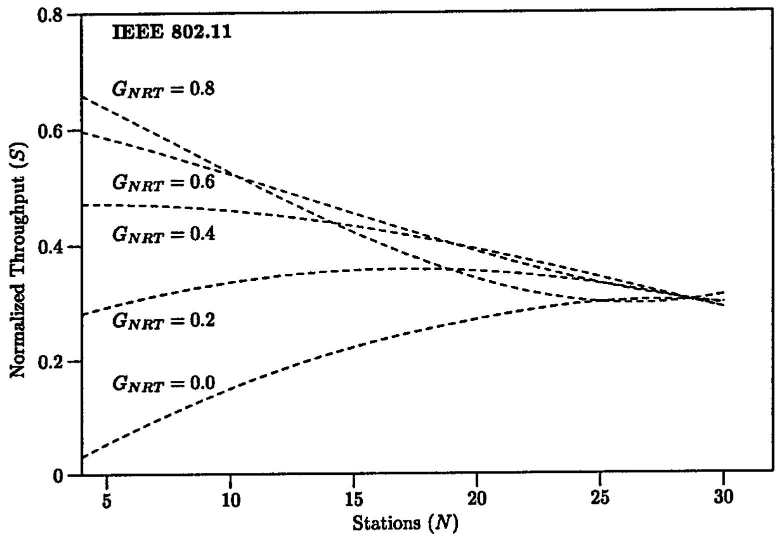


Figure 7.17: Normalized Throughput – Voice Traffic Model (1 Mbps) (1 of 2)

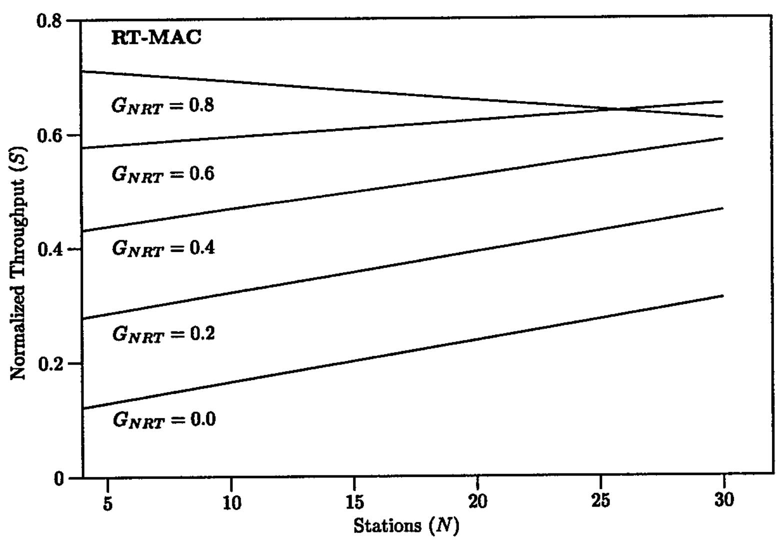


Figure 7.18: Normalized Throughput – Voice Traffic Model (1 Mbps) (2 of 2)

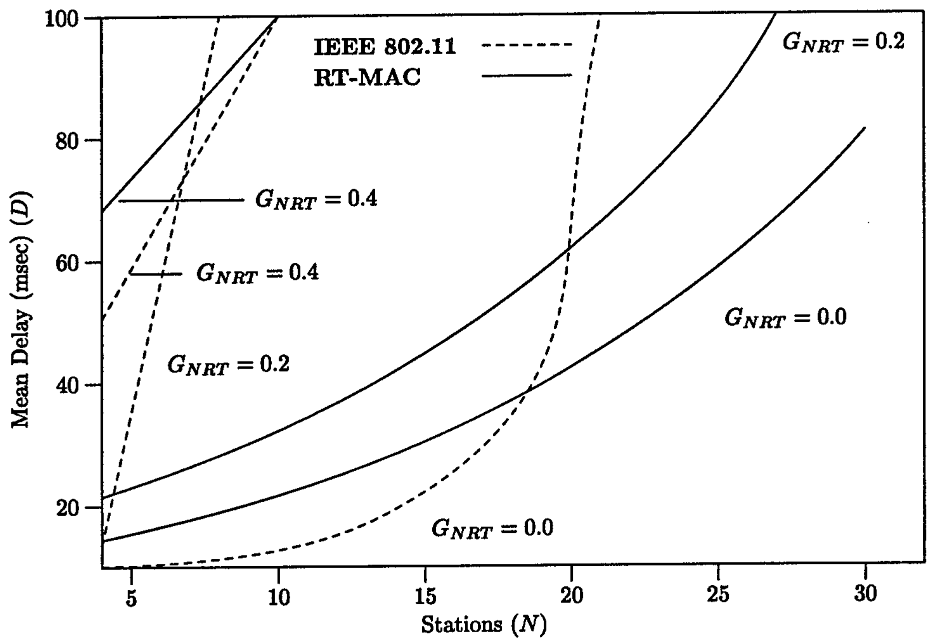


Figure 7.19: Mean Delay – Voice Traffic Model (1 Mbps) (1 of 3)

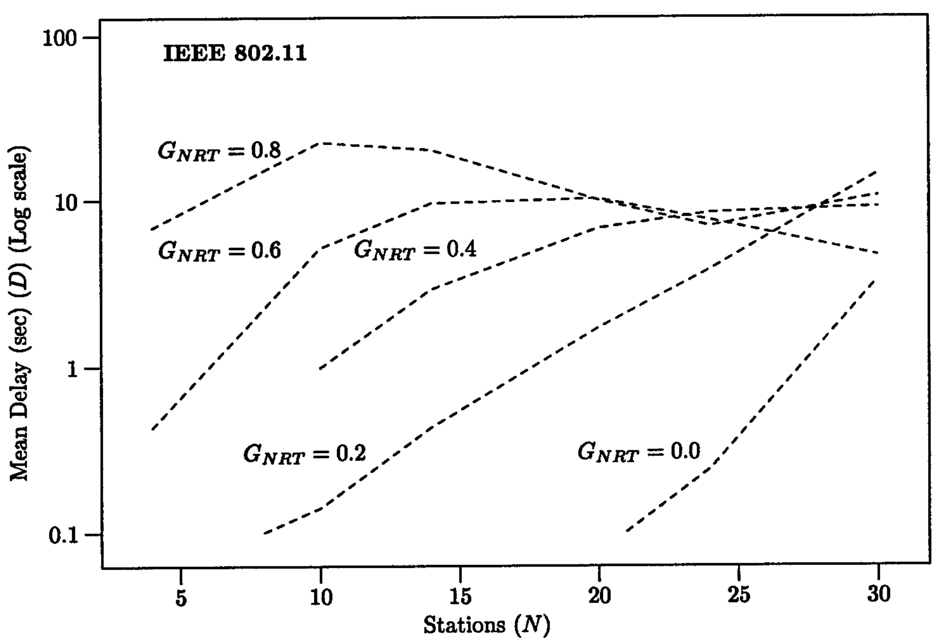


Figure 7.20: Mean Delay – Voice Traffic Model (1 Mbps) (2 of 3)

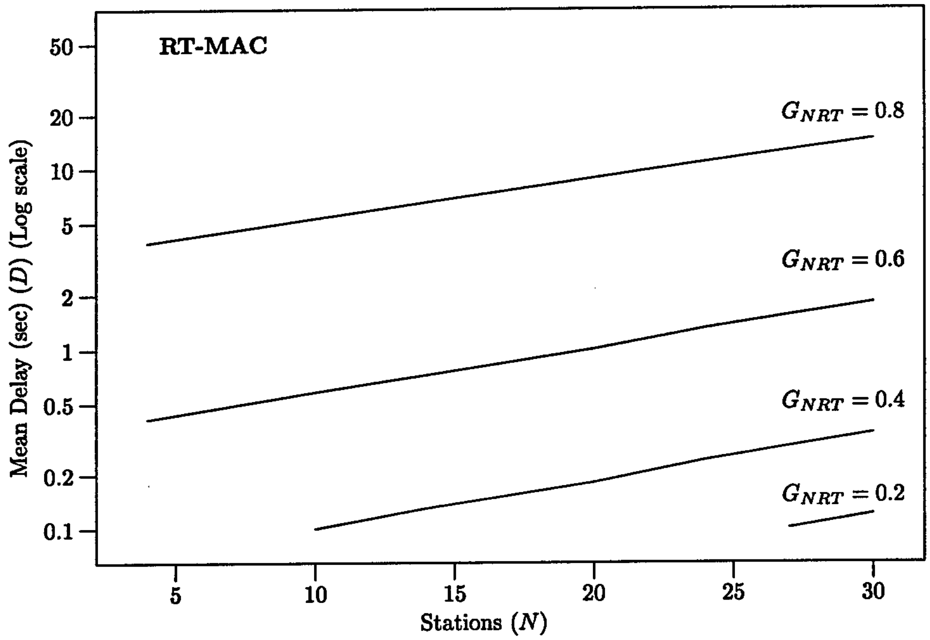


Figure 7.21: Mean Delay – Voice Traffic Model (1 Mbps) (3 of 3)

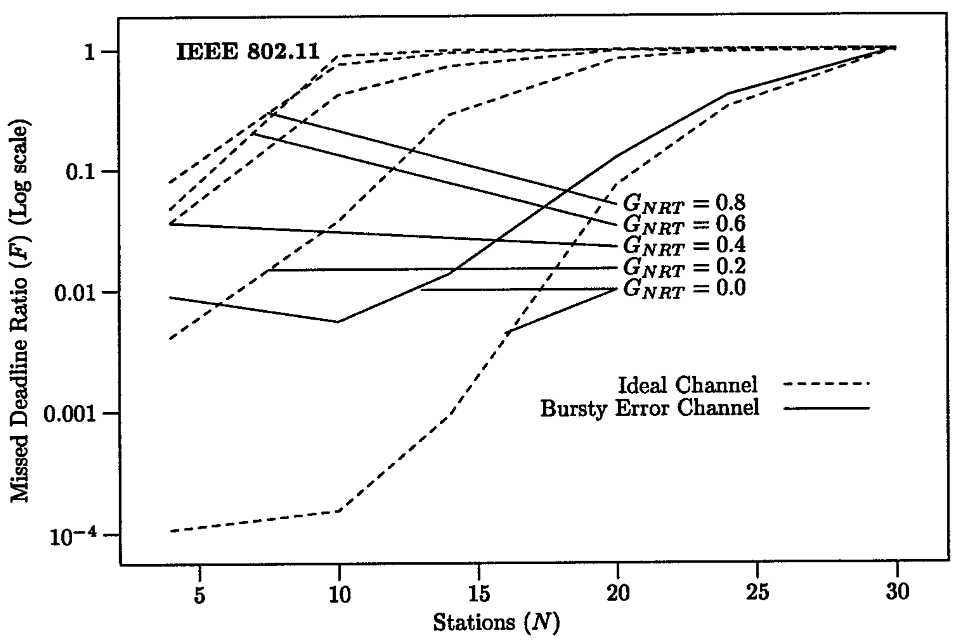


Figure 7.22: Missed Deadlines – Voice Traffic Model (1 Mbps) (1 of 2)

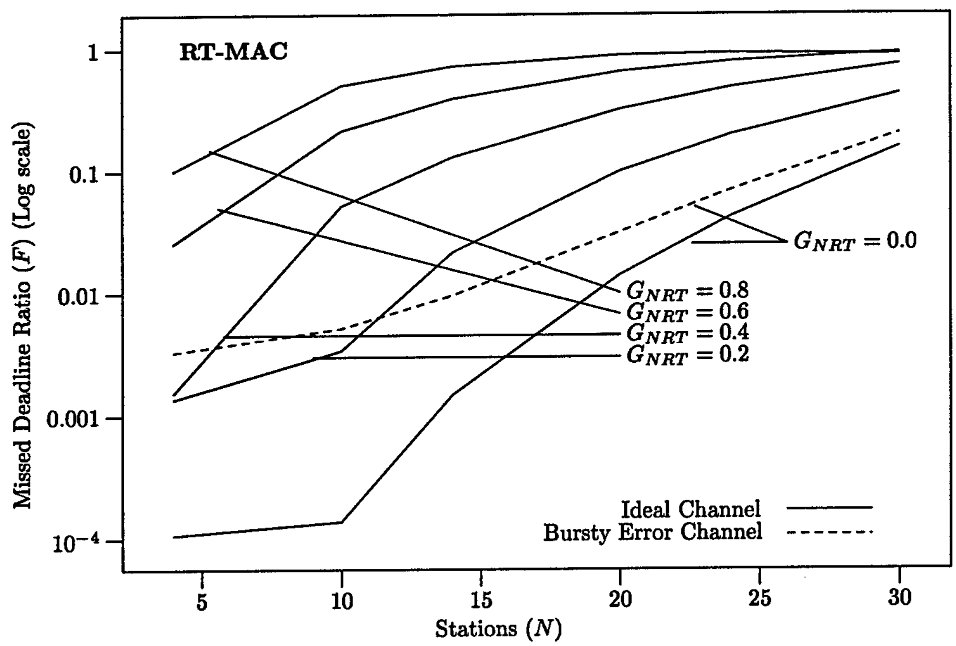


Figure 7.23: Missed Deadlines – Voice Traffic Model (1 Mbps) (2 of 2)

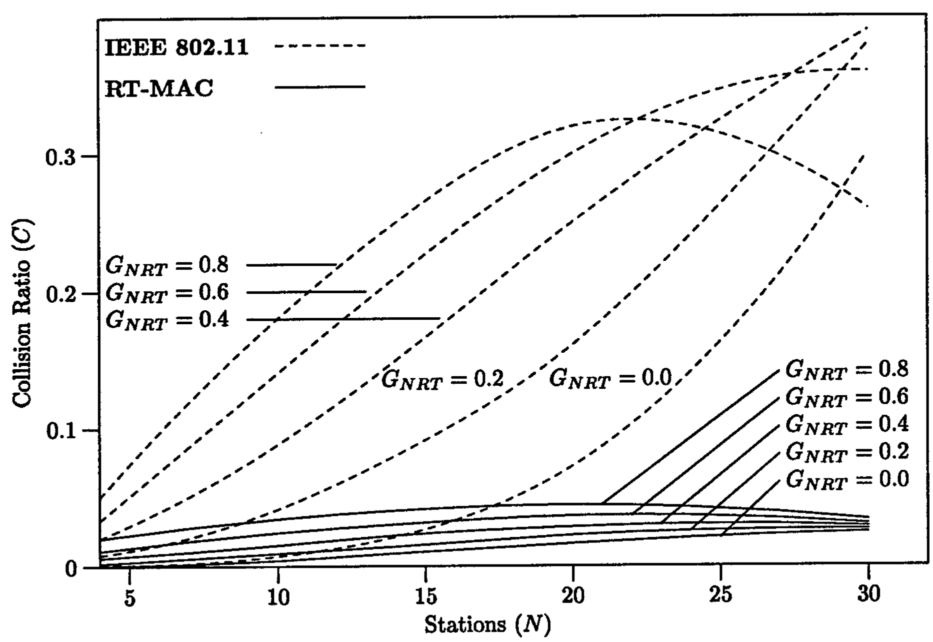


Figure 7.24: Collisions – Voice Traffic Model (1 Mbps)

7.2.3.2 10 Mbps

Table 7.4 shows the regression models for the IEEE 802.11 and RT-MAC networks with telemetry traffic. Model R^2 is generally quite high (> 0.92), and the residual quantiles are linear. As with Table 7.3, the offered load, G, is understood to be the non real-time offered load G_{NRT}.

Table 7.4: Regression Model — Voice Traffic (10 Mbps)

Response Variable		Regression Model	Model R^2	Residual Quantile-Quantile R^2	90% Confidence Interval for Predicted Response for m Future Experiments		
					$m=1$	$m=10$	$m=\infty$
Throughput (IEEE 802.11)	$S_{80211} =$	$3.614\times10^{-2}G^3N - 3.576\times10^{-2}G^2N$ $+1.280\times10^{-5}N^2 - 1.114G^2 + 1.427G$ $+0.02417$	0.952	0.988	± 4.06E-02	±1.37E-02	±4.94E-03
Throughput (RT-MAC)	$S_{RT} =$	$-5.696\times10^{-3}GN + 1.730\times10^{-5}N^2$ $-0.878G^2 + 1.372G + 0.0132$	0.977	0.979	±3.53E-02	±1.18E-02	±3.93E-03
Delay (sec) (IEEE 802.11)	$D_{80211} =$	$(5.232\times10^{-3}GN + 2.357G^3E$ $+1.946\times10^{-4}NE - 9.264G^3 + 0.142)^2$ $[G < 0.2; G = 0.2, N \leq 50]$	0.942	0.888	± 9.17E-03	± 3.35E-03	± 1.76E-03
	$D_{80211} =$	$(6.094\times10^{-5}G^3N^3 - 5.468\times10^{-5}G^2N^3$ $-0.345G^2N - 0.338GN + 4.193G^2$ $-1.069\times10^{-5}N^3 - 1.092\times10^{-3} - 1.125)^2$ $[G = 0.2, N > 50; G \geq 0.2]$	0.926	0.948	± 3.40E-01	± 1.20E-01	± 5.58E-02
Delay (sec) (RT-MAC)	$D_{RT} =$	$(7.519\times10^{-5}G^3N^3 - 9.603\times10^{-3}G^3N^2$ $+0.0908G^2N + 1.186\times10^{-6}N^2$ $-1.887G^2 + 0.824)^{20}$ $[G < 0.2; G = 0.2, N < 40]$	0.978	0.888	± 4.69E-03	± 1.71E-03	± 8.91E-03
	$D_{RT} =$	$(2.355\times10^{-5}G^3N^3 - 3.761\times10^{-3}G^3N^2$ $+0.132G^2N - 21.906G^3 + 36.052G^2$ $-15.842G + 1.847)^2$ $[G = 0.2, N \geq 40; G > 0.2]$	0.931	0.940	± 3.42E-01	± 1.18E-01	± 5.00E-02
Missed Dead-line Ratio (IEEE 802.11)	$F_{80211} =$	$\sin^2(7.374\times10^{-5}G^3N^3 - 0.390G^3N$ $-9.319\times10^{-5}G^2N^3 + 0.444G^2N$ $+2.524\times10^{-5}GN^3 - 0.0719GN + 0.0158)$	0.924	0.955	± 2.52E-01	± 8.58E-02	± 3.31E-02
Missed Dead-line Ratio (RT-MAC)	$F_{RT} =$	$\sin^2(-8.503\times10^{-4}G^3N^2$ $+9.202\times10^{-4}G^2N^2 + 0.0195)$	0.941	0.952	± 1.14E-01	± 3.71E-02	± 9.80E-03
Collision Ratio (IEEE 802.11)	$C_{80211} =$	$\sin^2(3.573\times10^{-3}G^3N^2 - 0.236G^3N$ $-4.203\times10^{-3}G^2N^2 + 0.253G^2N$ $+7.029\times10^{-6}GN^3 + 2.316\times10^{-5}N^2$ $+0.0339)$	0.946	0.987	± 1.05E-01	± 3.58E-02	± 1.38E-02
Collision Ratio (RT-MAC)	$C_{RT} =$	$\sin^2(-4.074\times10^{-7}G^2N^3 + 2.450\times10^{-3}N$ $-0.225G^3 + 0.522G + 7.560\times10^{-3})$	0.972	0.974	± 3.02E-02	± 1.01E-02	± 3.36E-03

Figures 7.25–7.26 show the regression models behavior for throughput. IEEE 802.11 and RT-MAC throughput is comparable for $G \leq 0.4$. RT-MAC is generally better for higher

loads.

For the same reasons already discussed in Section 7.2.2 for the avionics traffic model and in Section 7.2.3.1 for the 1 Mbps voice model, the regression models for mean delay (Figures 7.27–7.29) have been separated into two models. Figures 7.27 and 7.28 show the mean delay for IEEE 802.11. RT-MAC mean delay is shown in Figure 7.29.

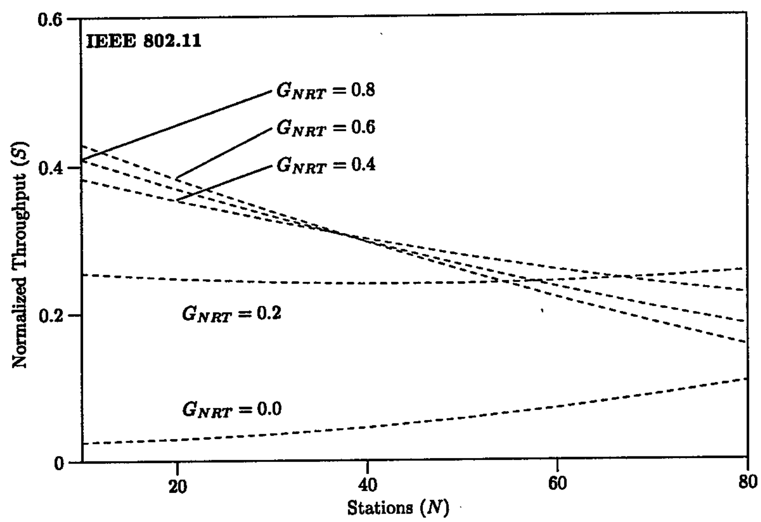


Figure 7.25: Normalized Throughput – Voice Traffic Model (10 Mbps) (1 of 2)

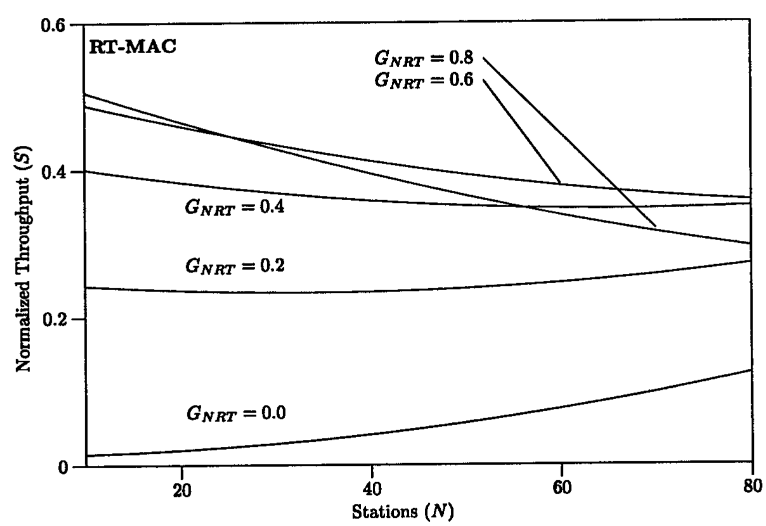


Figure 7.26: Normalized Throughput – Voice Traffic Model (10 Mbps) (2 of 2)

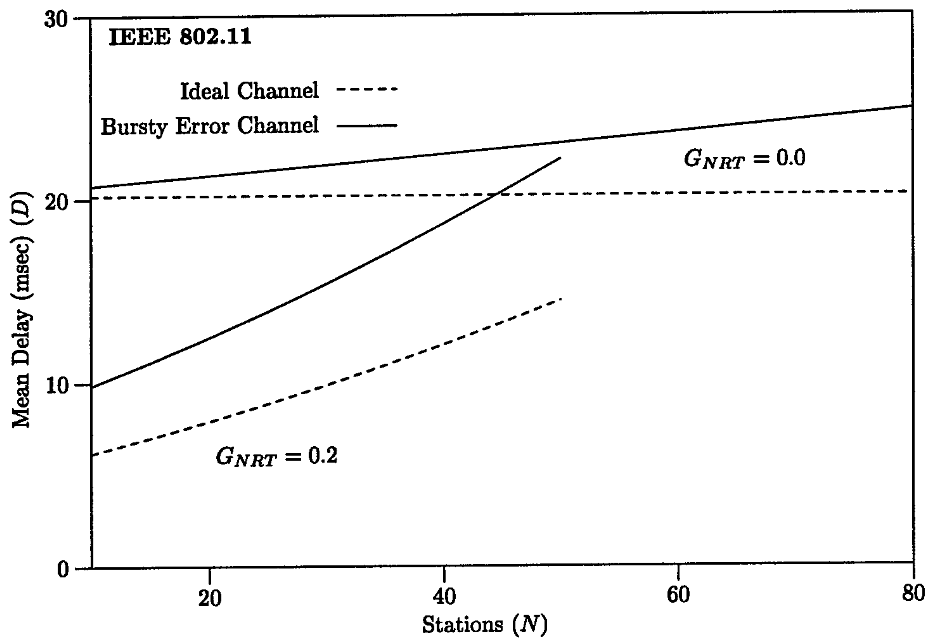


Figure 7.27: Mean Delay – Voice Traffic Model (10 Mbps) (1 of 3)

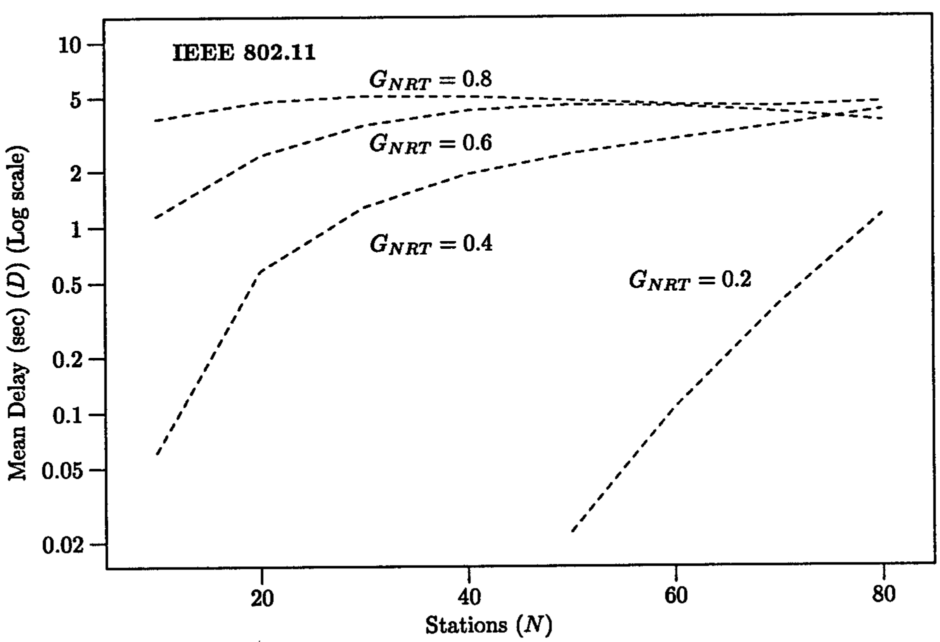


Figure 7.28: Mean Delay – Voice Traffic Model (10 Mbps) (2 of 3)

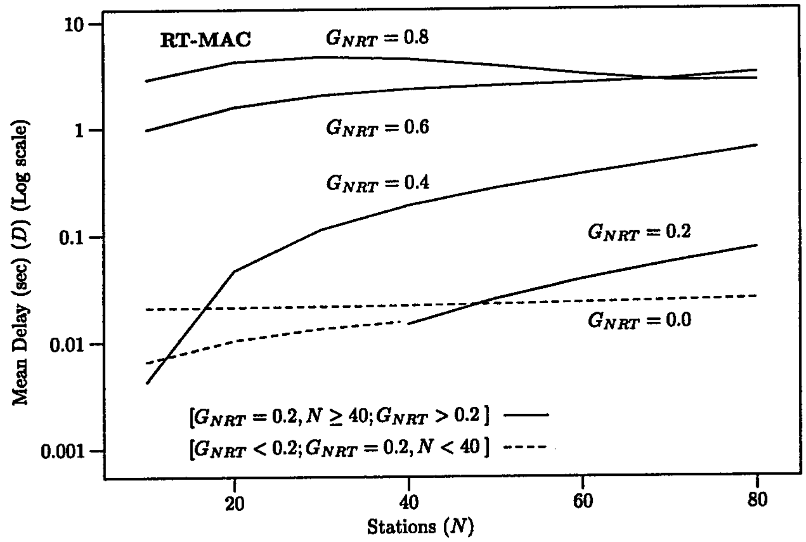


Figure 7.29: Mean Delay – Voice Traffic Model (10 Mbps) (3 of 3)

Figures 7.30 and 7.31 show the missed deadline ratio for IEEE 802.11 and RT-MAC respectively. The RT-MAC figure clearly shows that RT-MAC can transmit significantly more non real-time traffic than IEEE 802.11 while still meeting the real-time requirements. Collision for IEEE 802.11 and RT-MAC are shown in Figure 7.32.

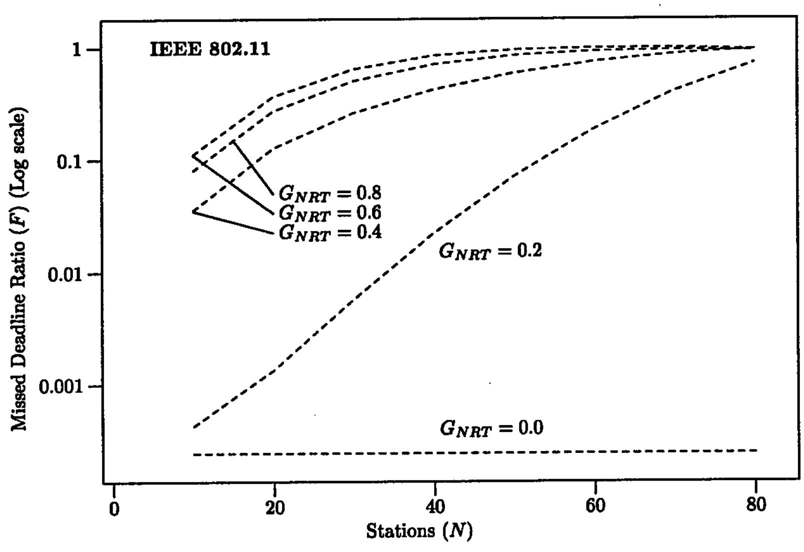


Figure 7.30: Missed Deadlines – Voice Traffic Model (10 Mbps) (1 of 2)

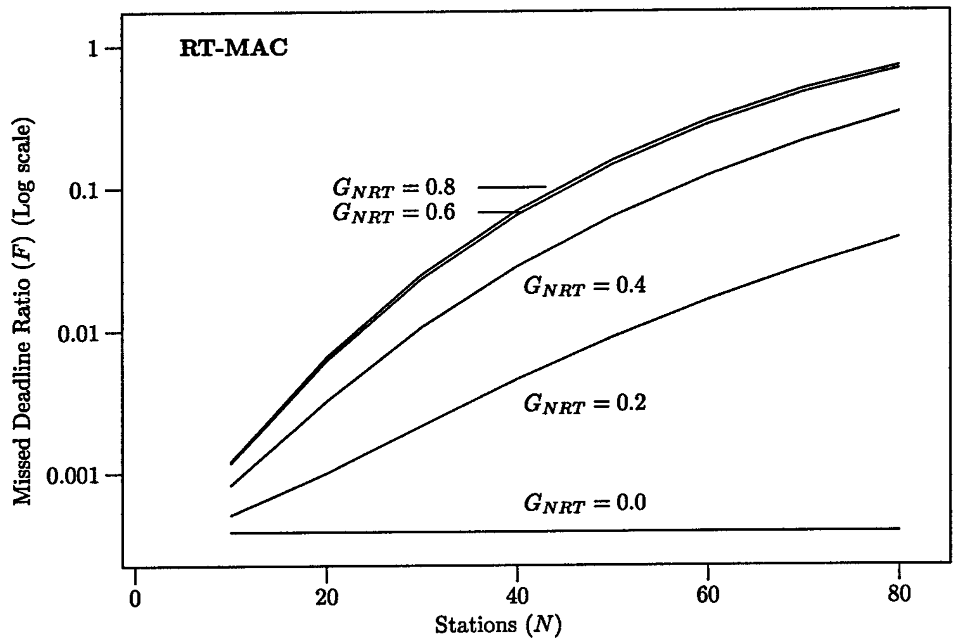


Figure 7.31: Missed Deadlines – Voice Traffic Model (10 Mbps) (2 of 2)

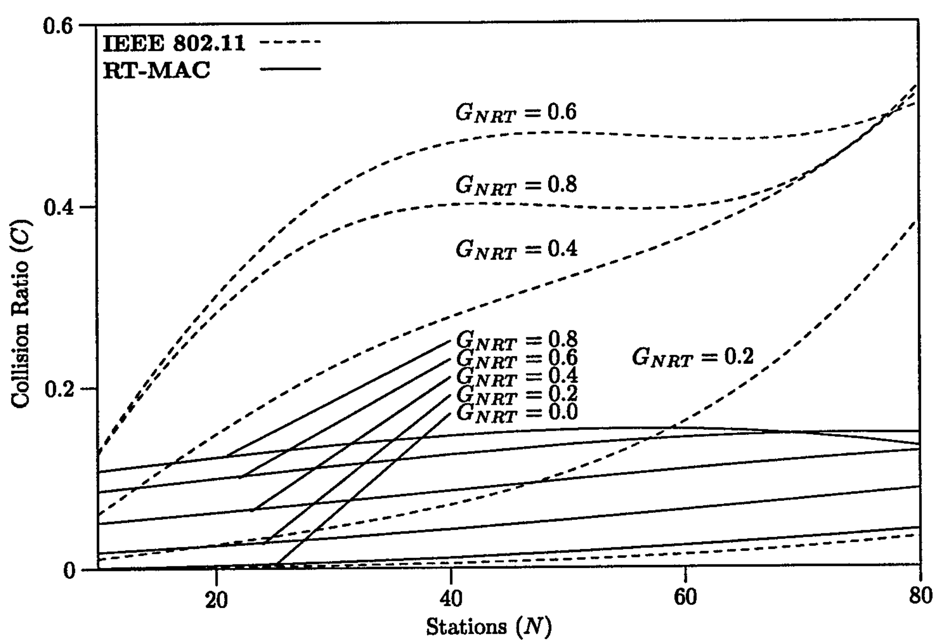


Figure 7.32: Collisions – Voice Traffic Model (10 Mbps)

7.3 Predictive Power of Models

In this section, several models were chosen as a representative sample to determine the predictive power of the models, i.e., how well the regression models predict simulation results. In this study, regression models are used to predict performance metric outcomes using network factor values that have not been simulated. These predictions are then compared to simulation results using those network factor values. Tables 7.5–7.8 contain the results for the throughput, mean delay, missed deadline ratio, and collision ratio, respectively.

In the tables, the *Model Prediction 90% C.I.* contains the confidence interval of the regression model for $m = 5$ future experiments. The mean result for the simulation (with 5 replications) using the network factors is listed in column *Simulation Mean.* The last column (*Simulation results agree with Model prediction?*) contain a yes or no. A yes means that the simulation and regression model results and corresponding C.I.s have been compared using the method described in Section C.1 and have been found to be not different. A no means the comparison has determined that the model and simulation results are statistically different.

Table 7.5: Predictive Power of Regression Models – Throughput

Traffic Model	Protocol	Network Factors	Model Prediction 90% C.I.	Simulation Mean	Simulation results agree with Model prediction?
Telemetry	IEEE 802.11	$G = 0.3, N = 35$	[2.771E-01, 2.849E-01]	2.850E-01	no
		$G = 0.6, N = 25$	[3.011E-01, 3.089E-01]	3.013E-01	yes
	RT-MAC	$G = 0.4, N = 25$	[3.107E-01, 3.199E-01]	3.200E-01	yes*
		$G = 0.6, N = 25$	[3.174E-01, 3.267E-01]	3.121E-01	no
Avionics	IEEE 802.11	$G = 0.6, N = 25$	[5.846E-01, 6.052E-01]	5.980E-01	yes
		$G = 0.8, N = 35$	[6.474E-01, 6.680E-01]	6.164E-01	no
	RT-MAC	$G = 0.6, N = 25$	[5.949E-01, 6.035E-01]	5.978E-01	yes
		$G = 0.8, N = 35$	[7.582E-01, 7.667E-01]	5.680E-01	no
Voice (1 Mbps)	IEEE 802.11	$G_{NRT} = 0.1, N = 28$	[2.869E-01, 3.251E-01]	3.068E-01	yes
		$G_{NRT} = 0.25, N = 12$	[3.593E-01, 3.974E-01]	4.087E-01	yes*
	RT-MAC	$G_{NRT} = 0.1, N = 28$	[3.477E-01, 4.000E-01]	3.781E-01	yes
		$G_{NRT} = 0.25, N = 12$	[3.467E-01, 3.990E-01]	4.053E-01	yes*
Voice (10 Mbps)	IEEE 802.11	$G_{NRT} = 0.3, N = 16$	[3.004E-01, 3.378E-01]	3.192E-01	yes
		$G_{NRT} = 0.7, N = 46$	[2.489E-01, 2.862E-01]	2.677E-01	yes
	RT-MAC	$G_{NRT} = 0.3, N = 16$	[3.069E-01, 3.392E-01]	3.063E-01	yes*
		$G_{NRT} = 0.7, N = 46$	[3.809E-01, 4.132E-01]	3.420E-01	no

* - determined by t-test

Table 7.6: Predictive Power of Regression Models – Mean Delay

Traffic Model	Protocol	Network Factors	Model Prediction 90% C.I.	Simulation Mean	Simulation results agree with Model prediction?
Telemetry	IEEE 802.11	$G = 0.3, N = 35$	[3.982E-02, 5.343E-02]	3.668E-02	no
		$G = 0.6, N = 25$	[1.003E+01, 1.005E+01]	1.071E+01	no
	RT-MAC	$G = 0.4, N = 25$	[1.874E-02, 1.976E-02]	2.059E-02	no
		$G = 0.6, N = 25$	[1.472E-02, 1.574E-02]	1.434E-02	no
Avionics	IEEE 802.11	$G = 0.6, N = 25$	[7.246E-02, 1.150E-01]	1.756E-02	no
		$G = 0.8, N = 35$	[1.967E+01, 1.971E+01]	1.715E+01	yes*
	RT-MAC	$G = 0.6, N = 25$	[1.592E-02, 2.276E-02]	2.159E-02	yes
		$G = 0.8, N = 35$	[6.256E-02, 6.940E-02]	1.967E-02	no
Voice (1 Mbps)	IEEE 802.11	$G_{NRT} = 0.1, N = 28$	[4.756E+00, 4.817E+00]	4.645E+00	yes
		$G_{NRT} = 0.25, N = 12$	[4.114E-01, 4.720E-01]	3.245E-02	no
	RT-MAC	$G_{NRT} = 0.1, N = 28$	[5.623E-02, 9.974E-02]	1.048E-01	no
		$G_{NRT} = 0.25, N = 12$	[2.385E-02, 6.736E-02]	2.729E-02	yes
Voice (10 Mbps)	IEEE 802.11	$G_{NRT} = 0.3, N = 16$	[0.000E+00, 1.778E-01]	6.158E-03	yes
		$G_{NRT} = 0.7, N = 46$	[4.714E+00, 5.035E+00]	4.541E+00	yes
	RT-MAC	$G_{NRT} = 0.3, N = 16$	[0.000E+00, 1.665E-01]	6.980E-03	yes
		$G_{NRT} = 0.7, N = 46$	[3.615E+00, 3.933E+00]	2.507E+00	no

* - determined by *t*-test

Table 7.7: Predictive Power of Regression Models – Missed Deadline Ratio

Traffic Model	Protocol	Network Factors	Model Prediction 90% C.I.	Simulation Mean	Simulation results agree with Model prediction?
Telemetry	IEEE 802.11	$G = 0.3, N = 35$	[0.000E+00, 8.591E-02]	3.112E-03	yes
		$G = 0.6, N = 25$	[9.471E-01, 1.000E+00]	1.000E+00	yes
	RT-MAC	$G = 0.4, N = 25$	[1.342E-01, 1.595E-01]	5.940E-02	no
		$G = 0.6, N = 25$	[3.707E-01, 3.960E-01]	3.831E-01	yes
Avionics	IEEE 802.11	$G = 0.6, N = 25$	[0.000E+00, 1.424E-01]	5.993E-02	yes
		$G = 0.8, N = 35$	[8.189E-01, 9.838E-01]	9.013E-01	yes
	RT-MAC	$G = 0.6, N = 25$	[2.253E-03, 1.350E-02]	1.814E-03	no
		$G = 0.8, N = 35$	[5.624E-02, 6.749E-02]	1.408E-03	no
Voice (1 Mbps)	IEEE 802.11	$G_{NRT} = 0.1, N = 28$	[7.569E-01, 9.438E-01]	9.698E-01	no
		$G_{NRT} = 0.25, N = 12$	[1.316E-01, 3.389E-01]	3.151E-02	no
	RT-MAC	$G_{NRT} = 0.1, N = 28$	[1.147E-01, 1.928E-01]	2.553E-01	no
		$G_{NRT} = 0.25, N = 12$	[0.000E+00, 1.011E-01]	4.779E-04	yes
Voice (10 Mbps)	IEEE 802.11	$G_{NRT} = 0.3, N = 16$	[0.000E+00, 1.382E-01]	0.000E+00	yes
		$G_{NRT} = 0.7, N = 46$	[8.116E-01, 1.000E+00]	8.363E-01	yes
	RT-MAC	$G_{NRT} = 0.3, N = 16$	[0.000E+00, 5.275E-02]	0.000E+00	yes
		$G_{NRT} = 0.7, N = 46$	[7.027E-02, 1.733E-01]	9.569E-02	yes

Table 7.8: Predictive Power of Regression Models – Collision Ratio

Traffic Model	Protocol	Network Factors	Model Prediction 90% C.I.	Simulation Mean	Simulation results agree with Model prediction?
Telemetry	IEEE 802.11	$G = 0.3, N = 35$	[2.688E-01, 2.965E-01]	2.581E-01	no
		$G = 0.6, N = 25$	[2.734E-01, 3.011E-01]	3.034E-01	no
	RT-MAC	$G = 0.4, N = 25$	[3.684E-02, 4.062E-02]	3.829E-02	yes
		$G = 0.6, N = 25$	[3.684E-02, 4.062E-02]	4.033E-02	yes
Avionics	IEEE 802.11	$G = 0.6, N = 25$	[3.241E-02, 9.175E-02]	3.194E-02	no
		$G = 0.8, N = 35$	[2.979E-01, 3.572E-01]	3.496E-01	yes
	RT-MAC	$G = 0.6, N = 25$	[5.566E-03, 7.949E-03]	5.872E-03	yes
		$G = 0.8, N = 35$	[1.555E-02, 1.794E-02]	1.674E-02	no
Voice (1 Mbps)	IEEE 802.11	$G_{NRT} = 0.1, N = 28$	[2.476E-01, 3.305E-01]	3.180E-01	yes
		$G_{NRT} = 0.25, N = 12$	[3.116E-02, 1.141E-01]	5.183E-02	yes
	RT-MAC	$G_{NRT} = 0.1, N = 28$	[1.645E-02, 3.265E-02]	2.548E-02	yes
		$G_{NRT} = 0.25, N = 12$	[5.166E-03, 2.137E-02]	1.305E-02	yes
Voice (10 Mbps)	IEEE 802.11	$G_{NRT} = 0.3, N = 16$	[6.999E-03, 1.044E-01]	2.438E-02	yes
		$G_{NRT} = 0.7, N = 46$	[4.317E-01, 5.291E-01]	4.041E-01	no
	RT-MAC	$G_{NRT} = 0.3, N = 16$	[2.455E-02, 5.222E-02]	2.716E-02	yes
		$G_{NRT} = 0.7, N = 46$	[1.302E-01, 1.578E-01]	1.406E-01	yes

As the above tables indicate, the predictive power of a given regression model is quite varied. Due to the small number of cases considered, it is not possible to draw any general conclusions about the results. However, even in some cases where the model and the simulation have been determined to be different, they are quite close if one uses fewer significant digits than those listed. For example, in Table 7.5 for the telemetry traffic model, IEEE 802.11 protocol, and $G = 0.3, N = 35$, the simulation mean is 0.2850. The upper bound of the regression model C.I. is 0.2849. Therefore, even when not strictly within the C.I., the model prediction may in fact be quite adequate.

Figures 7.33 and 7.34 show how the model predictions might be adequate even though they are not statistically the same as the results obtained by simulation. Figure 7.33 shows the IEEE 802.11 throughput regression models (dashed lines) overlaid with the actual simulation data (various symbols). For the network factors in Table 7.5 this regression model did not agree with the simulation data. Figure 7.34 shows the opposite. It shows the IEEE 802.11 collision ratio regression models overlaid with the actual simulation data. For the network factors in Table 7.8 this regression model *did* agree with the simulation data. As these two figures show, the regression models may be entirely adequate depending on the purpose for which they are used.

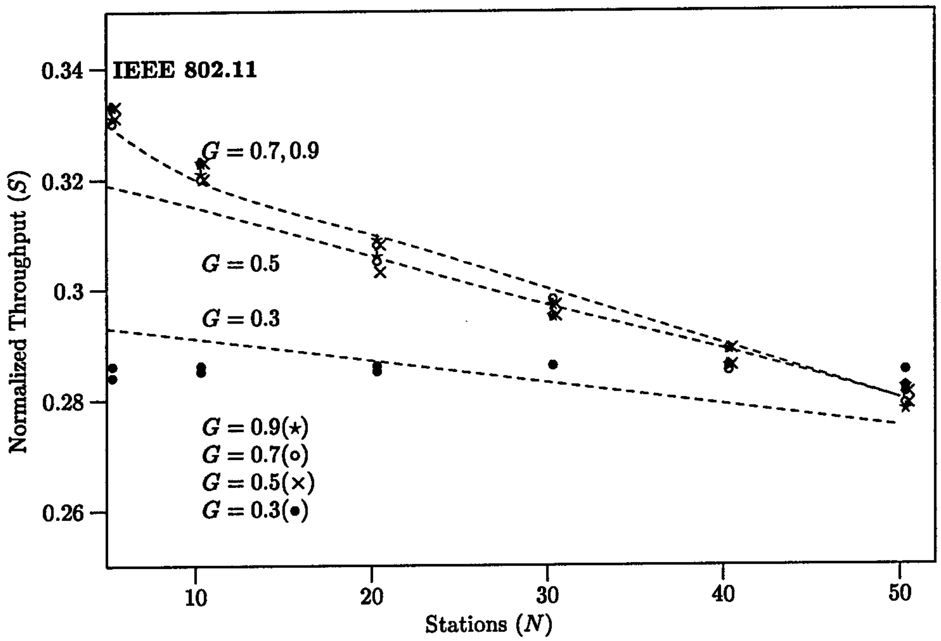


Figure 7.33: IEEE 802.11 Telemetry Throughput Model and Simulation Data

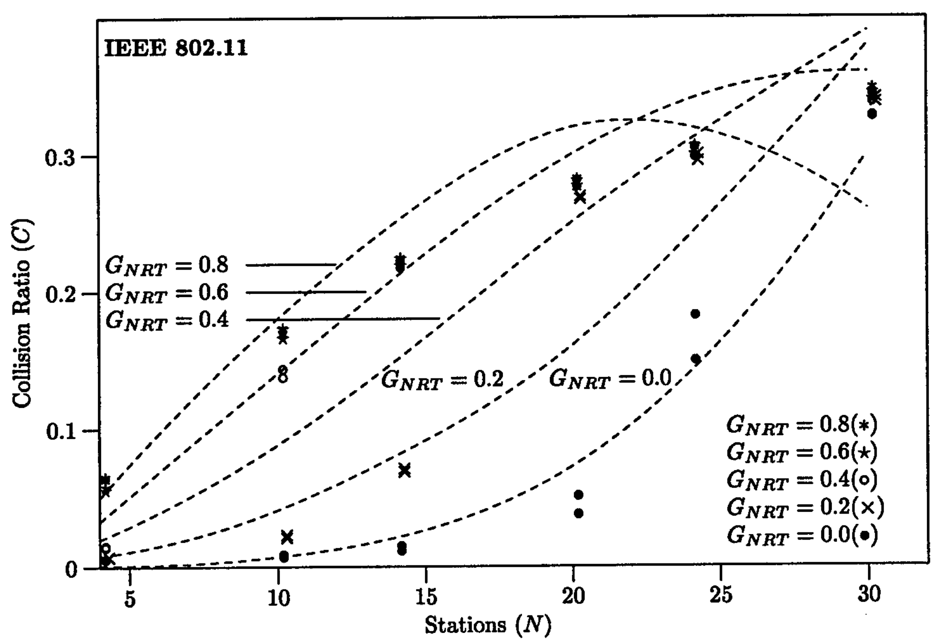


Figure 7.34: IEEE 802.11 1 Mbps Voice Collision Ratio Model and Simulation Data

7.4 Summary

In this chapter, regression models from simulation data were developed. In Section 7.1, we discussed the assumptions that need to be satisfied to develop a valid regression. In Section 7.2, the regression models themselves were presented. In general, model R^2 was above 0.9, indicating that the models accounted for most of the variance in the simulation data. Further, model errors were generally normally distributed indicating that most of the systematic effects had been accounted for. Therefore, the models presented can be characterized as very accurate for the particular network configurations simulated.

In several cases, it was necessary to divide a model into low offered load case and a high offered load case. This was done to produce a more accurate model in the low offered load case. In most instances, when this was done, it was found that the channel model (ideal or bursty) became a significant factor for the low load case. As mentioned in Sections 6.1.5 and 7.2, the effect of the channel model in higher load cases is often masked by other factors such as N and G.

In Section 7.3, the predictive power of the regression models was briefly examined. That is, the models ability to predict the performance of network configurations not specifically simulated was tested. The number of cases looked at was limited and the results were mixed. In many cases the predictions were within the expected confidence interval. Overall, about 61% of the selected cases the model correctly predicted the observed outcome. In some cases, the model predictions were quite close although not strictly within the required bounds.

Chapter 8

Conclusions and Recommendations

This research effort focused on the development and evaluation of the RT-MAC wireless local area network medium access control protocol. RT-MAC dramatically improves the on-time delivery of real-time data through a combination of a transmission control protocol that discards late packets rather than transmit them and a distributed collision reduction algorithm. In many instances, throughput and mean delay are also improved. Simulation models were developed to verify performance improvements using telemetry, avionics, and voice traffic models. These simulations were used as a basis for comparison to the reference IEEE 802.11 system. Extensive studies were performed on various aspects of RT-MAC including, packet service disciplines, use of a static BER, and performance in the presence of IEEE 802.11 stations.

8.1 Summary of Research

Chapter 1 provided an introduction to the problem under investigation. The proliferation of real-time data and the challenges posed by transporting that data over a best effort or general purpose LAN is presented. The cost advantage and greater potential for market acceptance by using industry standards is emphasized. To date, research into real-time data transmission over a wireless link has been limited. Research that focused on improving or establishing the ability of an *ad hoc* network to transmit real-time data has seldom been done.

Chapter 2 presented background information relevant to this effort. First, the OSI network models is discussed. This model provided a reference framework from which all other networks are compared. Early wireless medium access control protocols were examined including ALOHA, several ALOHA variants, CSMA, and IEEE 802.11. The operation and performance of these protocols are compared and contrasted. Next, protocols specifically designed to transport real-time data were discussed. These include virtual-time CSMA, reservation ALOHA, and Distributed-Queuing Request Update Multiple Access. An important part of any simulation effort is the choosing of appropriate traffic and channel models. Various traffic and channel models were discussed in Chapter 2.

Methods used to perform analytical network analysis are surveyed in Chapter 3. Included in this survey were network classification, network balance, and a discussion of network reversibility. If a network is reversible, it may already have had a canonical solution developed for it, thus speeding the analysis. Exact analysis techniques are presented. However, since most real networks can have a large state space which makes exact analysis impractical, various approximation techniques are described as well including, Mean Value Analysis and Equilibrium Point Analysis. If nodes share an output channel, transmissions may fail due to collisions. This is known as an interfering queue. The intractability of analyzing real-time systems using these techniques is explored.

Research objectives and methodology are the topic of Chapter 4. The chapter begins with the problem definition and the presents the thesis and objectives of this research. Performance metrics are presented and the system parameters and factors are discussed. This chapter also includes a presentation of the evaluation technique chosen, the traffic models, and the experimental design.

Chapter 5 provides a description of RT-MAC. Its operation is described in detail. The transmission control protocol examines packets at three key points prior to transmission. If at any of these points the packet is determined to be late, it is discarded. The collision avoidance algorithm consists of both an expansion of the range from which backoff values are chosen, as well as transmitting the next backoff value to be used by the currently transmitting station.

Chapter 6 contains the simulation results. This chapter contains the results from the telemetry, avionics, and voice (1 and 10 Mbps) traffic models. Also contained are various other studies performed to investigate particular aspects of RT-MAC. This chapter shows that RT-MAC performs dramatically better with respect to IEEE 802.11 in most of the networks considered for every performance metric. It always performed better under a high load situation especially with respect to missed deadlines. This chapter demonstrates that each of the different components of the RT-MAC transmission control algorithm and enhanced collision avoidance protocol contribute to the performance improvement. It also shows that RT-MAC performs well in both a static and dynamic error environment. Further, it was shown that RT-MAC provides a significant performance benefit even when a sizable percentage of the network stations are using IEEE 802.11 rather than RT-MAC.

Chapter 7 presents the regression models for both the RT-MAC and IEEE 802.11 networks. This chapter demonstrates the quality of the models by showing that the models developed account for most of variation observed in the simulation data. Further, it is shown that the developed regression models are reasonably accurate in predicting the behavior of network configurations not specifically simulated. Therefore, these models can be used to great benefit in first-order estimates for network performance in the areas of throughput, mean delay, missed deadlines, and collisions.

Appendix A contains extensive documentation of the simulation model including validation data.

Appendices B and C contain data tables and output from the SAS statistical package.

8.2 Conclusions

This research effort developed and evaluated a novel medium access control protocol for wireless LANs designed to effectively transport real-time data. In Section 4.1.1, the thesis of this research was stated. It is repeated here. "The thesis of this research is that the ability of an *ad hoc* packet data network to successfully transport real-time data will be dramatically improved by better utilization of channel capacity and by reducing packet collisions."

The RT-MAC transmission control algorithm embodies the effort to better utilize channel capacity. By not transmitting packets that have (or will) exceed their deadlines, transmission queue throughput is increased, collision probabilities are decreased (by a reduction in traffic), and channel capacity is freed for use by other stations. The RT-MAC enhanced collision avoidance algorithm embodies the effort to reduce packet collisions. By widening the contention window and sharing backoff values throughput the network, collisions were reduced significantly.

Examples of the effectiveness of the approach are evident from the simulation data. For example, in a 50 station network with a normalized offered load of 0.7, mean delay is reduced from more than 14 seconds to less than 45 ms, late packets are reduced from 76% to less than 1%, and packet collisions are reduced from 36% to less than 1%. In a network with voice traffic, the number of conversations that can be supported increased 20% for a 1 Mbps channel and 60% for a 10 Mbps channel. Further, RT-MAC can simultaneously support a much greater level of non real-time traffic than can IEEE 802.11. Therefore, the results of this research strongly support our original thesis.

Regression models are developed from simulation data to describe network behavior in terms of throughput, mean delay, ratio of late packets, and ratio of collisions. These models were shown not only to be quite accurate in accounting for the observed variance in the simulation data, but also to be effective in predicting the behavior of networks not simulated. In addition, the virtual independence of several RT-MAC regression models on the offered load or number of stations in the network indicate that RT-MAC stabilized the behavior of the network with respect to those performance metrics.

By showing that the performance improvements are realized even in a network with a significant number of IEEE 802.11 stations, it was demonstrated that RT-MAC is a robust protocol exhibiting a graceful (almost linear) degradation. In the case of collision ratios, it was shown that a benefit can be realized even when 80% of the stations in the network are not RT-MAC stations.

RT-MAC was evaluated using a wireless LAN. The improvements offered by the RT-MAC protocol, however, are not limited to wireless LANs or even to real-time data traffic. The results extend to any time-slotted LAN, wired or wireless. Further, the enhanced collision avoidance algorithm can be implemented independent of the data being transported.

8.3 Recommendations for Future Research

This research effort has extended the knowledge base of transporting real-time data over wireless local area networks. A novel protocol, RT-MAC, has been developed that significantly improves the ability of wireless LANs to successfully transmit such data. While the improvements are noteworthy, extensions of this work may provide even more benefit. It is recommended that the following research areas be investigated.

1. Analyze the performance of RT-MAC using several spread spectrum transceivers.

2. Investigate whether adaptively modifying the contention window width based on channel traffic will result in further performance improvements.

3. Analyze an RT-MAC network with stations offering non-homogeneous traffic loads.

4. Investigate performance improvement by utilizing different service disciplines for multiple application streams on a single station.

5. Extend RT-MAC to apply to multi-hop networks.

6. Simulate RT-MAC using a video traffic model.

7. Use stochastic rather than fixed packet lengths.

8. Analyze RT-MAC transient network behavior.

9. Investigate tractable exact analysis methods for networks with interfering queues.

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Appendix A

Simulation Documentation

This appendix presents the documentation for the simulation model used in this research effort. Section A.1 contains a discussion of the simulation tool. Section A.2 is a concise overview of the Specification and Description Language (SDL-92) symbols used to document the behavior of the simulation. A complete description of this language can be found in [EHS97]. The next section, A.3, presents the simulation model itself. It highlights the structure of the model and documents the behavior using SDL. SDL was used as the formal description language in the IEEE 802.11 standard. The next section, A.4, describe the simulation parameters which can be varied within the model. Section A.5 discusses the validation of the model and the appendix is concluded with a summary in Section A.6.

A.1 Simulation Tool

This research used the communication network simulator OPNET, version 3.5.A by MIL3, Inc. [MIL97]. Simulations in OPNET are organized in a hierarchical structure of models consisting of (from the highest to lowest level) network models, node models, process models, and parameter models. Network models essentially describe the physical location of nodes and how they are connected (i.e., radio, bus, ring, etc.). Nodes are the stations in the network. Node models describe connections between the process models. Processes specify behavior and parameter models define the data structures used by processes for inter-process communication. Parameter models also define the structure of the packets transmitted on the network itself.

At a given level in the hierarchy, a model is defined using the models at the next lower level. For example, a network model consist of a set of node models arranged and connected in a particular way. Likewise, a node model consists of a number of process models connected in a given way. These different models can be thought of as objects, each with a set of attributes that can be modified. Thus, OPNET can be described as somewhat object-oriented in its approach to modeling components within the simulation program. Data from the simulation is collected by placing statistic "probes" at points of interest within the models. Data collected can be analyzed using the analysis tool provided or exported to be analyzed in external programs.

A.2 SDL Overview

The IEEE 802.11 specification has both a textual description of the standard and a formal description written in SDL-92. Both the textual and the formal description are normative. That is, if a system correctly implements the formal (and/or the textual) description, it is, by definition, an IEEE 802.11 implementation. This presents an obvious advantage to someone modeling the system since the model (correctly implemented) inherently conforms to the standard. Additionally, the formal description contains all of the subsystem interactions explicitly identified at the location where they occur and all subsystem interfaces are identified. Obviously, a complete description of SDL cannot be presented, however, the major components of the SDL language are quite intuitive and easily followed.

Three fundamental objects in SDL are blocks, processes, and signals. Blocks determine

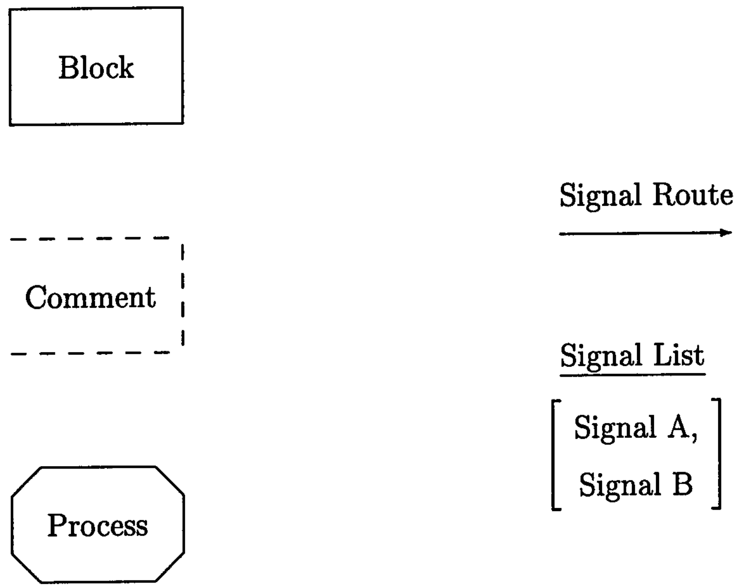

Figure A.1: SDL Legend

lexical scope and structural hierarchy while processes specify behavior using finite state machines. Processes operate concurrently and independently and they communicate using signals. Each block may contain other blocks and/or processes. These fundamental SDL objects are shown in Figure A.1. Note that this figure does not contain all (or even most) of the objects available in SDL. Figure A.2 is an example of an SDL diagram. It shows the subset of IEEE 802.11 functionality implemented in the simulation model. The solid line border that encloses the figure indicates the logical boundary of the object.

At some point in a hierarchy of SDL blocks behavior is specified by including process objects. Using the Transmission block in Figure A.2, the process objects and the symbols used will be described. Figure A.3 shows the view inside of the block Transmission. Note how the input and output signals in Figure A.3 correspond to those in Figure A.2 as one would expect. More detail about which processes these signals go to or are received from is included at this level.

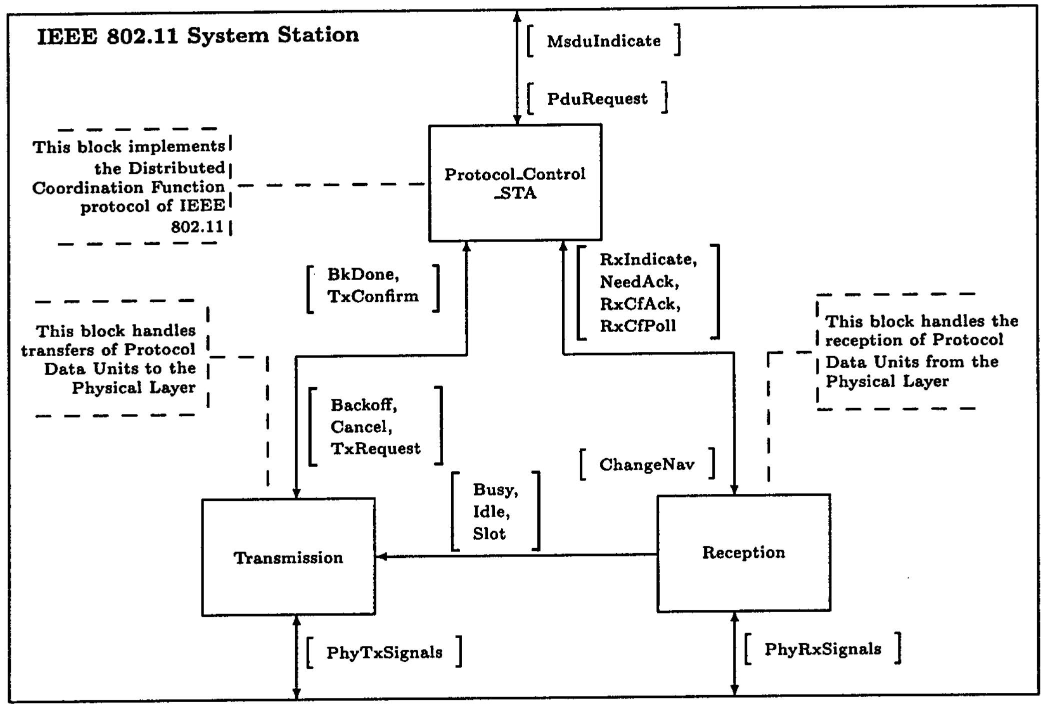

Figure A.2: IEEE 802.11 System Station

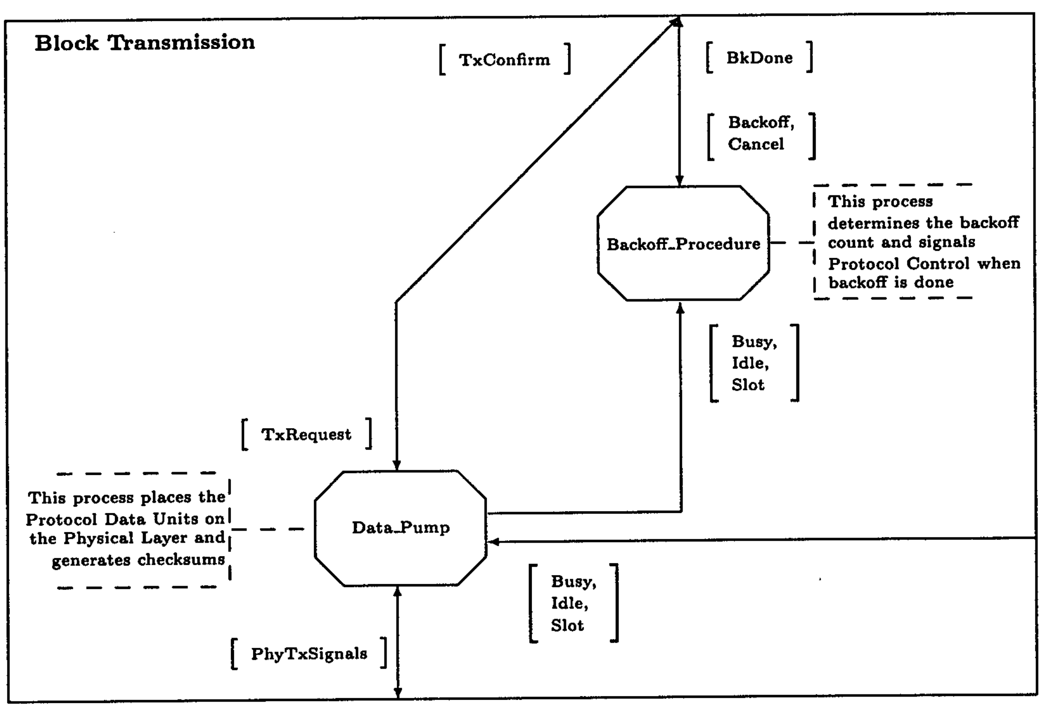

Figure A.3: Block Transmission

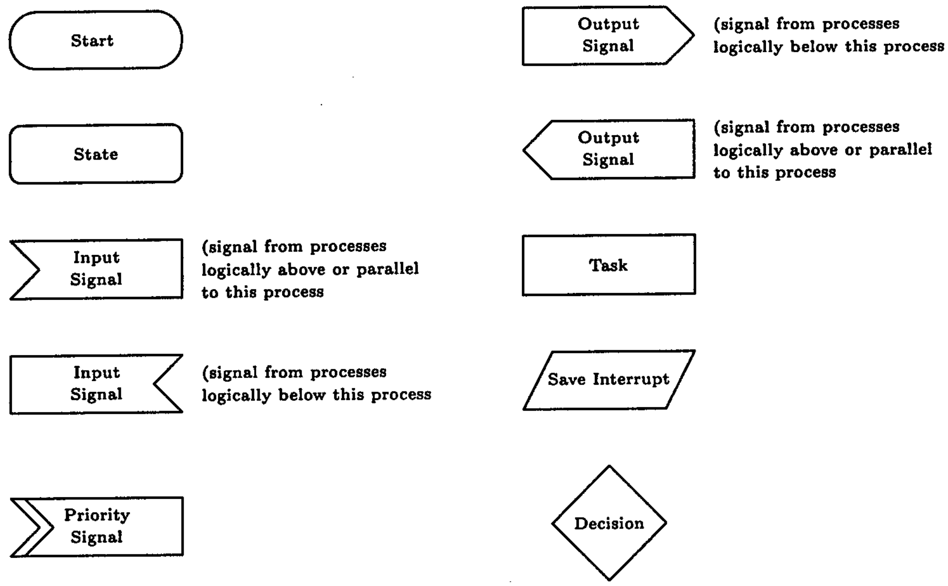

Figure A.4: Process Legend

The process objects have their own symbols, some of which include: start, state, input signal, output signal, priority signal, decision, save interrupt, and task. These process object symbols are shown in Figure A.4. They are self-explanatory if one keeps in mind that the process is essentially a finite state machine. One exception is the task symbol, which indicates algorithmic steps that need to be accomplished within the process.

Figure A.5 shows an extract of the process block for Data_Pump in Figure A.3. In this process, a computational task block is encountered first. Next, the process enters the Tx_Idle state where it remains until it receives one of the signals TxRequest, Busy, Idle, or Slot. If it receives TxRequest, the process transmits a packet via other processing not shown in the figure. If Data_Pump receives Busy, Idle, or Slot, Data_Pump sends the same signal to another process (in this particular example Backoff_Procedure) and returns to state Tx_Idle. The signal destinations are not explicitly identified in process objects. That information is contained in the appropriate SDL block.

These SDL objects map quite nicely to OPNET objects. The IEEE 802.11 System Station shown in Figure A.2 corresponds to a node. The processes within lower level blocks (i.e.,

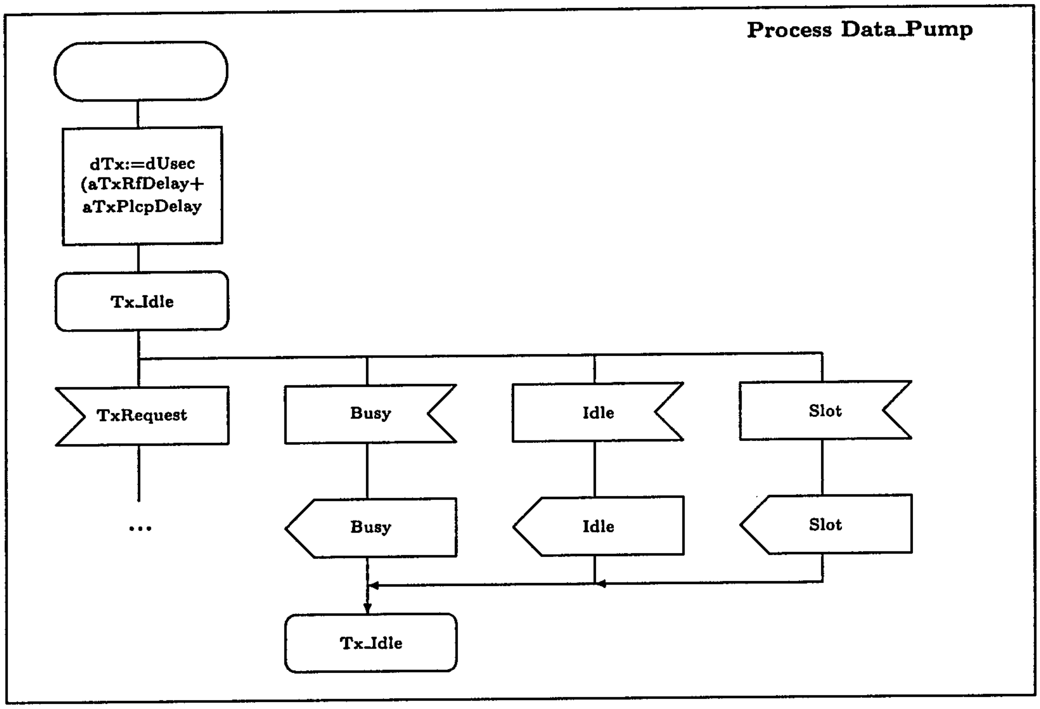

Figure A.5: Process Block

Data_Pump and Backoff_Procedure within Transmission) map to objects available within the OPNET Node Editor such as processors, queues, generators, etc. Referring to Figure A.5, the implementation of a process block corresponds to objects available within the OPNET Process Editor such as initial states, states, and transitions.

SDL signals are implemented using OPNET interrupts combined with state transition conditions. A task would be implemented using Proto-C code in state enter/exit executives or transition executives. Figure A.6 summarizes these mappings. SDL has other objects to model more complex behavior but it was found that they can all be implemented with ease in a manner similar to the objects discussed.

While metrics of programming errors were not collected, mapping the objects in the formal specification to OPNET objects seemed to greatly reduce the number of logical errors as well as reduce development time. This time included learning OPNET. In addition, the model was indeed a valid IEEE 802.11 implementation since it was translated directly from the

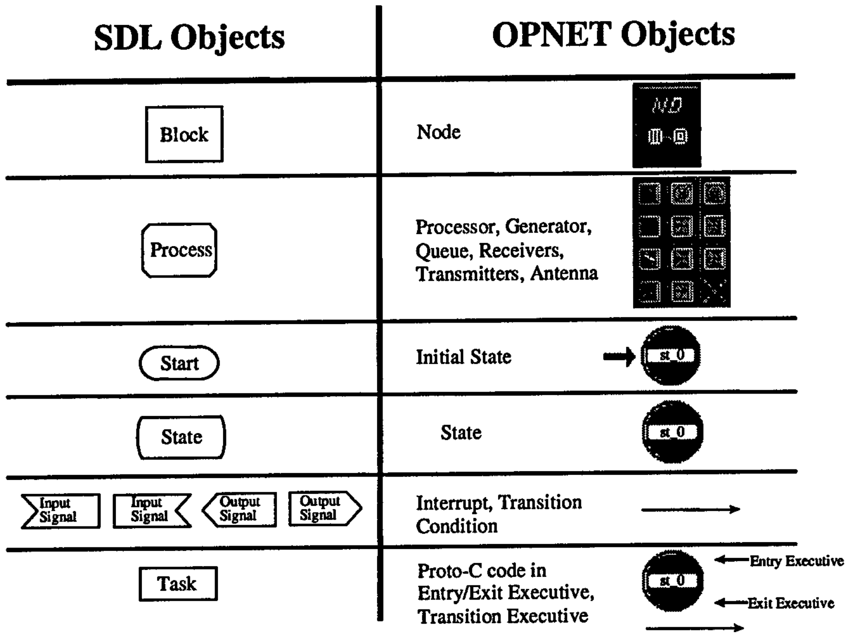

Figure A.6: SDL to OPNET Object Mapping

normative formal specifications.

A.3 Wireless LAN Simulation Model

This section documents the IEEE 802.11 simulation model. It begins at the node level and proceeds down the hierarchy to processes and parameters. The graphical portion of the SDL-92 specification language used in the IEEE 802.11 standard [Edi97] will also be used to document this simulation model. The specification contained in [Edi97] is a complete, valid SDL specification. The purpose of using SDL herein is to document the behavior of the simulation process models. Therefore, while elements of the SDL graphical language are used, it is not a complete SDL specification of the OPNET simulation model.

The simulation model implements the distributed coordination function (DCF) of IEEE 802.11. Stations (nodes) within the model form an *ad hoc* network (i.e., an independent basic service set (IBSS) in IEEE 802.11 terms). IEEE 802.11 functions not in the model include: encryption, authentication, power-save mode functions, fragmentation/de-fragmentation, and the point coordination function (PCF).

A.3.1 Node Model

The highest level SDL block in the model hierarchy is the System Station. This block is shown in Figure A.7 below and contains other blocks which specify functions within System Station. This figure is very similar to Figure A.2. The difference is that the signal names match the state transition condition name or state executive statement name used in the OPNET process models. The corresponding node level OPNET implementation is shown enclosed in the dashed-line box in Figure A.8; the solid-line boxes are the *MAC Service Access Point*, and the *PHYSICAL Service Access Point.* These functions are external to the System Station and are not defined by IEEE 802.11. Within the OSI network model (cf., Section 2.1.2, Figure 2.1), the *MAC Service Access Point* is part of the Logical Link Control sublayer within the Data Link Control layer. The *PHYSICAL Service Access Point* corresponds to the Physical layer in the OSI model. The signals shown in Figure A.7 are generally implemented by interrupts in OPNET and do not appear explicitly in Figure A.8. The solid and dotted lines with arrows in Figure A.8 represent packet flows within the System Station.

Moving down one level in the SDL hierarchy, the blocks within Figure A.7 (e.g., Protocol_Control_STA, Transmission, and Reception) are defined in terms of process models. Figures A.9, A.10, A.11 show the Protocol_Control_STA, Transmission, Reception blocks respectively.

A.3.2 Process Models

Process models describe the behavior of process objects (i.e., Data_Pump, Backoff_Procedure, Tx_Coordination_sta, Rx_Coordination, etc. of Figures A.3 and A.9) and are essentially

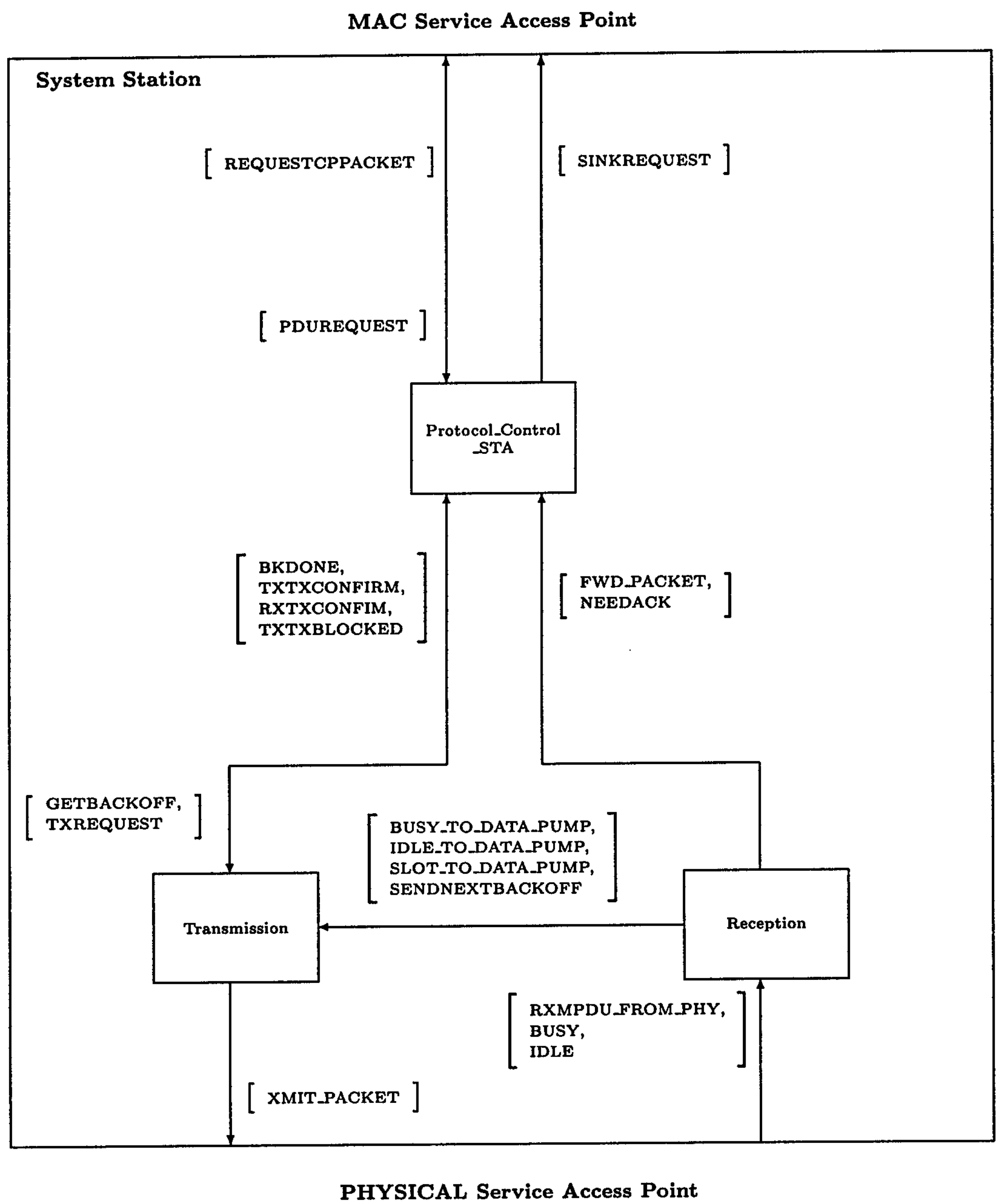

Figure A.7: SDL – System Station

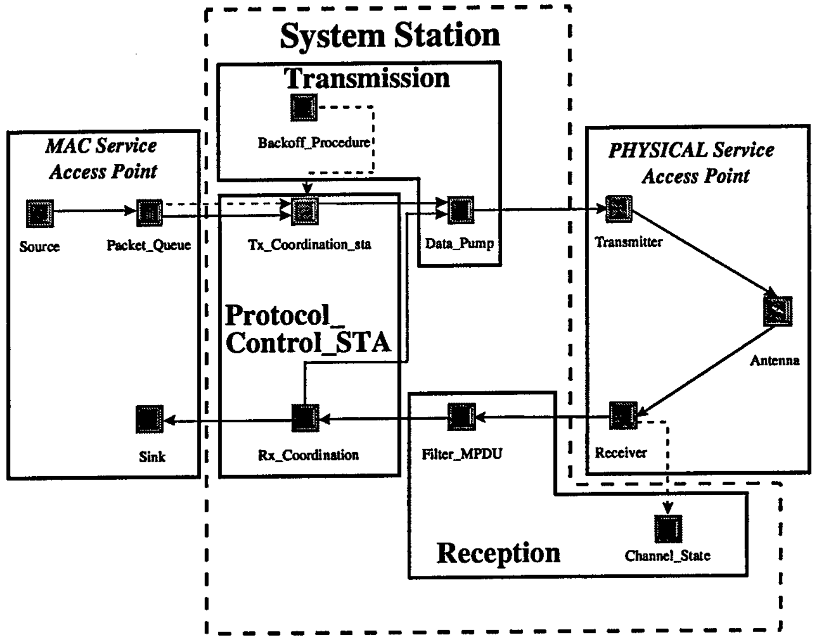

Figure A.8: OPNET Node – System Station

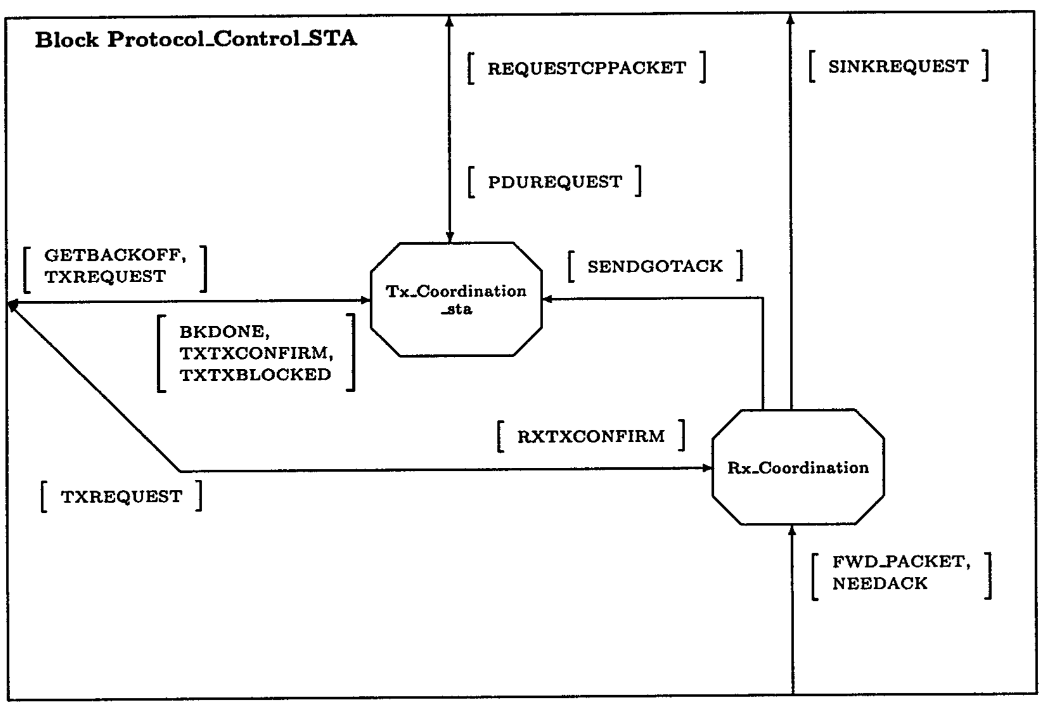

Figure A.9: SDL – Block Protocol_Control_STA

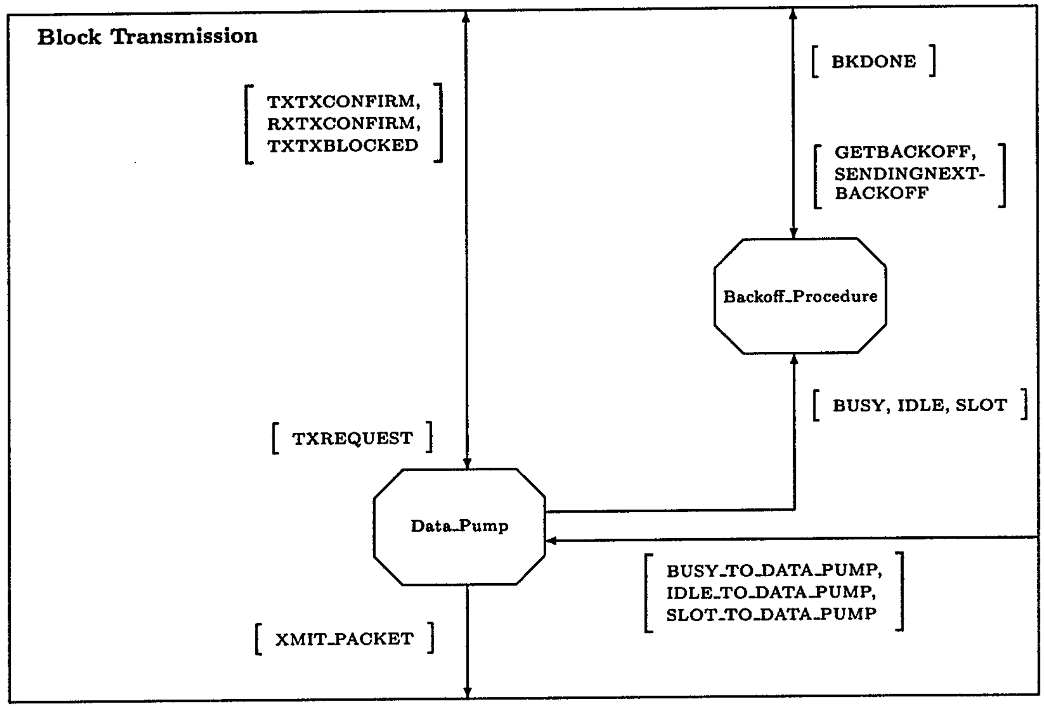

Figure A.10: SDL – Block Transmission

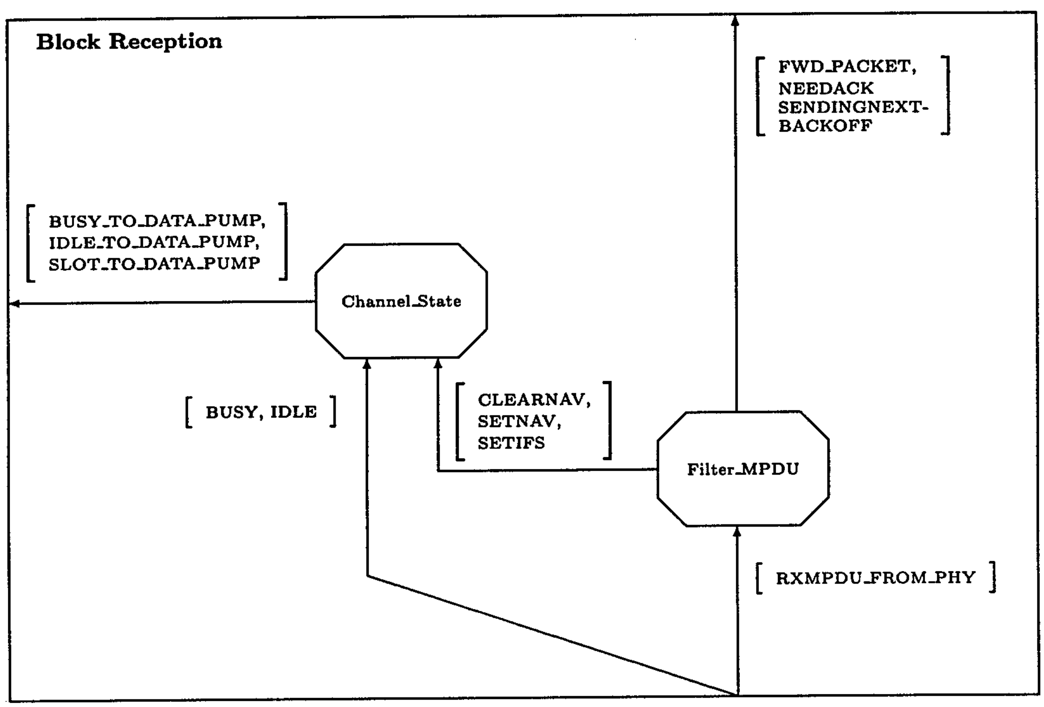

Figure A.11: SDL – Block Reception

finite state machines. The following sections describe the process models in the IEEE 802.11 simulation model.

A.3.2.1 Source

The Source process model (cf., Figure A.8) is not specified in the IEEE 802.11 standard. Source generates the packets that the station transmits. Source can generate three classes of data packets: hard real-time (i.e., packets with deadlines that cannot be missed), soft real-time (i.e., packets with deadlines that can be met within a certain tolerance), and ordinary data packets with no deadlines. Each class of data packets has up to three independent input streams that can be specified to simulate different applications running on the station. The packet arrival, size, and deadline distributions can be any of the predefined distributions supported by OPNET. In addition, the packet arrival distribution can be a Pareto distribution or an ON-OFF process. In an ON-OFF process stations are either transmitting (ON) at a specified rate or idle (OFF). The time spent in each state is exponentially distributed.

Figure A.12 shows the OPNET implementation of the Source process model. The circles are states that the process can be in. Source has four states: Start, Create Packet, Resubmit Packet, and idle. Within these states, processing, in the form of C language statements, is performed. These C language statements are not shown. The large solid arrow indicates the state the process starts in. Typically, any needed initialization is performed in this state. The gray circles indicate that any processing associated with the state is performed and then the state is exited. OPNET terms this a "forced" state. A process remains in an black colored state until a transition condition becomes true. Transitions that occur in response to a particular condition are shown by a dotted line with an arrow. The condition that triggers the transition is shown in parenthesis beside the line (e.g., (CREATEPACKET) in Figure A.12). Solid lines with arrows show unconditional transitions. In all process models, these transition conditions are implemented by C language statements and are all disjoint. That is, only one of the transition conditions is true at a particular time.

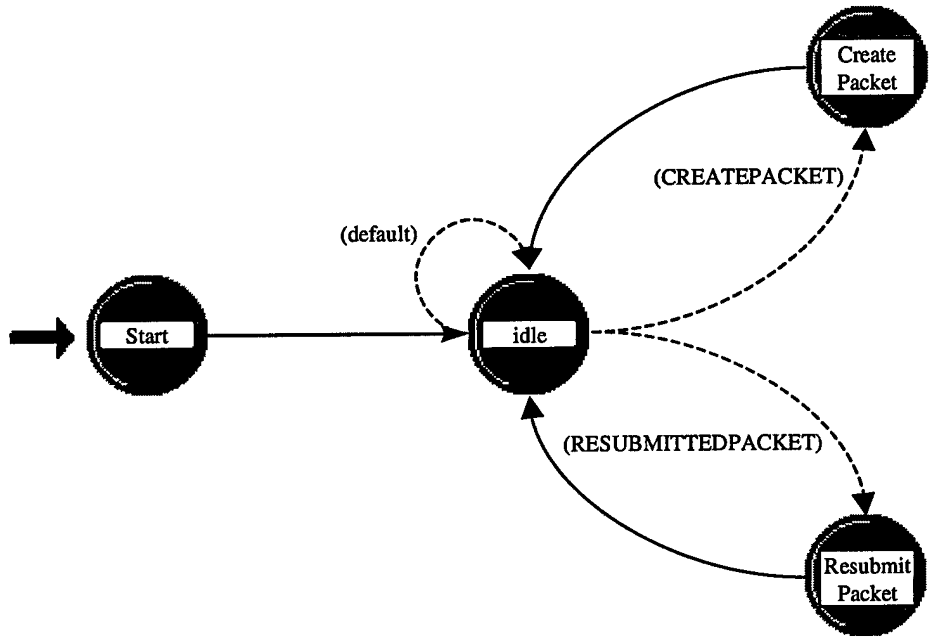

Figure A.12: Source Process Model

In the process Source, initialization occurs in the Start state. This initialization includes setting up the interrupts for the arriving packets and other OPNET specific initializations. After this is done, Source goes to the idle state. The only conditions which will cause Source to leave the idle state are CREATEPACKET and RESUBMITTEDPACKET. All other conditions cause idle to be exited and re-entered via the default transition. The CREATEPACKET condition is implemented in C and becomes true when any interrupt to create a packet occurs. When CREATEPACKET becomes true, the process goes to the Create Packet state. In this state, the interrupt source is determined, the particular class of packet indicated by the interrupt (i.e., hard, soft, or data) is created and sent to the process Packet_Queue. Source then unconditionally returns to the idle state. RESUBMITTEDPACKET becomes true when a packet discarded prior to transmission because it is late is sent back to Source for retransmission. When this occurs, the process goes to the Resubmit Packet state and the packet is recreated with the same characteristics as the discarded packet except that the deadline is updated (with respect to the current time). Source then unconditionally returns to the idle state.

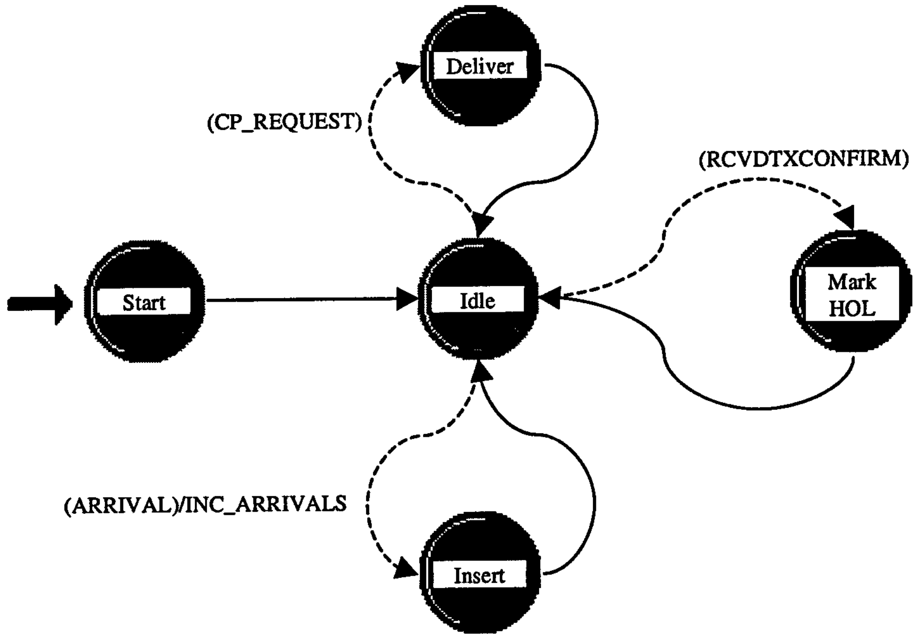

Figure A.13: Packet_Queue Process Model

A.3.2.2 Packet_Queue

Packet_Queue receives packets from Source and sends packets, upon request, to the process Tx_Coordination_sta. Figure A.13 is the process model for Packet_Queue. Packet_Queue, as with Source, is not part of the IEEE 802.11 specification.

Packet_Queue begins in the Idle state. If CP_REQUEST (i.e., contention period packet request) become true, it goes to the Deliver state. If transmission control is true (cf., Section A.4.1.32), Packet_Queue will check the packet to be delivered to see if can be transmitted before its deadline. If it can, it is delivered to Tx_Coordination_sta. Otherwise, it is discarded and the next eligible packet for delivery is chosen. The delivery order is by packet class; first, hard real-time packets, next, soft real-time packets, and finally, data packets. The queue discipline is either first-come-first-served (FCFS), last-come-first-served (LCFS), earliest-deadline-first (EDF), shortest-job-first (SJF), longest-job-first (LJF), or random (cf., Section A.4.1.26).

ARRIVAL is true when a packet arrives from Source. Along with the transition condition ARRIVAL, there is also what is called an "executive" statement (e.g. (ARRIVAL)/ - INC_ARRIVAL). The statement INC_ARRIVAL is executed after ARRIVAL becomes true and before entering the Insert state. INC_ARRIVAL is simply a C statement that increments a counter to track the number of packet arrivals. The counter is used for statistical purposes to determine the percentage of packets blocked due to a full queue. After INC_ARRIVAL is executed, the arriving packet is placed in the appropriate queue (i.e., hard, soft, or data). After a packet has been transmitted, RCVDTXCONFIRM becomes true. Packet_Queue transitions to the Mark HOL state and marks the next packet to be selected for transmission with the current time. This is done for statistical purposes only. The number of packets that can be held in the queue can be set to any desired value by adjusting the appropriate parameter in the Node Editor. The default value is 200 packets for each subqueue; hard real-time, soft real-time, and data.

A.3.2.3 Sink

The Sink process receives packets from the Rx_Coordination process. Currently, its only function is to destroy the packet. Its process model is not shown.

A.3.2.4 Transmitter, Receiver, and Antenna

The last process models which are not part of the IEEE 802.11 specification to be discussed are the transmitter, receiver, and antenna. The transmitter allows packets to be sent outside the node. Three types of transmitters are supported: point-to-point, bus, and radio. The receiver allows packets to be received from other nodes and has the same supported types as the transmitter. The antenna process model are used to specify antenna properties for radio transmitters and receivers. Attributes of the antenna such as antenna type, aiming parameters, and antenna patterns may be specified. The simulation model uses the default transmitter, receiver, and antenna (i.e., omni) available in the Node Editor. Their process models are not accessible to the user and are not shown.

A.3.2.5 Backoff_Procedure

This process implements the backoff function of IEEE 802.11 and is shown in Figure A.14. After Start, the process is in the No_Backoff state. This means that either the backoff counter is not active or has reached zero. Normally, it stays in this state until it gets a request to choose another backoff count (i.e., RCVDBACKOFF). If the RT-MAC (real-time MAC) protocol is active (cf., Section A.4.1.17), the RCVDNEXTBACKOFF and RCVDSLOT signals will cause the executives update_backoff_values() or decrement_slot_count() to be executed respectively (cf., Section A.3.2.2). These executives will also execute when RT-MAC is not active but it that case, they will return immediately. When RT-MAC is active update_backoff_values() records backoff values (or slot counts) obtained from other stations transmissions (even if the packet was not meant for this station). The decrement_slot_count() executive decrements all the slot counts that have been received from the other stations in the network (if any). Refer to Chapter 5 for a complete description of the purpose and operation of this algorithm. When RCVDBACKOFF becomes true, Tx_Coordination_sta has requested a backoff timer be set and get_slotCnt() is executed. This executive chooses an initial backoff value (if RT-MAC is active, it also ensures that the backoff value is not the same as any other stations backoff value) and then enters the Channel_Busy state.

In the Channel_Busy state, backoff values received from other stations will be recorded if RT-MAC is active (via (RCVDNEXTBACKOFF)/ update_backoff_values()). If a cancel (i.e., RVCDCANCEL) is received from Tx_Coordination_sta (i.e., the packet waiting to be transmitted will not be transmitted after all) the process returns to the No_Backoff state and send_bkdone_slotcnt() sends to Tx_Coordination_sta the current slot count value. If RCVDIDLE becomes true, the process goes to the Channel_Idle state. If RCVDSLOT becomes true the executive decrement_slot_count_from_nobackoff() is executed prior to entering the Channel_Idle state. The decrement_slot_count_from_nobackoff() executive decrements the

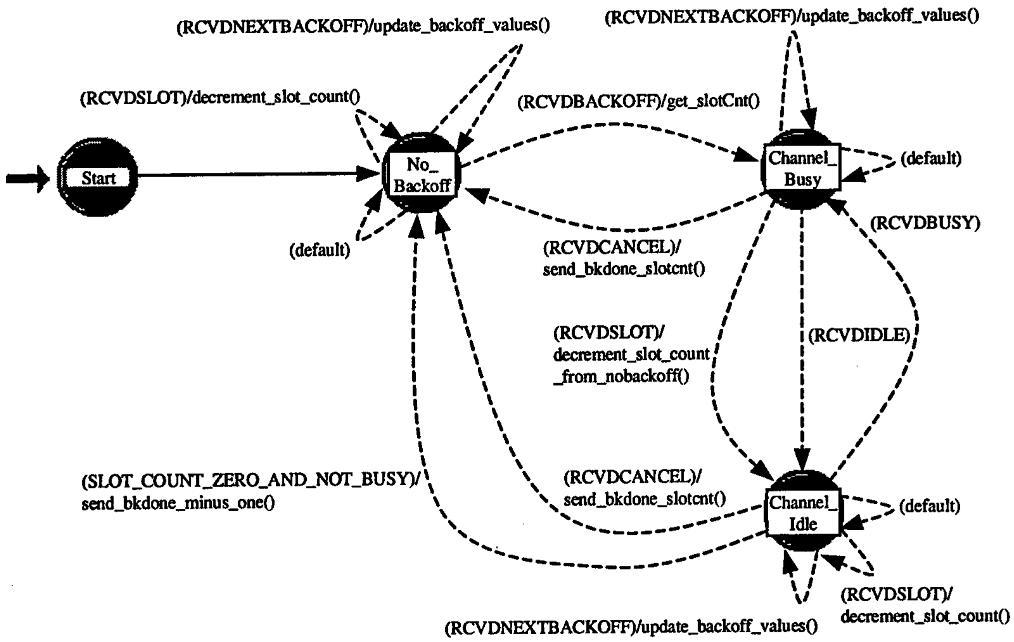

Figure A.14: Backoff_Procedure Process Model

slot counts from other stations but does not decrement this stations slot count.

In the Channel_Idle state, the slot counters (this stations and the other stations) are decremented once for every slot (i.e., (RCVDSLOT)/decrement_slot_count()). If the channel becomes busy, the process returns to Channel_Busy. When the backoff count reaches zero in the Channel_Idle state, the BkDone signal is sent (i.e., (SLOT_COUNT_ZERO_AND_-NOT_BUSY)/ send_bkdone_minus_one()). If a cancel is received in this state, the executive send_bkdone_slotcnt() is executed as in the Channel_Busy state.

The graphical SDL description of this part of the simulation model is shown in Figure A.15. This SDL description defines the behavior of the process and shows the computations that the executive statements and process states implement.

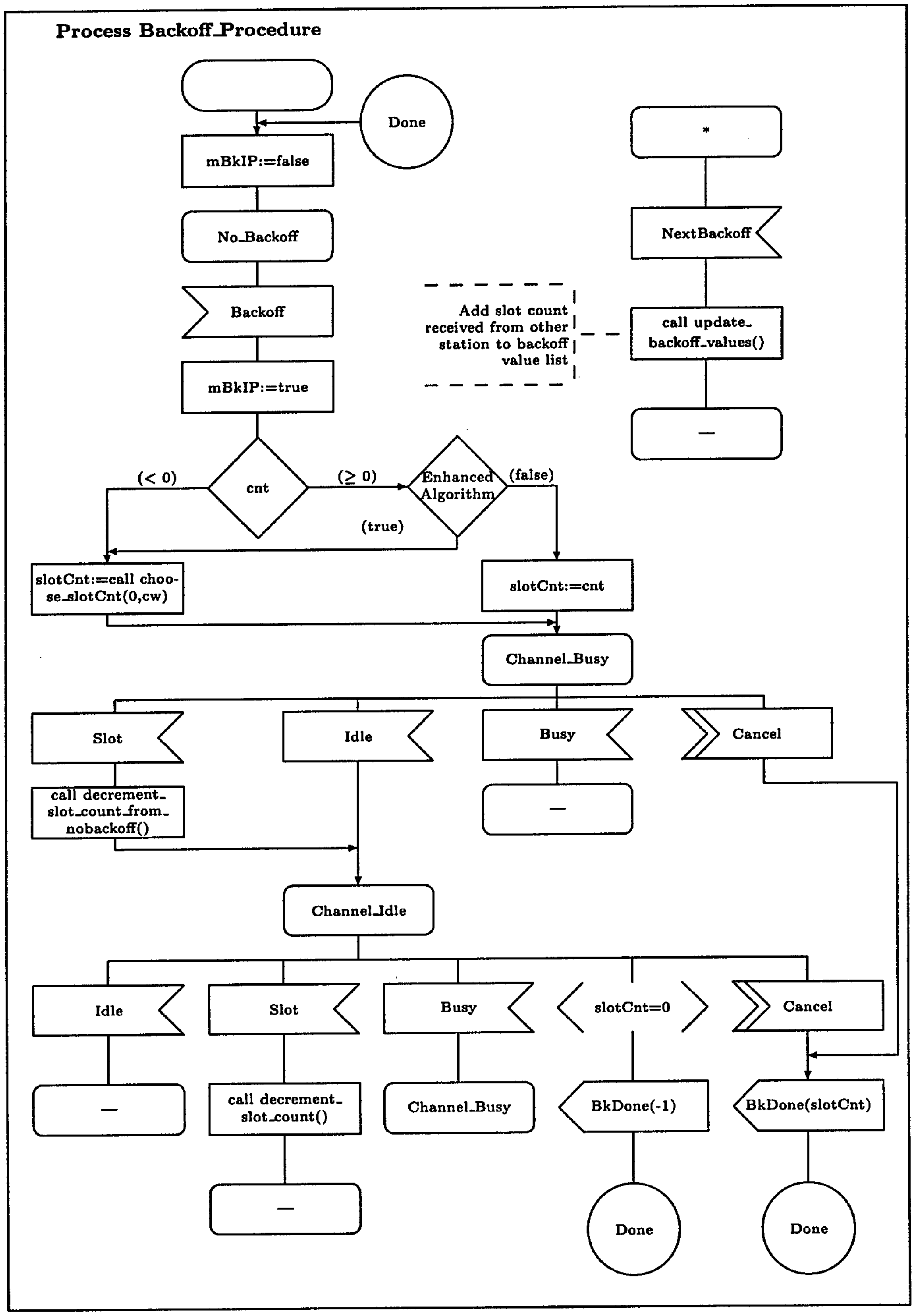

Figure A.15: Backoff_Procedure – SDL Description

A.3.2.6 Data_Pump

Data_Pump (Figure A.16) is the process that receives the packet to be transmitted and places it onto the channel. The process begins, as usual, in Start and immediately proceeds to the Tx_Idle state. If the process receives a TXREQUEST, it obtains the packet to transmit and sends a busy signal to the station. Then it goes to the Wait_TxStart state. It will stay in this state until an idle or a slot has been detected, whereupon it will go to the Send_Frame state and, like Packet_Queue, if transmission control is true will check the packet to see if can be transmitted before its deadline. If the packet cannot be transmitted prior to its deadline, it is discarded and Tx_Coordination_sta is informed. Otherwise, Data_Pump transmits the frame. After transmitting the frame, it returns to the Tx_Idle state. A similar procedure occurs from the Tx_Idle state when the ACKREQUEST condition is true. In this case, however, the process does not need to wait for an idle or a slot to be detected since sending an ACK implies that this station alone needs to respond. Hence, there is no possibility of a collision occurring. The SDL description of Data_Pump behavior is shown in Figure A.17 below.

A.3.2.7 Filter_MPDU

This process determines whether a received packet is bound for the station that received it. In the simulation model, its function is greatly simplified since the process does not need to handle the point coordination function (PCF) control packets, authentication, or multicast packets and the like, which have not been implemented. The Filter_MPDU process model is shown in Figure A.18. After beginning in the Start state, the process proceeds to Filter_Idle. In this state, the process simply waits for an incoming packet. When a packet arrives, the process transitions to the Process Packet state. In this state the packet is examined and discarded if it is corrupt due to bit errors or collisions. If it is not corrupt, the process determines whether the packet is bound for this station. If so, it is sent on to Rx_Coordination. If not, the Network Allocation Vector (NAV) contained in the packet

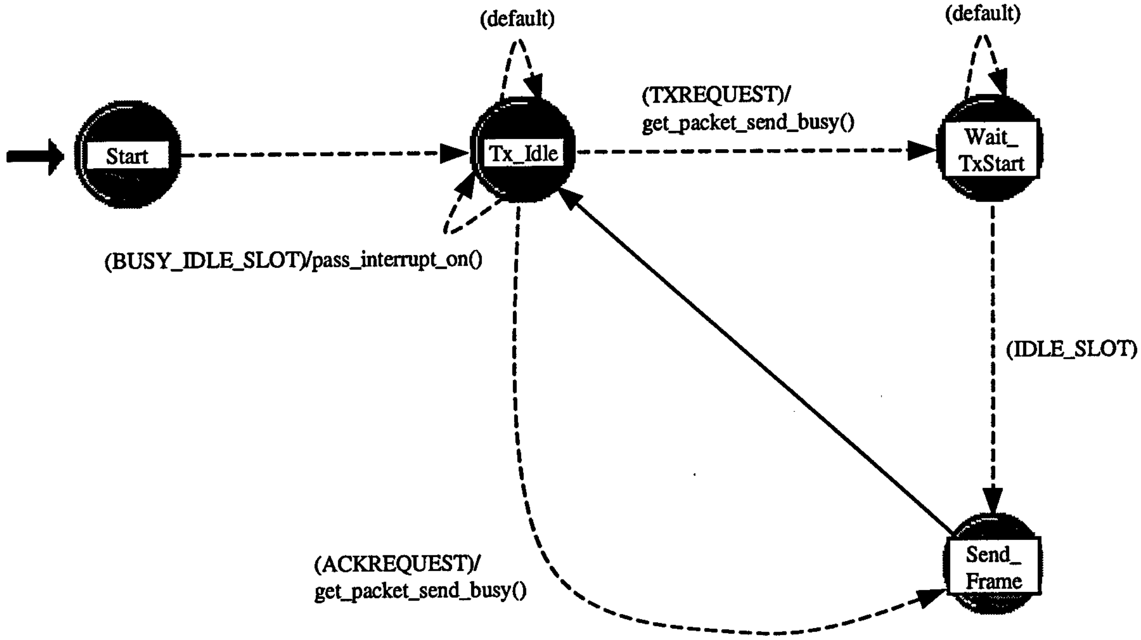

Figure A.16: Data_Pump Process Model

(e.g., the amount of time the channel will be in use due to this transmission) is obtained, and then the packet is discarded. If RT-MAC is being used, the packet will also contain the next backoff value that the transmitting station will be using. This value will be sent to Backoff_Procedure via the SENDBACKOFF signal. The process model is quite simple since most of the processing is contained within the Process Packet state. The SDL description of the process are shown in Figures A.19 and A.20. The cache referred to in the SDL description is a cache of packet identifiers to permit duplicate packet filtering. This allows the station to detect and discard packets that may have been resent due to a lost ACK.

A.3.2.8 Channel_State

The state names in the Channel_State process (Figure A.21) reflect the physical and virtual busy channel detection capability of an IEEE 802.11 station. The physical busy channel detection capability uses a standard carrier sensing (CS) process. The virtual busy channel detection capability uses a network allocation vector (NAV). The NAV is a value contained

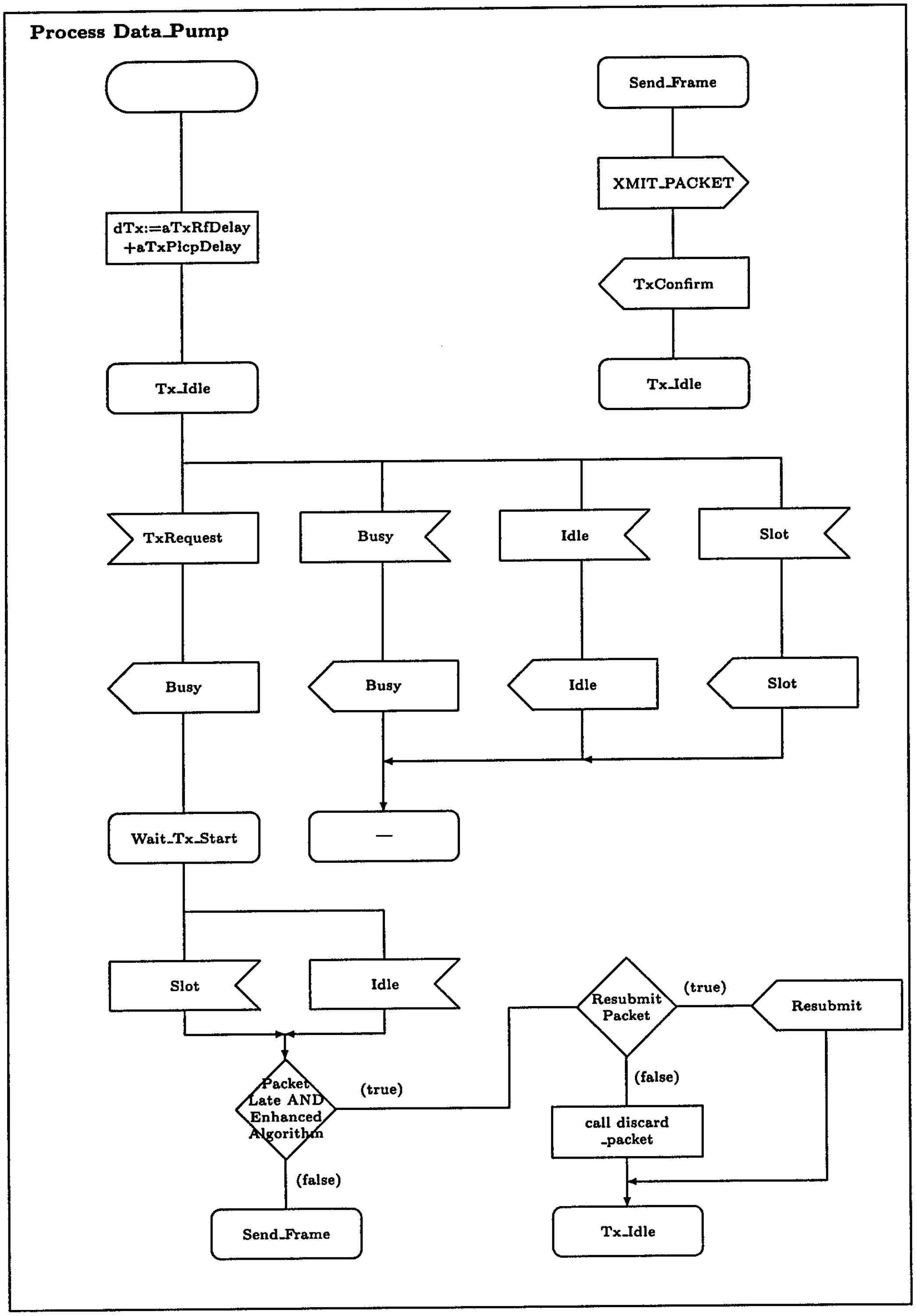

Figure A.17: Data_Pump – SDL Description

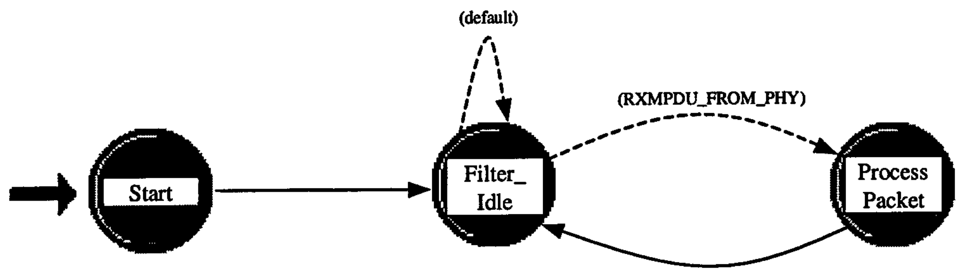

Figure A.18: Filter_MPDU Process Model

in an incoming packet which indicates the amount of time the channel will be needed to complete the current transmission (i.e., transmit an acknowledgment in response to a received packet). Stations in the network will not initiate a transmission for the duration of a NAV. This ensures that the ACK for the current packet does not collide with a new packet transmission. Both the CS and the NAV must indicate an idle channel for a station to initiate a transmission. The process will be in state Cs_Nav when the channel is both physically (CS) and virtually (NAV) busy. The process will be in Cs_noNav when the channel is physically busy but not virtually busy, and so on.

As always, the process model begins in the Start state. From there it goes to the Cs_noNav state. There are several transition conditions which are common to most states. Those common transition conditions are: RCVDCHANGENAV, DIFS_OR_ EIFS, and SETNAV_-CLEARNAV. The condition RCVDCHANGENAV becomes true after the Filter_MPDU process decodes a packet containing a NAV and determines that the current NAV needs to be changed. Channel_State will update its NAV and return to whatever state it was in prior to the condition becoming true. When the condition DIFS_OR_EIFS is true, Channel_State will update the value used for the inter-frame space (IFS) and then return to the state it was in prior to DIFS_OR_EIFS becoming true. The IFS is the amount of time the station waits after the channel is both physically and virtually idle before actually declaring the channel idle. The DIFS value is the smaller value and is used as the IFS when the packet cyclic redundancy code (CRC) is verified as good. If the CRC check fails, then the longer EIFS is used for the IFS. The condition SETNAV_CLEARNAV becomes true after the Filter_MPDU

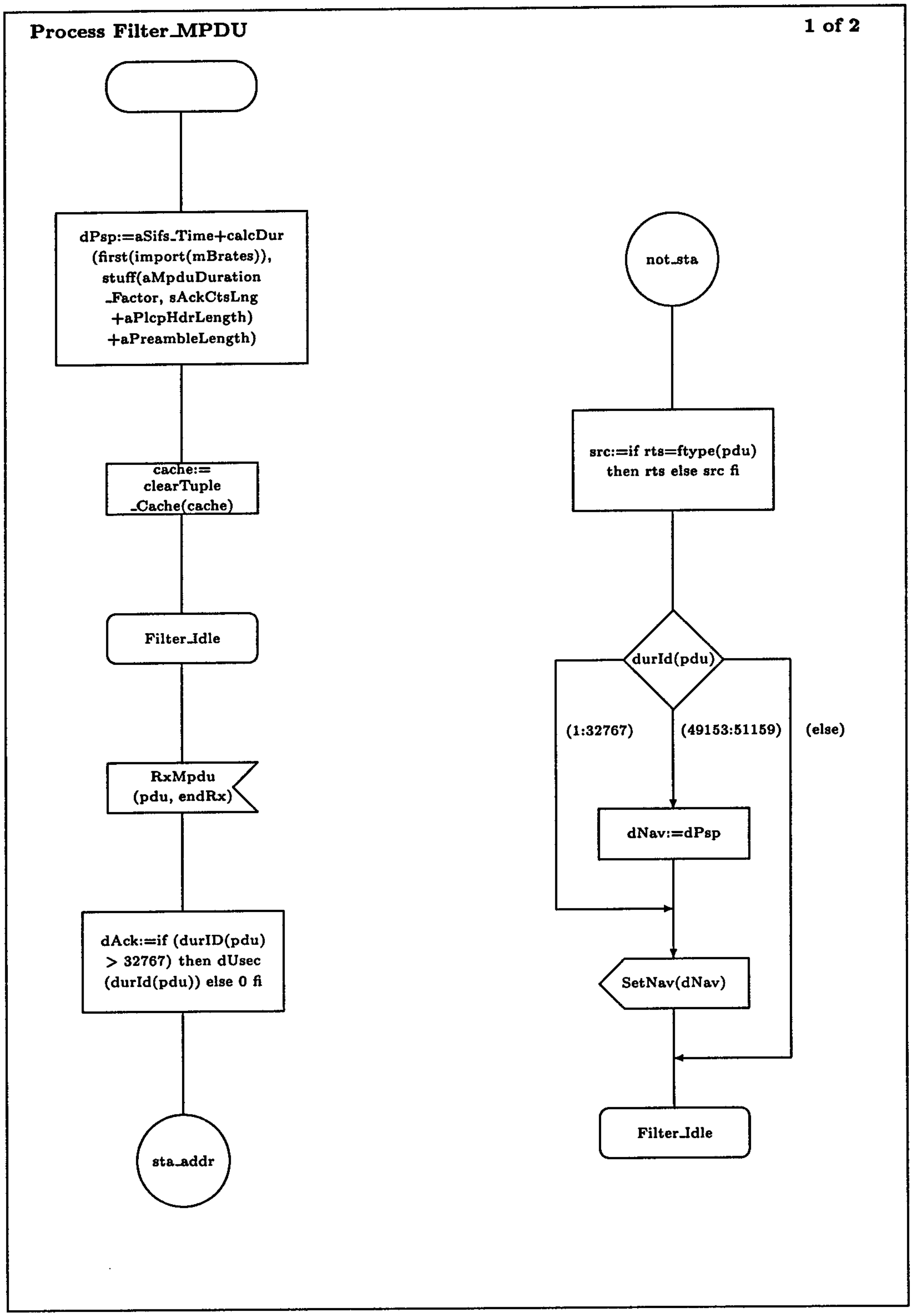

Figure A.19: Filter_MPDU – SDL Description (1 of 2)

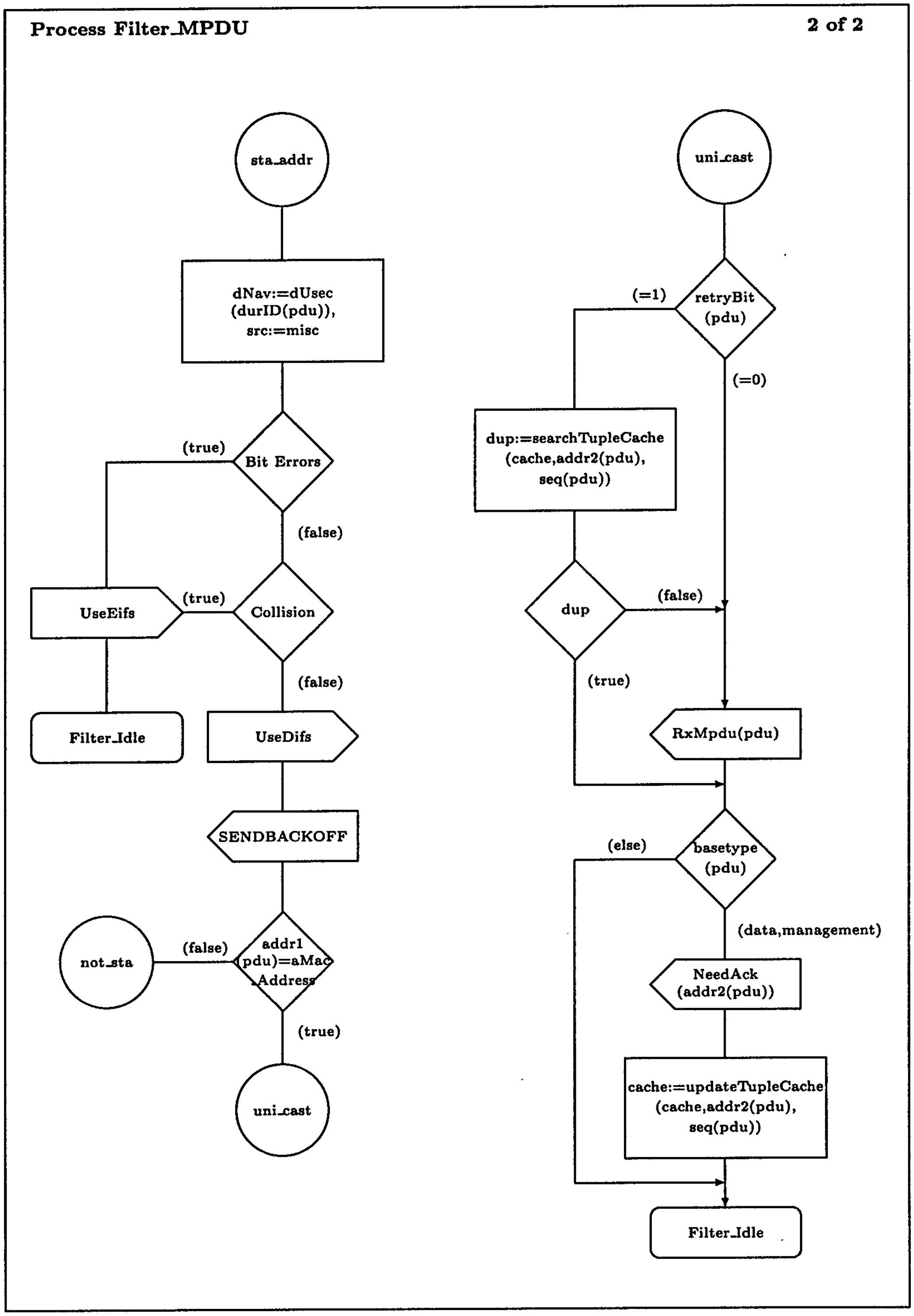

Figure A.20: Filter_MPDU – SDL Description (2 of 2)

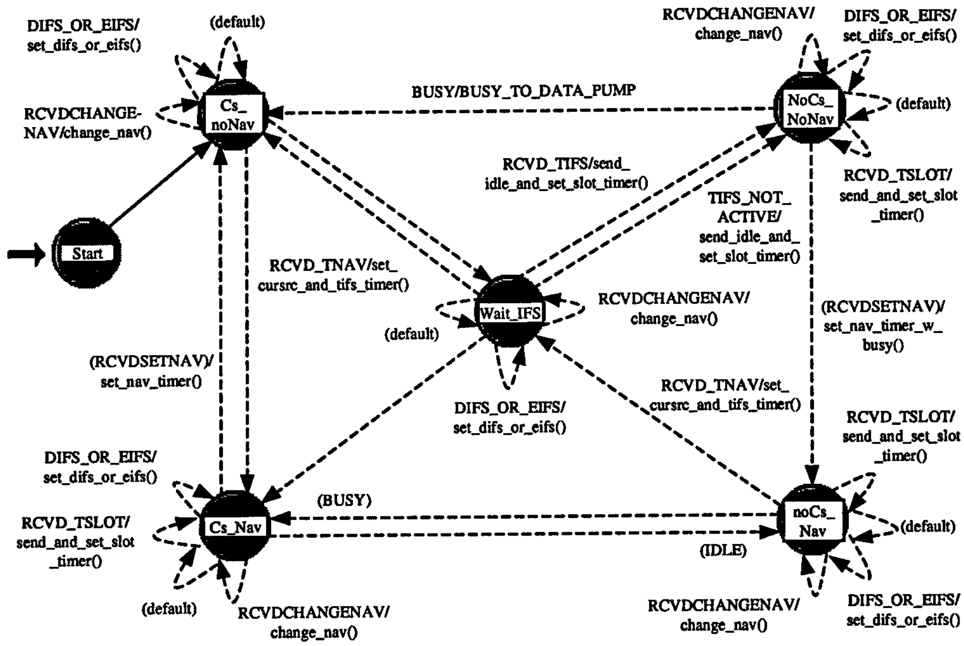

Figure A.21: Channel_State Process Model

process decodes a packet containing a NAV and determines that the NAV needs to be set or cleared. After setting or clearing the NAV the process again returns to the state it left from.

There are two ways to go to another state from Cs_noNav. First, the condition RCVDSET-NAV becomes true, indicating that the process now has a non-zero NAV. This will take the process to the Cs_Nav state and set the NAV timer. The second way to leave Cs_noNav is for the channel to physically be detected as idle. When this happens the process sets a timer based on the current value for the IFS, and then goes to the Wait_IFS state.

In the Wait_IFS state, there are three possibilities: (1) the condition RCVDSETNAV could become true, (2) the IFS timer could expire or be inactive, or (3) the channel could again become busy. If the RCVDSETNAV becomes true, the process goes to the Cs_Nav state (even though the channel is only virtually busy) and sets the NAV timer. If the IFS timer expires or it is not active, the process will declare the channel idle, start a slot timer (to begin counting slots) and go to the noCs_noNav state. If the channel is detected as busy prior to the IFS timer expiring, the process will go to the Cs_noNav state. When the IFS timer does expire in the Cs_noNav state, it will be ignored.

The Cs_Nav state will be left if the NAV timer expires or the channel is detected as idle. In the first case, the process will set the IFS timer and go to the Cs_noNav state. In the second case, the process will simply go to the noCs_Nav state. The noCs_Nav state will be exited if the channel is detected as busy. In that case, the process will go to the Cs_Nav state. The other way to exit this state is for the NAV timer to expire. When this happens, the process will set the IFS timer and go to the state Wait_IFS.

The noCs_noNav state will be exited if the channel is detected as busy. When this happens, the process sends a busy interrupt to the process Data_Pump and goes to Cs_noNav. If the RCVDSETNAV condition becomes true in this state, the NAV timer is set with the appropriate value, a busy interrupt is sent, and the process goes to noCs_Nav. The SDL description of Channel_State are shown in Figures A.22 and A.23.

A.3.2.9 Tx_Coordination_sta

The Tx_Coordination_sta process model is shown in Figure A.24. After Start, Tx_Coordination_sta goes to the TxC_Idle state. The process will leave TxC_Idle when it detects that the station queue has a packet to transmit (i.e., PDUREQUEST is true). It will request the packet be delivered from the queue and then enter the state GET_PACKET to wait for its arrival. From here, if NOELIGIBLEPACKET becomes true, the process returns to TxC_Idle. NOELIGIBLEPACKET could become true if transmission control is true and Queue determines that no packet in the queue will arrive on time if transmitted. Once SENTPACKET is true, the process obtains the packet, makes a copy of it (for later retransmission if necessary), and then goes to the Wait_MPDU_Backoff state. It stays in Wait_MPDU_Backoff while the backoff timer is non-zero. When the backoff timer is determined to be zero (i.e., INTRPT-NOTINBACKOFF is true), the packet is sent to the process Data_Pump for transmission and the Wait_Pdu_Sent state is entered.

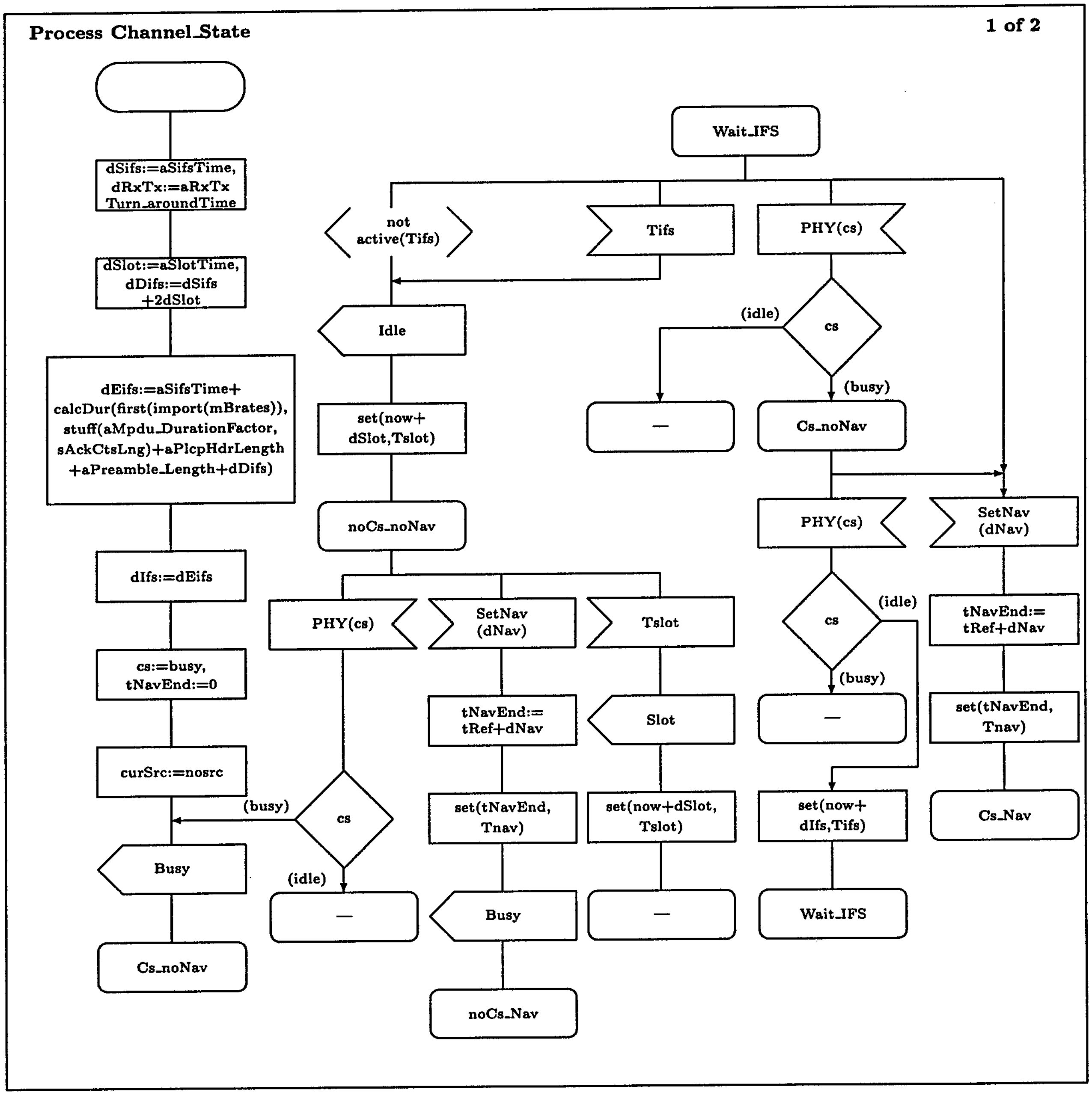

Figure A.22: Channel_State – SDL Description (1 of 2)

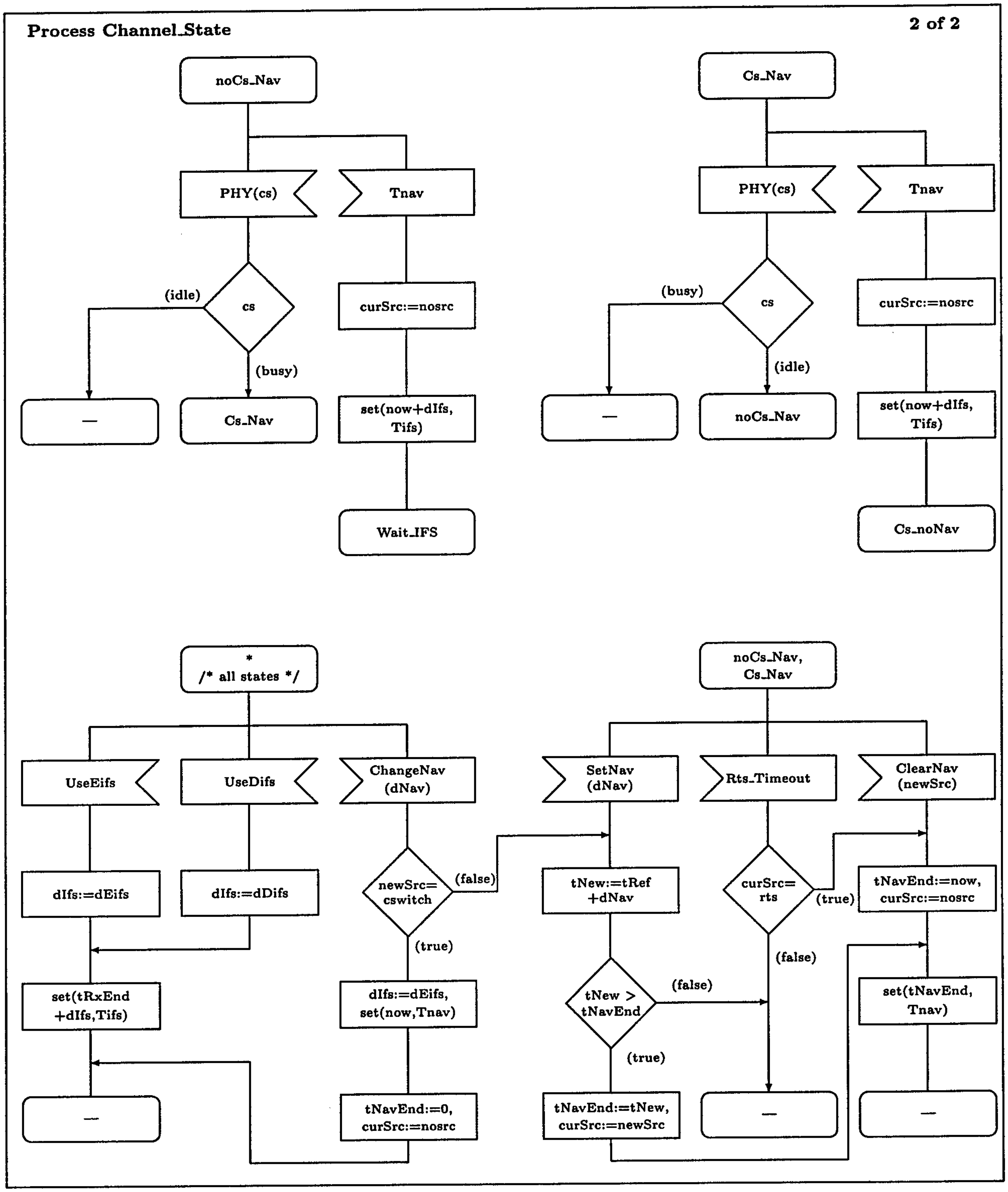

Figure A.23: Channel_State – SDL Description (2 of 2)

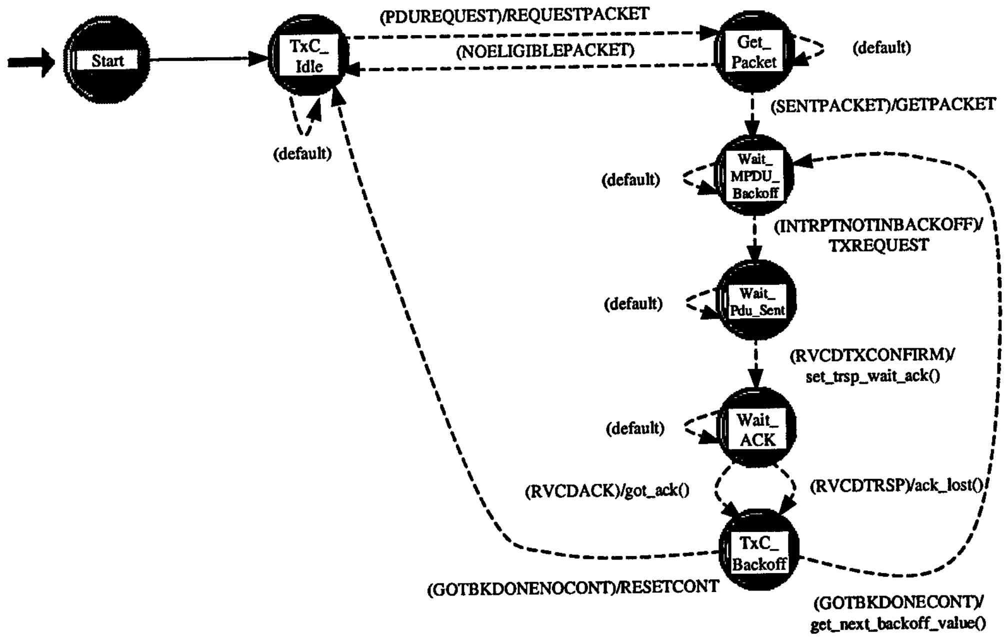

Figure A.24: Tx_Coordination_sta Process Model

If Data_Pump sent the packet, RCVDTXCONFIRM will become true. A timer is then set to wait for the ACK from the receiving station and the process goes to Wait_Ack. If the timer expires in this state, the packet is assumed to have been lost and a flag is set to reflect that assumption. If transmission control is true, the executive ack_lost() will check to see if the packet is late. If so, or if the maximum number of retries has been exceeded, it will discard the packet. If the ACK is received, the same flag is set to reflect a received ACK and the process goes to TxC_Backoff. In this state, another backoff count is obtained and the station waits for the backoff timer to expire. When this occurs, based on the value of the flag, the process goes to TxC_Idle, if an ACK was received, or to Wait_Mpdu_Backoff, if the ACK was not received.

If Data_Pump discarded the packet (since it was late or would have arrived late), RCVDTX-BLOCKED will become true and Tx_Coordination_sta will behave as above when an ACK is successfully received.

The SDL description of Tx_Coordination_sta are shown in Figures A.25 and A.26.

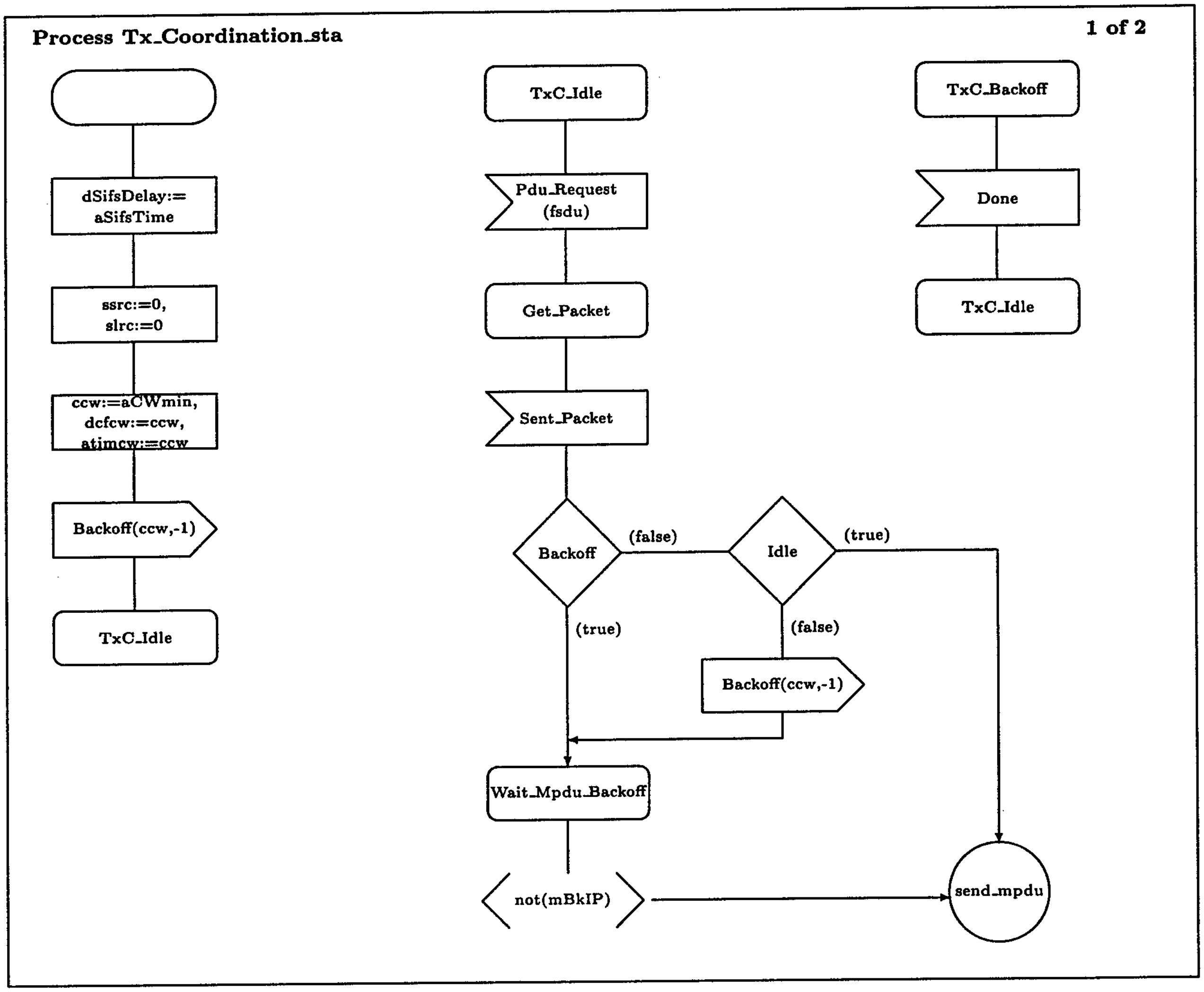

Figure A.25: Tx_Coordination_sta – SDL Description (1 of 2)

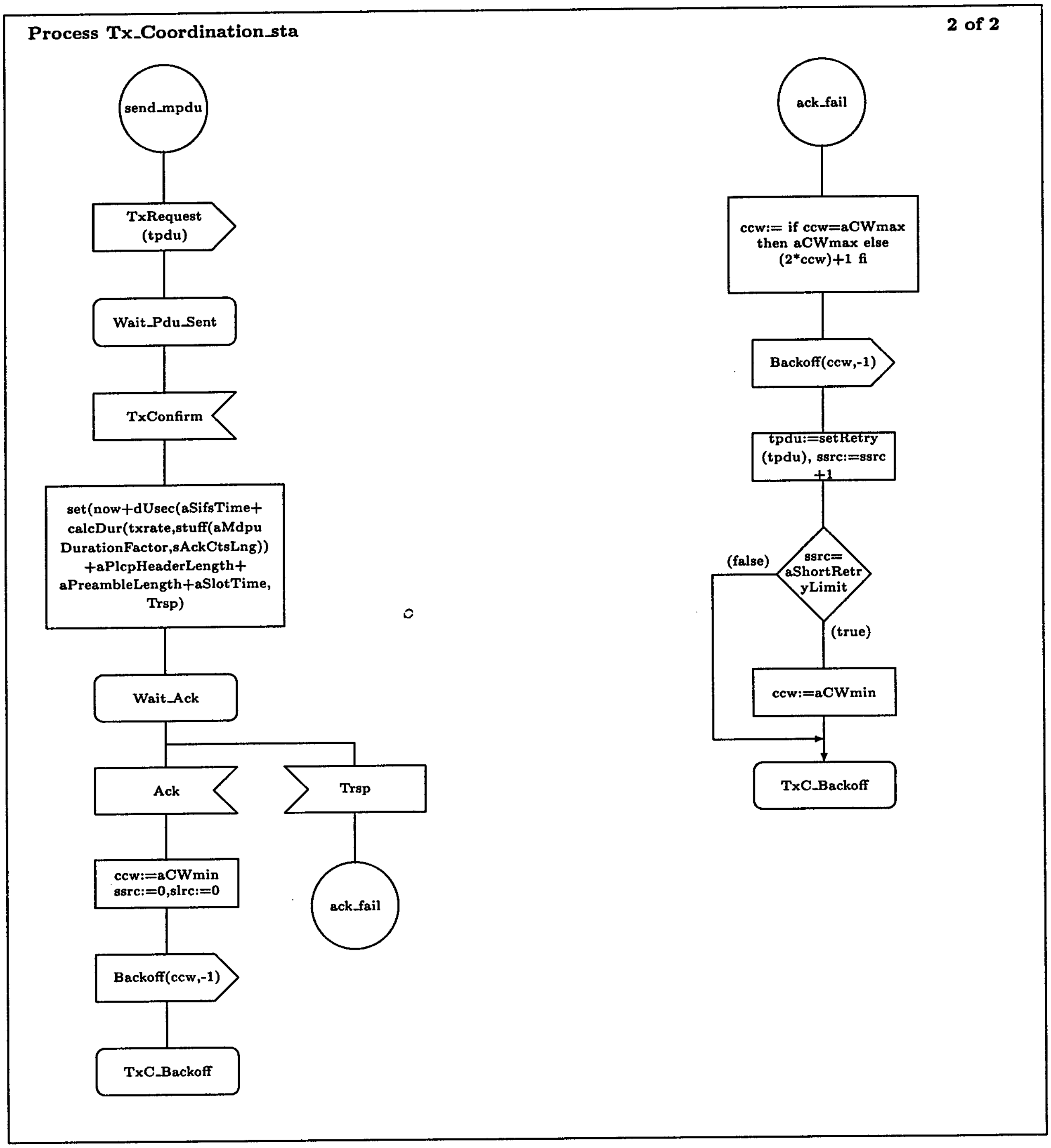

Figure A.26: Tx_Coordination_sta – SDL Description (2 of 2)

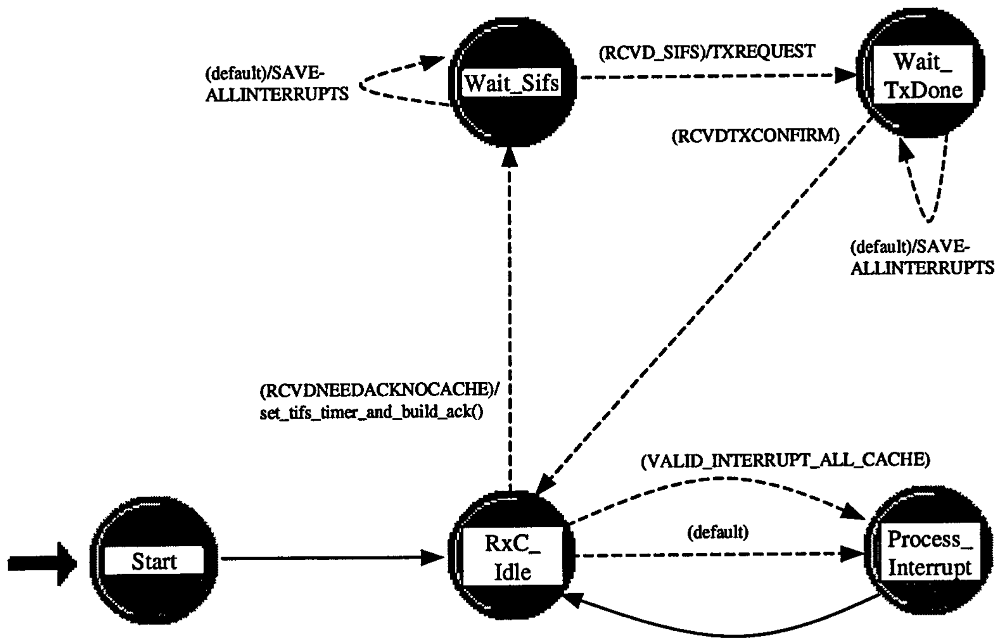

Figure A.27: Rx_Coordination Process Model

A.3.2.10 Rx_Coordination

The process model for Rx_Coordination (Figure A.27) begins in Start and goes to Rx_Idle. If an interrupt occurs or there are any saved interrupts (i.e., VALID_INTERRUPT_ALL_-CACHE) the process will transition to the Process_Interrupt state, process the interrupts, and return to RxC_Idle. The RCVDNEEDACKNOCACHE condition being true indicates that an ACK needs to be sent in response to a received packet. The process will set a timer, build the ACK and go to the Wait_Sifs state. After the timer expires the process will send the ACK packet for transmission and enter the Wait_ TxDone state. After receiving confirmation of packet transmission, the process leaves Wait_TxDone and returns to RxC_Idle. The SDL description of Rx_Coordination is shown below in Figure A.28.

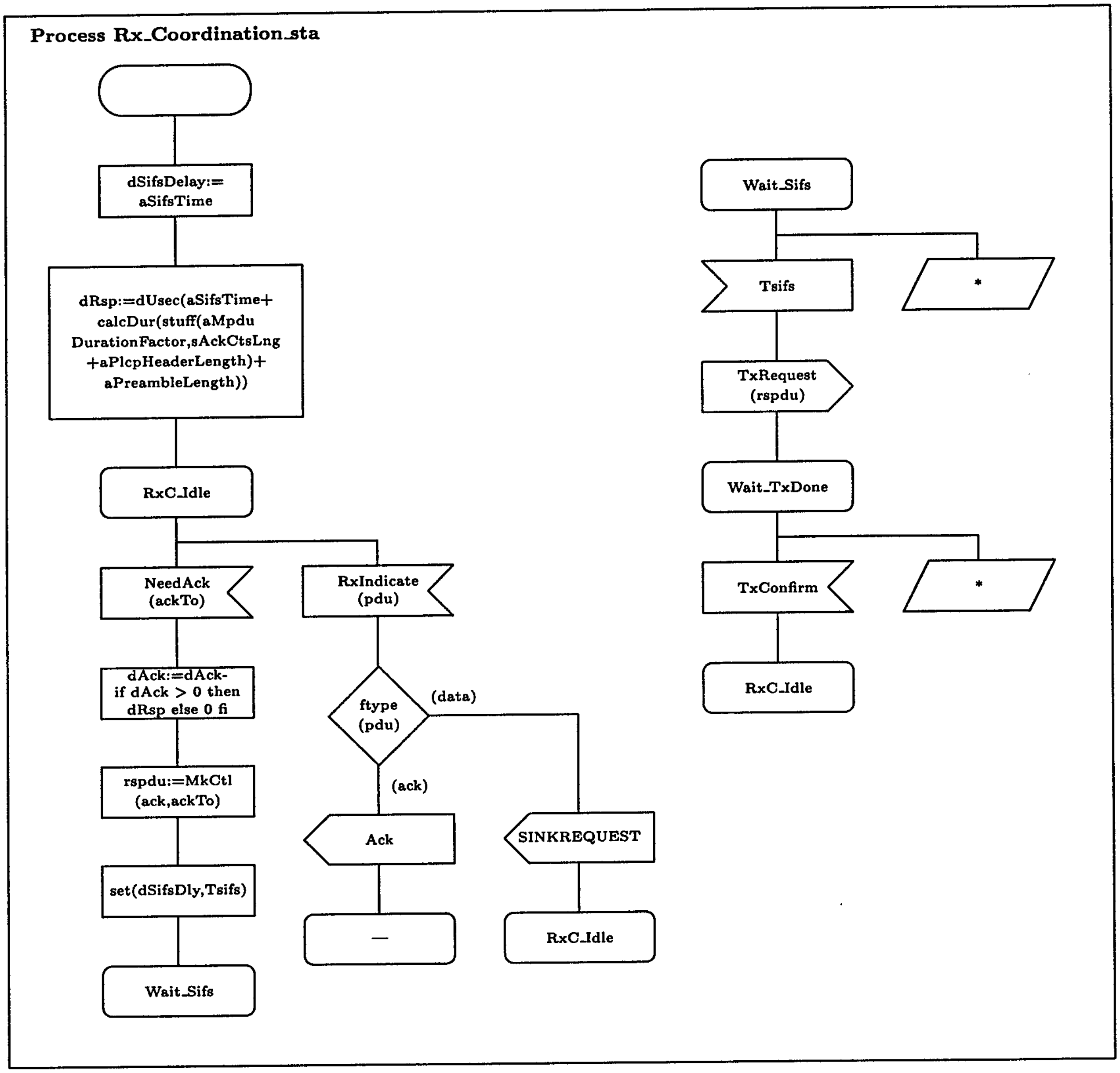

Figure A.28: Rx_Coordination – SDL Description

A.3.2.11 Packet Format

The packets that are transmitted in the simulation model contain several fields, some of which are specified by IEEE 802.11 and some which are used to record information about the packet as it moves through the network. The packet format used in the simulation model is shown below in Table A.1. The fields Mean Time in Good State, Mean Time in Bad State, and Probability of Bit Error are used to pass error model information to the error model in the transceiver pipeline (Section A.4.6.3). This information is used to initialize the model and is needed only once, but there does not appear to be any other way to get the required information to the model within the transceiver pipeline.

A.3.2.12 Traffic_Monitor

The purpose of Traffic_Monitor is to gather statistics about the network. It acts as a network "sniffer" or oracle by receiving all transmissions and recording traffic statistics. The OPNET node model consists of a single processor node.

The Traffic_Monitor process model (Figure A.29) begins in Start and then goes to the Idle state. Upon reception of a packet it goes to Process Packet, records all the statistics and then returns to Idle. Several statistics of interest cannot be determined from packet traffic. These include transmission attempts, station queue size, packets turned away due to a full queue, and packets not transmitted due to deadline expiration. These statistics are sent to Traffic_Monitor via RVCDATTEMPTSTAT, RVCDQSTAT, RCVDTURNEDAWAYSTAT, and RCVDBLOCKEDSTAT respectively. After recording the statistic, Traffic_Monitor returns to Idle. The only stations' queue size and % packets turned away tracked is that of Node 0. They are used as an indication of the behavior of the other stations.

Table A.1: Simulation Model Packet Format

Field Name	Data Type	Description
Type	integer	Packet type
Subtype	integer	Packet subtype
Address 1	integer	Address of the destination station
Address 2	integer	Address of the source station
Duration/ID	integer	Network Allocation Vector
Deadline	double	Packet deadline
Retry	integer	Retry bit
Sequence Number	integer	Packet sequence number
Fragment Number	integer	Packet fragment number
Timestamp	double	General purpose timestamp
endRx	double	Time reception ended
Class	integer	Packet class
Xmit Duration	double	Transmit time
Debug Packet	integer	Debug packet flag
Data Octets	integer	Number of data octets in packet
Attempts	integer	Number of attempts to send original packet
Creation Time	double	Time original packet was created
Transmit Start Time	double	Starting time for current transmission
HOL Time	double	Time packet reached head-of-line in transmit queue
Deadline Variance	double	Allowable deadline variance
Next Backoff Value	integer	Sending stations next backoff value
Mean Time in Good State	double	Mean good time for error model
Mean Time in Bad State	double	Mean bad time for error model
Probability of Bit Error	double	Bit error probability for error model

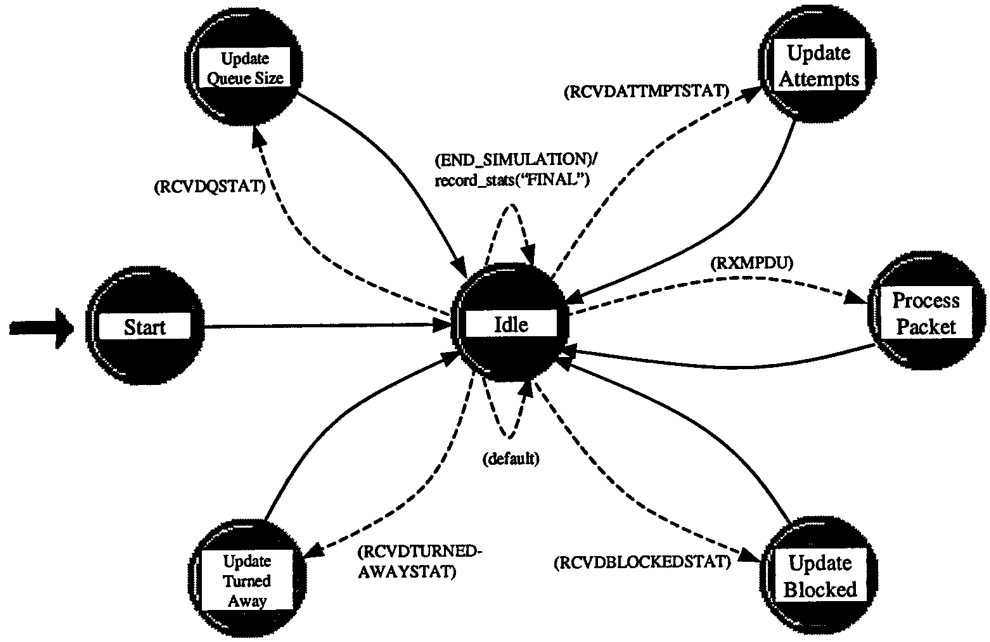

Figure A.29: Traffic_Monitor Process Model

A.4 Simulation Parameters

There are two types of simulation parameters. One type controls the simulation model such as simulation length and data collection start time. The other defines a characteristic of the network such as the number of stations. These parameters are discussed in this section. The parameters are organized by node and process models. The parameters are presented within the node or process model section in which they are originally defined.

A.4.1 IEEE80211STA

IEEE80211STA is the node model which defines an IEEE 802.11 station within the simulation model. It defines the interconnections between the process models. It is shown in Figure A.8. Over 30 different parameters can be varied, most of which are IEEE 802.11 parameters. These parameters are described below.

A.4.1.1 aCCATime

This parameter specifies the amount of time within every slot the clear channel assessment (CCA) mechanism has to determine whether the channel is idle. Its default value is 15 usec.

A.4.1.2 aCWmax

This is the maximum value (in slots) of the contention window. Its default value is 1023.

A.4.1.3 aCWmin

This is the minimum value (in slots) of the contention window. Its default value is 31.

A.4.1.4 aMPDUMaxLength

This specifies the maximum supported MAC protocol data unit (PDU) length. Its default value is 8191 octets.

A.4.1.5 aPLCPHeaderLength

This parameter specifies the length of the header in the physical layer convergence protocol (PLCP). Its default value is 48 bits.

A.4.1.6 aPreambleLength

This parameter specifies the length in bits of the physical layer frame preamble. Its default value is 144 bits.

A.4.1.7 aRxPLCPDelay

This parameter specifies the delay introduced by the PLCP during frame reception. Its default value is 1 usec.

A.4.1.8 aRxRFDelay

This parameter determines the RF delay introduced during a reception. Its default value is 3 usec.

A.4.1.9 aRxTxTurnaroundTime

This parameter specifies the time the radio requires to change modes from receive to transmit or transmit to receive. The default value is 5 usec.

A.4.1.10 aShortRetryLimit

This parameter specifies how many attempts will be made to transmit a short packet. Its minimum value is 1. Its default value is 7.

A.4.1.11 aSifsTime

This parameter defines the short inter-frame space (SIFS) time. Its default value is 10 usec.

A.4.1.12 aSlotTime

This parameter specifies the width of a slot. Its default value is 20 usec.

A.4.1.13 aTxPLCPDelay

This parameter specifies the delay introduced by the PLCP. Its default value is 5 usec.

A.4.1.14 aTxRFDelay

This parameter determines the RF delay introduced during transmissions. Its default value is 1 usec.

A.4.1.15 ACK_Length

This determines the length, in bits, of an ACK packet. The value specified here will override the value specified in sAckCtsLng. Its default value is Default which uses the sAckCtsLng value.

A.4.1.16 ACK_Timeout

This determines the length of time the station will wait for an ACK. This is normally calculated by the station but can be specified. Its default value is Default, which uses the internal calculation.

A.4.1.17 Backoff Algorithm

This parameter changes the algorithm used to determine the contention window size and the collision avoidance algorithm. The possible values are "Enhanced Algorithm" (RT-MAC) and "Standard IEEE 802.11." Its default value is Standard IEEE 802.11.

A.4.1.18 MACHeaderLength

This parameter determines the length, in bits, of a MAC packet header. Normally the value is calculated internally. Specifying a value here will override this internal calculation. Its default value is Default.

A.4.1.19 Mean Time in Bad State

This determines the mean number of seconds the IEEE 802.11 channel is in a "bad" (i.e., error) state. The accepted values are any number greater than or equal to zero or "Static BER". The default value is 0.1 seconds.

The "Static BER" choice flags the simulation to use a static BER model rather than the bursty BER model (even if Static BER is not selected in Mean Time in Good State below). The static BER model can be thought of as always being in the "bad" state. The Probability of Bit Error (Section A.4.1.25) is used to set the average BER in the Static BER model.

A.4.1.20 Mean Time in Good State

This determines the mean number of seconds the IEEE 802.11 channel is in a "good" (i.e., no bit error) state. The default value is 5.0 seconds.

The "Static BER" choice flags the simulation to use a static BER model rather than the bursty BER model (even if Static BER is not selected in Mean Time in Bad State above). The static BER model can be thought of as always being in the "bad" state. The Probability of Bit Error (Section A.4.1.25) is used to set the average BER in the Static BER model.

A.4.1.21 Number of Stations

This parameter informs the station how many stations are in the network. It is used only to determine the set of valid station addresses to transmit to. Its default value is 0 and should be changed to reflect the number of stations in the network.

A.4.1.22 Packet format

This parameter determines the packet format to be used in the station. Its default value is IEEE80211frame. Note the simulation accesses many fields within this frame format. Specifying another frame format that does not include the fields in IEEE80211frame will cause the simulation to fail.

A.4.1.23 Print Errored Packets

This Boolean parameter determines whether the station will print information about packets that have errors in them. Normally, packets with errors are discarded without warning. This can generate a large amount of output and should be used for debugging purposes only. Its default value is false.

A.4.1.24 Print Packets

This Boolean parameter determines whether the station will print information about packets transmitted and received by the station. This can generate a large amount of output and should only be used for debugging purposes. Its default value is false.

A.4.1.25 Probability of Bit Error

This parameter defines the probability of a bit error when the IEEE 802.11 channel is in a "bad" state or is using the static BER model (cf., Section A.4.1.19, A.4.1.20). The default value is 0.8.

A.4.1.26 Queue Discipline

This parameter defines the queue discipline used in the Queue process. The choices are first-come-first-served, last-come-first-served, earliest-deadline-first, shortest-job-first, longest-job-first, or random. The default value is first-come-first-served.

A.4.1.27 RxTxRate

This parameter specifies the receive and transmit rate for the station. It is integer valued and the RxTxRate multiplied by 500 kbps determines the station's transmit and receive rate. Its default value is 2 or 1,000,000 bps.

A.4.1.28 sAckCtsLng

This parameter specifies the length of an ACK and a clear-to-send CTS frame. Its default value is 112 bits.

A.4.1.29 sMaxMsduLng

This parameter specifies the maximum length, in octets, of the MAC service data unit (SDU). Its default value is 2304.

A.4.1.30 SA

This parameter specifies the station address (SA). A stations address is a positive integer and must be specified. If this parameter is left to the default value of -1, a simulation error will occur.

A.4.1.31 Sequence Number

This parameter determines the initial value for packet sequence numbers. Its default value is -1.

A.4.1.32 Transmission Control

This Boolean parameter controls whether transmission control is active. The default value is Off.

A.4.2 IEEE80211MON

IEEE80211MON is the node model for Traffic_Monitor discussed in Section A.3.2.12. It has three parameters that can be specified: Data Collection Start, Data Collection Stop, and Backoff Algorithm. The default values are 5.0, 1,000,000.0 seconds, and Standard IEEE 802.11 respectively. The Backoff Algorithm parameter is only used during debugging to turn on or off certain debug statements.

A.4.3 Traffic Monitor

Within this process model, parameters regarding the simulation termination conditions, screen output and file output are defined. There are numerous parameters that can be specified, but they are largely redundant. Sometimes the parameter names will include brackets (i.e., []). The brackets denote other parameters of the same purpose but with different names. For instance, ABC[1-3] would denote three parameters: ABC1, ABC2, and ABC3.

A.4.3.1 [Throughput, HRT Failure, Collision, Mean Delay] Termination Condition

This parameter determines whether the statistic named (i.e., Throughput, Collision, etc.) will be used as a condition for simulation termination. When all statistics used for termination are within the desired confidence interval (specified below) the simulation will terminate. The allowed values for this parameter are Yes or No. The default value is No.

A.4.3.2 [Throughput, HRT Failure, Collision, Mean Delay] Confidence Interval Width

This parameter specifies the desired width of the statistics confidence interval as a percentage of the mean value of the statistic. The allowed values are 0.5%, 1%, 2%, 5%, 10%, and 20%. For example, if the mean of the statistic is 100.0 and the desired confidence interval width is 2%, the desired width would be achieved when the confidence interval of the statistic was within the range ± 1.0. The default value is 2%.

A.4.3.3 [Throughput, HRT Failure, Collision, Mean Delay] Confidence Level

This parameter specifies the desired confidence level of the statistic. The allowed values are 80%, 90%, 95%, and 99%. The default value is 90%.

A.4.3.4 Statistics File

This parameter specifies whether the statistics are saved in a file. The allowed values are NONE (for no statistics file), Use .ef filename (to construct a filename based on the simulation .ef file), or a user specified filename. The default value is NONE.

A.4.3.5 Print Statistics to Screen

This parameter determines whether the statistics gathered during the simulation are written to the screen. The default value in No.

A.4.4 Source

Within the source process model, the characteristics of the packets submitted for transmission are defined. There are a large number of parameters that can be specified, but they are largely redundant. The type of the parameter is enclosed in parenthesis. Sometimes the parameter names will include brackets (i.e., []). The brackets denote other parameters of the same type and purpose but with different names. For instance, ABC[1-3] (integer) would denote three parameters of type integer: ABC1, ABC2, and ABC3.

A.4.4.1 Active Source (Boolean)

The Source process model can be prevented from placing any data onto the network by setting this parameter to Disabled. If set to Active, Source will generate packets according to the values specified in the other parameters. The default value for this parameter is Active.

A.4.4.2 [Hard Real Time, Soft Real Time, Data] Sources (integer)

This parameter specifies the number of independent sources for the three classes of data (i.e., hard, soft, and data). The number of sources may be from zero to three. The default value is zero.

A.4.4.3 Number of Stations Transmitted To (double)

This parameter sets the number or percentage of stations in the network this station will transmit to. If value is ≤ 1.0, then the number of stations to transmitted to will be the truncated result of the value of the parameter multiplied by the number of stations in the network. For example, if there are 16 stations in the network and Number of Stations Transmitted To is equal to 0.2, the number of stations transmitted to will be $\lfloor 0.2(16) \rfloor$ or 3 stations. If the number is > 1.0, its truncated value is taken to be the number of stations to transmit to. For example, if the values of the parameter is 10.1, the number of stations transmitted to will be 10 stations. To transmit to all stations set the parameter to 1.0. To specify only one station use 1.1! Any value greater than zero is allowed. To turn off source traffic generation altogether, use the parameter described in Section A.4.4.1. Some preset choices available are: All, One, Two, 10%, 20%, and 50%. Once the number of stations to transmit to is determined, the stations are chosen according to a uniform distribution. The default value for this parameter is 20%.

A.4.4.4 [HRT[1–3], SRT[1–3], D[1–3]] Interarrival Distribution (string)

This parameter specifies the interarrival distribution for the packet sources. If there are 2 Data Sources specified (cf., Section A.4.4.2), the D1 Interarrival Distribution and the D2 Interarrival Distribution will be used to generate packets. The distributions that can be specified are: Bernoulli, chi_square, constant, Erlang, exponential, normal, ON-OFF, Pareto, Poisson, uniform, and uniform_int. The default value is exponential.

A.4.4.5 [HRT[1–3], SRT[1–3], D[1–3]] Interarrival Parameter [1,2] (double)

This parameter is used to specify the parameters for the interarrival distribution chosen in Section A.4.4.4 above. Up to two parameters can be specified. If a distribution only requires one parameter [HRT[1–3], SRT[1–3], D[1–3]] Interarrival Parameter 1 will be used.

Typically, the mean values for the distribution is specified by Interarrival Parameter 1. If the distribution is ON-OFF, Interarrival Parameter 1 specifies the mean ON time, Interarrival Parameter 2 specifies the mean OFF time. If the distribution is Pareto, Interarrival Parameter 1 specifics the mean interarrival time and Interarrival Parameter 2 specifies the Pareto shape parameter. The shape parameter must be greater than 1 and less than two. The default values for these parameters are zero. Refer to the OPNET Simulation Kernel manual [MIL98] for complete details on distribution parameters.

A.4.4.6 [HRT[1–3], SRT[1–3], D[1–3]] ON-OFF Rate (double)

This parameter specifies the rate (in kbps) at which bits arrive when the interarrival distribution is ON-OFF and the source is in the ON state (cf., Section A.4.4.4). The default value is 0.0.

A.4.4.7 [HRT[1–3], SRT[1–3]] Deadline Distribution (string)

This parameter specifies the deadline distribution for the packet sources. If there are 2 Hard Real Time Sources specified (c.f., Section A.4.4.2), the HRT1 Deadline Distribution and the HRT2 Deadline Distribution will be used to generate deadlines. The distributions that can be specified are: Bernoulli, chi_square, constant, Erlang, exponential, normal, Poisson, uniform, and uniform_int. The default value is exponential.

A.4.4.8 [HRT[1–3], SRT[1–3]] Deadline Parameter [1,2] (double)

This parameter is used to specify the parameters for the deadline distribution chosen in Section A.4.4.7 above. Up to two parameters can be specified. If a distribution only requires one parameter [HRT[1–3], SRT[1–3]] Deadline Parameter 1 will be used. The default values for these parameters is zero.

A.4.4.9 [HRT[1–3], SRT[1–3] Deadline Lower Bound (double)

This parameter is used to specify an lower bound on deadline values. This allows the deadline distribution to be truncated at a minimum value. The default value is zero (or no lower bound).

A.4.4.10 [HRT[1–3], SRT[1–3] Deadline Upper Bound (double)

This parameter is used to specify an upper bound on deadline values. This allows the deadline distribution to be truncated at a maximum value. The default value is zero (or no upper bound).

A.4.4.11 [HRT[1–3], SRT[1–3], D[1–3]] Packet Size Distribution (string)

This parameter specifies the packet size distribution for the packet sources. If there are 2 Data Sources specified (c.f., Section A.4.4.2), the D1 Packet Size Distribution and the D2 Packet Size Distribution will be used to generate packets sizes. The distributions that can be specified are: constant, geometric, and uniform_int. The default value is constant.

A.4.4.12 [HRT[1–3], SRT[1–3], D[1–3]] Packet Size Parameter [1,2] (double)

This parameter is used to specify the parameters for the packet size distribution chosen in Section A.4.4.11 above. Up to two parameters can be specified. If a distribution only requires one parameter [HRT[1–3], SRT[1–3], D[1–3]] Packet Size Parameter 1 will be used. The default value for Parameter 1 is 200. The default value for Parameter 2 is zero.

A.4.5 Data_Pump

A.4.5.1 Percentage of Blocked Packets Resubmitted

This parameters specifies the percentage of packets not transmitted due to deadline expiration that are resubmitted to the Queue process. The resubmitted packets are selected based on the outcome of a uniform random number generator in the range 0.0 to 1.0. For example, if the percentage of packets to be resubmitted is 0.10 and the outcome of the random number generator is 0.23, the packet is not resubmitted. If the outcome is ≤ 0.10 the packet is resubmitted. The default value is 0.0.

A.4.6 Receiver, Transceiver Pipeline, Transmitter, Antenna

The parameters for these OPNET objects generally do not need to be changed. If they do need to be changed, the OPNET Node Editor is used. Within the simulation model, the transceiver pipeline has been left in the default configuration as supplied by MIL3 (except for the cases noted below in Section A.4.6.3). The source files and routine names have, however, been changed to be specific to this simulation model. This allows the transceiver pipeline to be changed without affecting other OPNET models.

A.4.6.1 Receiver

The default values for the Receiver parameters are as follows:

1. modulation - bpsk
2. channel.channel - channel[0]
3. channel.data rate - 1,000,000
4. channel.packet formats - all formatted, unformatted

5. channel.bandwidth - 22,000
6. channel.min frequency - 2,400
7. channel.spreading code - 1.0
8. channel.processing gain - channel bw/dr
9. noise figure - 1.0
10. ecc threshold - 1.0
11. ragain model - IEEE80211_ragain
12. power model - IEEE80211_power
13. bkgnoise model - IEEE80211_bkgnoise
14. inoise model - IEEE80211_inoise
15. snr model - IEEE80211_snr
16. ber model - IEEE80211_ber
17. error model - IEEE80211_error
18. ecc model - IEEE80211_ecc

A.4.6.2 Transmitter

The default values for the Transmitter parameters are as follows:

1. modulation - bpsk
2. channel.channel - channel[0]
3. channel.data rate - 1,000,000

4. channel.packet formats - all formatted, unformatted
5. channel.bandwidth - 22,000
6. channel.min frequency - 2,400
7. channel.spreading code - 1.0
8. channel.power - 1.0
9. rxgroup model - IEEE80211_rxgroup
10. txdel model - IEEE80211_txdel
11. closure model - IEEE80211_closure_all
12. chanmatch model - IEEE80211_chanmatch
13. tagain model - IEEE80211_tagain
14. propdel model - IEEE80211_propdel

A.4.6.3 Transceiver Pipeline

Bit Error Rate Model – IEEE80211_ber

This model originally calculated average bit error rate based on the SNR of the received signal. It has been changed so that the bit error rate is zero.

Error Model – IEEE80211_error

This model assigned the errors to packets based on the bit error rate calculated in IEEE-80211_ber above. It has been changed to assign no bit errors.

Error Correction Model – IEEE80211_ecc

This model originally implemented the error correction function (if any) for the station. It was chosen to be the pipeline stage to implement the bursty and static error model since it is invoked only once per transmitted packet. The IEEE80211_ber and IEEE80211_error models may be invoked several times per packet depending on changes in the SNR or collisions that may occur. This model has been changed to include the error models described below. No error correction is performed.

The bursty error model is a simple continuous-time 2-state model. In the "good" state, no errors are generated. In the "bad" state, errors occur with a fixed probability. The time that is spent in each state is exponentially distributed with a given mean. The means may be different for each state. The parameters used to set up the error model are discussed in Sections A.4.1.19, A.4.1.20, and A.4.1.25.

The static error model simply assigns errors to transmitted packets based on an average BER. Every bit transmitted is subject to being in error (e.g., the model is always in a "bad" state). The parameters used to set up the model are discussed in Sections A.4.1.19, A.4.1.20, and A.4.1.25.

A.4.6.4 Antenna

The only value changed in the Antenna parameters is pattern. The value is IEEE80211 which implements a standard omnidirectional pattern.

A.5 Model Validation

The simulation model was validated by comparing the performance metrics obtained by the model against those obtained in [BFO96]. Because [BFO96] was based on an earlier draft of the IEEE 802.11 standard, several of that paper's parameters did not match those in the latest IEEE 802.11 standard. For the validation, the values of these parameters in our model were changed to match [BFO96]. Figure A.30 shows throughput for 5, 10 and 20 station networks. Figure A.31 shows the average transmission attempts per packet for various values

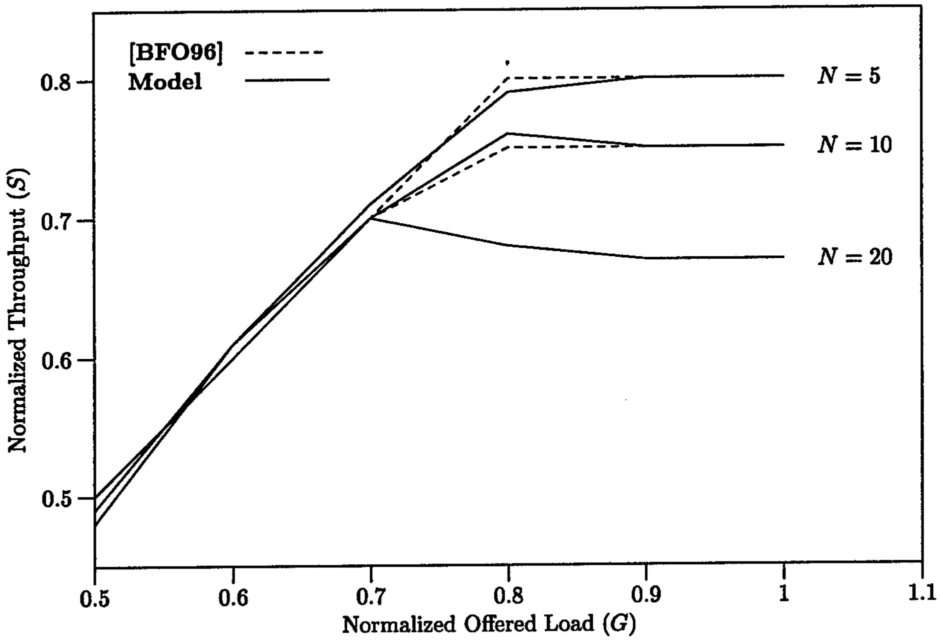

Figure A.30: Throughput versus Offered Load

of the contention window, CWmin, and CWmax. Figure A.32 shows saturation throughput versus number of stations for various values of the contention window, CWmin, and CWmax. The agreement between the two models is quite good. In fact, the data obtained in the two uppermost plots in Figure A.31 were so close to [BFO96] that the simulation model data and their data virtually overlap. Average access delays for various values of the contention window are shown in Figure A.33.

A.6 Summary

This appendix describes the simulation model used in the course of this research. The appendix begins with a discussion of the simulation tool, OPNET, in Section A.1. Section A.2 presents on overview of the SDL specification language. In Section A.3 the simulation model is described. The node and process models are presented and the model behavior is described using SDL. Section A.4 discusses the simulation parameters which may be varied within the

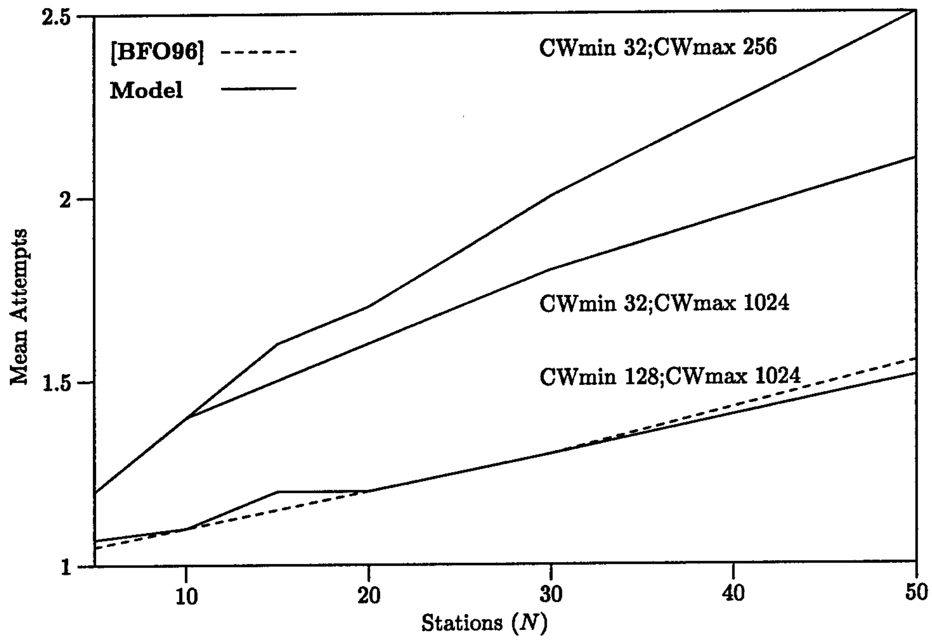

Figure A.31: Mean Attempts per Packet

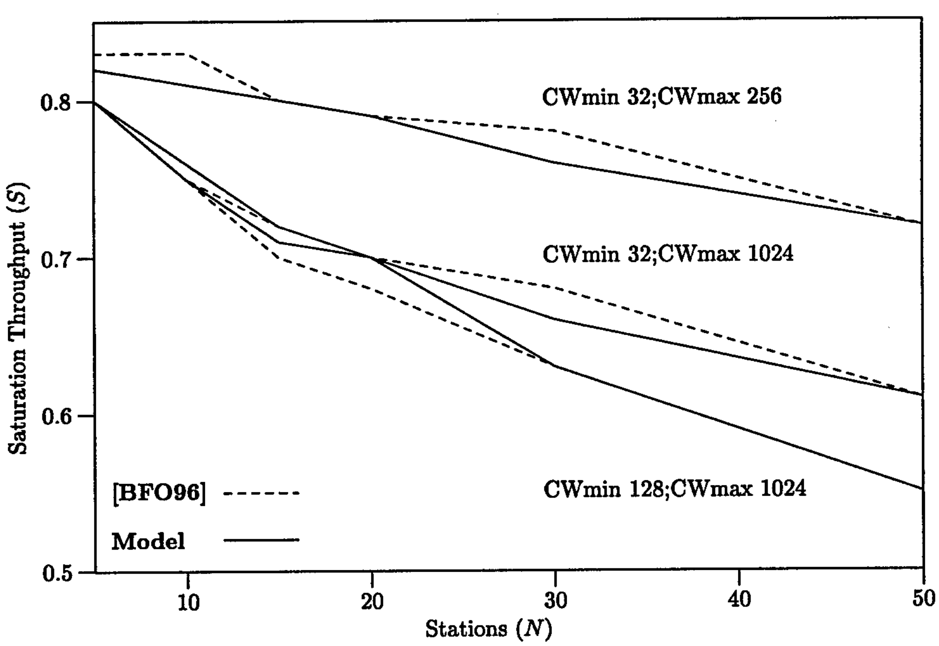

Figure A.32: Saturation Throughput

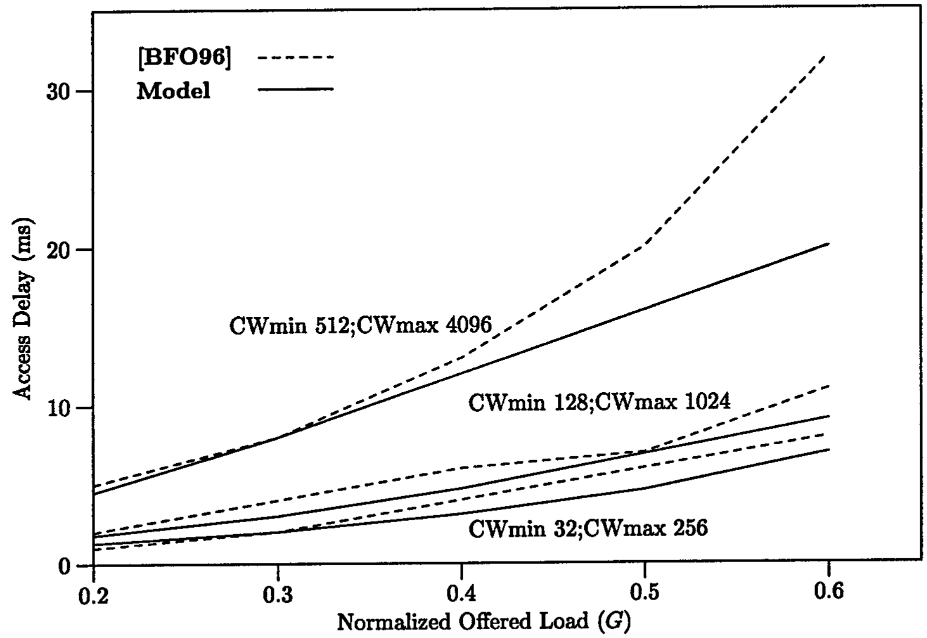

Figure A.33: Average Access Delay

model. Validation of the model is discussed in Section A.5.

Appendix B

Simulation Data Tables

This appendix contains the data gathered during the simulations. Reporting the individual sample values would make this appendix even more voluminous, therefore, the mean values for the number of replications are given along with the associated confidence interval half width. For example, the confidence interval for a table entry of $x(y)$ would be $(x-y, x+y)$. The figure reference in the table caption in parenthesis (e.g., (Figure 6.99)) refers to the figure which used the data in the table.

Since the number of samples, n, for each value is small, the confidence interval used for means, x, is $(\overline{x} - t_{[1-\alpha/2;n-1]}s/\sqrt{n}, \overline{x} + t_{[1-\alpha/2;n-1]}s/\sqrt{n})$ where $t_{[1-\alpha/2;n-1]}$ is the $(1-\alpha/2)$-quantile of a t-variate with $n-1$ degrees of freedom and s is the standard deviation of the samples. The confidence interval used for ratios, p, is $(p - z_{[1-\alpha/2]}\sqrt{\frac{p(1-p)}{n}}, p + z_{[1-\alpha/2]}\sqrt{\frac{p(1-p)}{n}})$ where $z_{[1-\alpha/2]}$ is the $(1-\alpha/2)$-quantile of a unit normal variate [Jai91]. Unless otherwise stated $n = 5$ and $\alpha = 0.10$.

B.1 Telemetry Traffic Model

Table B.1: Telemetry Throughput - Ideal Channel (Figure 6.1)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	2.83E-01 (1.72E-03)	3.32E-01 (6.18E-04)	3.32E-01 (7.68E-04)	3.32E-01 (1.04E-03)
5 Sta - RT-MAC	2.85E-01 (1.84E-04)	3.33E-01 (5.21E-03)	2.99E-01 (7.43E-03)	3.02E-01 (1.18E-02)
10 Sta - 802.11	2.85E-01 (1.97E-05)	3.22E-01 (1.68E-03)	3.22E-01 (1.15E-03)	3.22E-01 (1.35E-03)
10 Sta - RT-MAC	2.85E-01 (2.26E-05)	3.13E-01 (4.67E-04)	3.00E-01 (8.02E-04)	2.96E-01 (1.26E-03)
20 Sta - 802.11	2.85E-01 (1.93E-05)	3.07E-01 (5.07E-04)	3.07E-01 (2.93E-04)	3.08E-01 (1.28E-03)
20 Sta - RT-MAC	2.85E-01 (7.37E-05)	3.16E-01 (8.83E-04)	3.08E-01 (4.12E-04)	3.00E-01 (6.53E-04)
30 Sta - 802.11	2.85E-01 (5.20E-05)	2.96E-01 (7.07E-04)	2.97E-01 (5.81E-04)	2.96E-01 (5.97E-04)
30 Sta - RT-MAC	2.85E-01 (3.33E-05)	3.37E-01 (4.90E-03)	3.28E-01 (3.35E-03)	3.19E-01 (2.84E-03)
40 Sta - 802.11	2.85E-01 (4.74E-05)	2.88E-01 (1.70E-03)	2.88E-01 (1.00E-03)	2.88E-01 (9.63E-04)
40 Sta - RT-MAC	2.85E-01 (5.76E-05)	3.38E-01 (2.36E-03)	3.28E-01 (4.15E-03)	3.21E-01 (4.26E-03)
50 Sta - 802.11	2.80E-01 (5.88E-03)	2.80E-01 (8.59E-04)	2.81E-01 (1.37E-03)	2.81E-01 (1.09E-03)
50 Sta - RT-MAC	2.85E-01 (6.58E-05)	3.39E-01 (2.70E-03)	3.29E-01 (2.97E-03)	3.23E-01 (3.12E-03)

Table B.2: Telemetry Throughput - Bursty Error Channel (Figure 6.2)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	2.85E-01 (5.58E-04)	3.30E-01 (3.66E-03)	3.29E-01 (5.80E-03)	3.30E-01 (2.11E-03)
5 Sta - RT-MAC	2.80E-01 (3.68E-03)	3.27E-01 (1.11E-02)	2.93E-01 (6.39E-03)	2.96E-01 (5.82E-03)
10 Sta - 802.11	2.84E-01 (3.98E-04)	3.19E-01 (2.87E-03)	3.19E-01 (1.79E-03)	3.20E-01 (1.28E-03)
10 Sta - RT-MAC	2.80E-01 (3.07E-03)	3.10E-01 (4.28E-03)	2.98E-01 (1.97E-03)	2.92E-01 (6.34E-03)
20 Sta - 802.11	2.84E-01 (4.80E-04)	3.02E-01 (3.52E-03)	3.04E-01 (3.53E-03)	3.05E-01 (4.90E-03)
20 Sta - RT-MAC	2.79E-01 (1.02E-02)	3.13E-01 (4.35E-03)	3.05E-01 (4.56E-03)	2.96E-01 (4.41E-03)
30 Sta - 802.11	2.85E-01 (2.74E-04)	2.94E-01 (2.70E-03)	2.94E-01 (2.07E-03)	2.94E-01 (2.86E-03)
30 Sta - RT-MAC	2.78E-01 (8.44E-03)	3.34E-01 (4.69E-03)	3.24E-01 (4.93E-03)	3.17E-01 (9.12E-03)
40 Sta - 802.11	2.85E-01 (1.74E-03)	2.85E-01 (3.66E-03)	2.84E-01 (4.38E-03)	2.85E-01 (1.08E-03)
40 Sta - RT-MAC	2.81E-01 (2.87E-03)	3.31E-01 (3.55E-03)	3.23E-01 (6.45E-03)	3.15E-01 (5.66E-03)
50 Sta - 802.11	2.84E-01 (1.12E-03)	2.78E-01 (3.41E-03)	2.78E-01 (3.01E-03)	2.77E-01 (2.86E-03)
50 Sta - RT-MAC	2.80E-01 (2.48E-03)	3.31E-01 (5.05E-03)	3.21E-01 (5.23E-03)	3.17E-01 (6.18E-03)

Table B.3: Telemetry Mean Delay - Ideal Channel (Figure 6.6)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	6.39E-03 (2.91E-05)	1.64E+00 (9.40E-03)	1.69E+00 (7.72E-03)	1.69E+00 (9.76E-03)
5 Sta - RT-MAC	4.61E-03 (1.83E-05)	3.76E-03 (8.71E-06)	2.73E-03 (4.67E-06)	2.27E-03 (6.29E-06)
10 Sta - 802.11	1.05E-02 (6.27E-05)	3.15E+00 (5.46E-02)	3.49E+00 (2.51E-02)	3.54E+00 (2.11E-02)
10 Sta - RT-MAC	8.85E-03 (2.49E-05)	7.03E-03 (1.44E-05)	5.00E-03 (1.43E-05)	4.05E-03 (1.32E-05)
20 Sta - 802.11	1.99E-02 (1.11E-04)	5.76E+00 (8.19E-02)	6.85E+00 (3.61E-02)	7.11E+00 (4.46E-02)
20 Sta - RT-MAC	1.74E-02 (7.65E-05)	1.37E-02 (3.56E-05)	1.00E-02 (4.24E-05)	7.82E-03 (2.42E-05)
30 Sta - 802.11	3.07E-02 (3.30E-05)	7.92E+00 (1.21E-01)	9.85E+00 (3.06E-02)	1.04E+01 (6.71E-02)
30 Sta - RT-MAC	2.59E-02 (6.23E-05)	2.04E-02 (6.35E-05)	1.48E-02 (3.30E-05)	1.17E-02 (2.92E-05)
40 Sta - 802.11	4.37E-02 (7.13E-04)	9.68E+00 (2.62E-01)	1.26E+01 (1.71E-01)	1.35E+01 (5.60E-02)
40 Sta - RT-MAC	3.44E-02 (1.09E-04)	2.71E-02 (4.84E-05)	1.97E-02 (3.98E-05)	1.55E-02 (2.04E-05)
50 Sta - 802.11	7.93E-02 (1.50E-02)	1.13E+01 (1.21E-01)	1.50E+01 (1.72E-01)	1.63E+01 (1.10E-01)
50 Sta - RT-MAC	4.29E-02 (9.96E-05)	3.38E-02 (7.29E-05)	2.46E-02 (4.99E-05)	1.93E-02 (4.70E-05)

Table B.4: Telemetry Mean Delay - Bursty Error Channel (Figure 6.7)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	1.52E-02 (1.19E-02)	1.67E+00 (5.28E-02)	1.71E+00 (5.02E-02)	1.71E+00 (3.25E-02)
5 Sta - RT-MAC	4.61E-03 (5.76E-06)	3.76E-03 (1.07E-05)	2.73E-03 (3.81E-06)	2.27E-03 (9.37E-06)
10 Sta - 802.11	2.13E-02 (9.64E-03)	3.22E+00 (9.86E-02)	3.55E+00 (3.50E-02)	3.58E+00 (2.71E-02)
10 Sta - RT-MAC	8.88E-03 (1.97E-05)	7.03E-03 (1.77E-05)	5.00E-03 (7.01E-06)	4.06E-03 (4.10E-06)
20 Sta - 802.11	3.14E-02 (1.15E-02)	6.13E+00 (2.58E-01)	7.02E+00 (1.83E-01)	7.25E+00 (2.20E-01)
20 Sta - RT-MAC	1.74E-02 (8.94E-05)	1.37E-02 (1.31E-05)	1.00E-02 (4.33E-05)	7.82E-03 (1.45E-05)
30 Sta - 802.11	4.70E-02 (1.11E-02)	8.27E+00 (3.97E-01)	1.01E+01 (1.44E-01)	1.06E+01 (2.04E-01)
30 Sta - RT-MAC	2.60E-02 (4.59E-05)	2.04E-02 (4.42E-05)	1.48E-02 (3.63E-05)	1.17E-02 (2.99E-05)
40 Sta - 802.11	6.11E-02 (1.45E-02)	1.03E+01 (8.03E-01)	1.32E+01 (5.58E-01)	1.39E+01 (1.34E-01)
40 Sta - RT-MAC	3.46E-02 (2.39E-04)	2.71E-02 (4.39E-05)	1.97E-02 (2.38E-05)	1.55E-02 (2.49E-05)
50 Sta - 802.11	1.39E-01 (9.96E-02)	1.20E+01 (9.73E-01)	1.56E+01 (4.69E-01)	1.70E+01 (3.68E-01)
50 Sta - RT-MAC	4.31E-02 (1.08E-04)	3.38E-02 (6.25E-05)	2.46E-02 (4.23E-05)	1.94E-02 (4.38E-05)

Table B.5: Telemetry Missed Deadline Ratio - Ideal Channel (Figure 6.8)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	3.43E-02 (6.92E-04)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
5 Sta - RT-MAC	1.16E-03 (1.21E-04)	2.68E-01 (1.67E-03)	5.23E-01 (1.73E-03)	6.18E-01 (1.61E-03)
10 Sta - 802.11	4.76E-03 (2.44E-04)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
10 Sta - RT-MAC	4.80E-04 (7.78E-05)	2.56E-01 (2.26E-03)	4.98E-01 (2.09E-03)	6.15E-01 (1.80E-03)
20 Sta - 802.11	1.49E-03 (1.37E-04)	1.00E+00 (6.92E-05)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
20 Sta - RT-MAC	3.08E-04 (6.23E-05)	2.49E-01 (2.26E-03)	4.80E-01 (2.16E-03)	6.10E-01 (1.81E-03)
30 Sta - 802.11	1.92E-03 (1.56E-04)	1.00E+00 (8.60E-05)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
30 Sta - RT-MAC	2.56E-04 (5.68E-05)	2.47E-01 (1.76E-03)	4.79E-01 (1.70E-03)	6.07E-01 (1.44E-03)
40 Sta - 802.11	7.18E-03 (3.00E-04)	9.99E-01 (1.46E-04)	1.00E+00 (1.81E-05)	1.00E+00 (0.00E+00)
40 Sta - RT-MAC	1.72E-04 (4.66E-05)	2.45E-01 (1.76E-03)	4.77E-01 (1.72E-03)	6.05E-01 (1.44E-03)
50 Sta - 802.11	9.41E-02 (1.21E-03)	9.99E-01 (1.14E-04)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
50 Sta - RT-MAC	1.16E-04 (3.83E-05)	2.44E-01 (1.75E-03)	4.76E-01 (1.71E-03)	6.04E-01 (1.41E-03)

Table B.6: Telemetry Missed Deadline Ratio - Bursty Error Channel (Figure 6.9)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	1.03E-01 (1.08E-03)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
5 Sta - RT-MAC	1.86E-02 (4.80E-04)	2.82E-01 (1.68E-03)	5.29E-01 (1.80E-03)	6.25E-01 (1.61E-03)
10 Sta - 802.11	6.62E-02 (8.84E-04)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
10 Sta - RT-MAC	1.67E-02 (4.55E-04)	2.73E-01 (2.22E-03)	5.05E-01 (2.04E-03)	6.25E-01 (1.71E-03)
20 Sta - 802.11	5.39E-02 (8.03E-04)	1.00E+00 (6.30E-05)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
20 Sta - RT-MAC	1.82E-02 (4.89E-04)	2.62E-01 (2.23E-03)	4.90E-01 (2.09E-03)	6.20E-01 (1.71E-03)
30 Sta - 802.11	6.15E-02 (8.54E-04)	9.99E-01 (1.17E-04)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
30 Sta - RT-MAC	2.09E-02 (5.21E-04)	2.58E-01 (1.76E-03)	4.87E-01 (1.68E-03)	6.12E-01 (1.39E-03)
40 Sta - 802.11	6.46E-02 (8.76E-04)	9.99E-01 (9.51E-05)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
40 Sta - RT-MAC	1.44E-02 (4.23E-04)	2.61E-01 (1.80E-03)	4.86E-01 (1.71E-03)	6.12E-01 (1.42E-03)
50 Sta - 802.11	2.21E-01 (1.47E-03)	9.99E-01 (1.10E-04)	1.00E+00 (0.00E+00)	1.00E+00 (0.00E+00)
50 Sta - RT-MAC	1.67E-02 (4.55E-04)	2.58E-01 (1.81E-03)	4.87E-01 (1.73E-03)	6.11E-01 (1.41E-03)

Table B.7: Telemetry Missed Deadline Ratio (2-4 Stations) - Ideal Channel (Figure 6.11)

Stations - Protocol	Offered Load - $G = 0.3$
	$n = 2$
2 Sta - 802.11	1.97E-01 (2.23E-03)
2 Sta - RT-MAC	2.58E-02 (9.11E-04)
4 Sta - 802.11	4.26E-02 (1.41E-03)
4 Sta - RT-MAC	1.23E-03 (1.97E-04)

Table B.8: Telemetry Collision Ratio - Ideal Channel (Figure 6.12)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	2.74E-02 (6.12E-04)	7.93E-02 (1.51E-03)	7.87E-02 (1.51E-03)	7.96E-02 (1.52E-03)
5 Sta - RT-MAC	1.50E-02 (4.28E-04)	1.87E-02 (5.91E-04)	2.13E-02 (7.14E-04)	2.28E-02 (7.92E-04)
10 Sta - 802.11	6.87E-02 (8.67E-04)	1.61E-01 (1.88E-03)	1.61E-01 (1.88E-03)	1.60E-01 (1.88E-03)
10 Sta - RT-MAC	2.49E-02 (5.47E-04)	2.89E-02 (9.92E-04)	3.19E-02 (1.02E-03)	3.12E-02 (1.02E-03)
20 Sta - 802.11	1.48E-01 (1.16E-03)	2.58E-01 (1.98E-03)	2.58E-01 (1.99E-03)	2.56E-01 (1.99E-03)
20 Sta - RT-MAC	3.32E-02 (6.26E-04)	3.58E-02 (1.10E-03)	3.63E-02 (1.10E-03)	3.77E-02 (1.11E-03)
30 Sta - 802.11	2.23E-01 (1.30E-03)	3.26E-01 (1.94E-03)	3.23E-01 (1.95E-03)	3.24E-01 (1.95E-03)
30 Sta - RT-MAC	3.73E-02 (6.60E-04)	4.05E-02 (9.06E-04)	4.11E-02 (9.18E-04)	4.10E-02 (9.16E-04)
40 Sta - 802.11	2.88E-01 (1.36E-03)	3.67E-01 (1.88E-03)	3.68E-01 (1.88E-03)	3.66E-01 (1.88E-03)
40 Sta - RT-MAC	3.84E-02 (6.69E-04)	4.08E-02 (9.11E-04)	4.15E-02 (9.28E-04)	4.04E-02 (9.02E-04)
50 Sta - 802.11	3.88E-01 (1.58E-03)	3.98E-01 (1.81E-03)	3.96E-01 (1.81E-03)	3.97E-01 (1.81E-03)
50 Sta - RT-MAC	3.94E-02 (6.77E-04)	4.05E-02 (9.04E-04)	4.13E-02 (9.24E-04)	3.89E-02 (8.70E-04)

Table B.9: Telemetry Collision Ratio - Bursty Error Channel (Figure 6.13)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	3.13E-02 (6.03E-04)	7.97E-02 (1.49E-03)	7.89E-02 (1.48E-03)	7.79E-02 (1.47E-03)
5 Sta - RT-MAC	1.49E-02 (4.26E-04)	1.86E-02 (5.86E-04)	2.22E-02 (7.60E-04)	2.29E-02 (7.96E-04)
10 Sta - 802.11	7.31E-02 (8.79E-04)	1.57E-01 (1.80E-03)	1.57E-01 (1.80E-03)	1.58E-01 (1.82E-03)
10 Sta - RT-MAC	2.59E-02 (5.56E-04)	2.86E-02 (9.50E-04)	3.21E-02 (9.98E-04)	3.07E-02 (9.68E-04)
20 Sta - 802.11	1.54E-01 (1.16E-03)	2.52E-01 (1.88E-03)	2.53E-01 (1.91E-03)	2.53E-01 (1.91E-03)
20 Sta - RT-MAC	3.36E-02 (6.45E-04)	3.57E-02 (1.06E-03)	3.78E-02 (1.08E-03)	3.81E-02 (1.06E-03)
30 Sta - 802.11	2.30E-01 (1.29E-03)	3.17E-01 (1.89E-03)	3.20E-01 (1.89E-03)	3.20E-01 (1.89E-03)
30 Sta - RT-MAC	3.76E-02 (6.77E-04)	3.95E-02 (8.83E-04)	3.99E-02 (8.92E-04)	3.83E-02 (8.56E-04)
40 Sta - 802.11	3.01E-01 (1.35E-03)	3.60E-01 (1.82E-03)	3.60E-01 (1.79E-03)	3.62E-01 (1.81E-03)
40 Sta - RT-MAC	3.90E-02 (6.72E-04)	4.10E-02 (9.16E-04)	4.10E-02 (9.16E-04)	3.98E-02 (8.90E-04)
50 Sta - 802.11	3.87E-01 (1.34E-03)	3.95E-01 (1.76E-03)	3.95E-01 (1.76E-03)	3.89E-01 (1.73E-03)
50 Sta - RT-MAC	3.93E-02 (6.73E-04)	4.16E-02 (9.30E-04)	4.20E-02 (9.38E-04)	3.90E-02 (8.71E-04)

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Table B.10: Avionics Throughput - Ideal Channel (Figure 6.14)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	2.99E-01 (3.83E-03)	4.97E-01 (3.74E-03)	6.97E-01 (5.24E-03)	7.53E-01 (4.47E-03)
5 Sta - RT-MAC	2.99E-01 (4.68E-03)	4.97E-01 (4.79E-03)	6.95E-01 (3.76E-03)	8.25E-01 (3.03E-03)
10 Sta - 802.11	2.98E-01 (1.50E-03)	4.97E-01 (3.54E-03)	6.96E-01 (1.99E-03)	7.06E-01 (6.70E-03)
10 Sta - RT-MAC	2.98E-01 (2.48E-03)	4.97E-01 (4.92E-03)	6.94E-01 (2.89E-03)	8.18E-01 (1.44E-03)
20 Sta - 802.11	2.98E-01 (2.72E-03)	4.96E-01 (3.95E-03)	6.96E-01 (4.43E-03)	6.57E-01 (5.25E-03)
20 Sta - RT-MAC	2.98E-01 (1.63E-03)	4.97E-01 (5.30E-03)	6.93E-01 (2.13E-03)	8.14E-01 (3.55E-03)
30 Sta - 802.11	2.99E-01 (4.32E-03)	4.97E-01 (4.11E-03)	6.70E-01 (3.59E-02)	6.26E-01 (3.69E-03)
30 Sta - RT-MAC	2.98E-01 (3.04E-03)	4.97E-01 (6.21E-03)	6.94E-01 (6,88E-03)	8.09E-01 (4.48E-03)
40 Sta - 802.11	2.98E-01 (3.44E-03)	4.97E-01 (4.13E-03)	6.42E-01 (2.08E-02)	6.02E-01 (1.56E-03)
40 Sta - RT-MAC	2.98E-01 (3.79E-03)	4.96E-01 (6.57E-03)	6.92E-01 (4.15E-03)	8.08E-01 (9.54E-04)
50 Sta - 802.11	2.98E-01 (2.59E-03)	4.97E-01 (1.42E-03)	6.08E-01 (1.50E-02)	5.83E-01 (1.58E-03)
50 Sta - RT-MAC	2.98E-01 (2.97E-03)	4.97E-01 (5.33E-03)	6.94E-01 (6.45E-03)	8.07E-01 (2.14E-03)

Table B.11: Avionics Throughput - Bursty Error Channel (Figure 6.15)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	2.98E-01 (3.06E-03)	4.97E-01 (2.84E-03)	6.95E-01 (2.62E-03)	7.44E-01 (1.12E-02)
5 Sta - RT-MAC	2.98E-01 (3.35E-03)	4.95E-01 (4.58E-03)	6.90E-01 (5.30E-03)	8.08E-01 (3.07E-03)
10 Sta - 802.11	2.99E-01 (1.99E-03)	4.98E-01 (6.30E-03)	6.95E-01 (4.81E-03)	6.96E-01 (1.02E-02)
10 Sta - RT-MAC	2.97E-01 (2.48E-03)	4.95E-01 (3.35E-03)	6.87E-01 (4.82E-03)	8.02E-01 (1.11E-02)
20 Sta - 802.11	2.97E-01 (3.51E-03)	4.98E-01 (3.80E-03)	6.96E-01 (7.64E-03)	6.49E-01 (5.82E-03)
20 Sta - RT-MAC	2.97E-01 (2.73E-03)	4.96E-01 (3.00E-03)	6.89E-01 (2.43E-03)	7.97E-01 (8.88E-03)
30 Sta - 802.11	2.98E-01 (3.73E-03)	4.96E-01 (4.06E-03)	6.48E-01 (1.72E-02)	6.20E-01 (4.43E-03)
30 Sta - RT-MAC	2.98E-01 (2.35E-03)	4.96E-01 (2.29E-03)	6.89E-01 (6.69E-03)	7.94E-01 (6.50E-03)
40 Sta - 802.11	2.99E-01 (2.42E-03)	4.98E-01 (5.38E-03)	6.19E-01 (1.05E-02)	5.98E-01 (3.12E-03)
40 Sta - RT-MAC	2.98E-01 (3.43E-03)	4.95E-01 (4.00E-03)	6.90E-01 (6.44E-03)	7.93E-01 (7.31E-03)
50 Sta - 802.11	2.98E-01 (3.79E-03)	4.97E-01 (2.56E-03)	5.90E-01 (9.19E-03)	5.73E-01 (4.21E-03)
50 Sta - RT-MAC	2.98E-01 (1.79E-03)	4.96E-01 (4.32E-03)	6.88E-01 (3.41E-03)	7.92E-01 (5.05E-03)

Table B.12: Avionics Mean Delay - Ideal Channel (Figure 6.19)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	8.63E-03 (4.65E-05)	1.20E-02 (1.40E-04)	2.97E-02 (2.66E-03)	4.81E+00 (7.77E-01)
5 Sta - RT-MAC	9.14E-03 (2.91E-05)	1.25E-02 (1.40E-04)	2.51E-02 (7.27E-04)	1.25E-01 (5.28E-03)
10 Sta - 802.11	8.63E-03 (4.87E-05)	1.21E-02 (1.45E-04)	3.37E-02 (2.87E-03)	8.40E+00 (4.44E-01)
10 Sta - RT-MAC	9.77E-03 (3.88E-05)	1.35E-02 (8.65E-05)	2.66E-02 (1.04E-03)	1.19E-01 (5.04E-03)
20 Sta - 802.11	8.64E-03 (3.20E-05)	1.21E-02 (2.90E-04)	4.89E-02 (1.72E-02)	1.48E+01 (8.91E-01)
20 Sta - RT-MAC	1.10E-02 (5.84E-05)	1.54E-02 (2.88E-04)	3.07E-02 (4.41E-04)	1.21E-01 (3.28E-03)
30 Sta - 802.11	8.66E-03 (8.47E-05)	1.22E-02 (2.07E-04)	6.19E+00 (8.00E+00)	2.09E+01 (1.46E+00)
30 Sta - RT-MAC	1.22E-02 (5.35E-05)	1.73E-02 (2.78E-04)	3.51E-02 (1.15E-03)	1.23E-01 (8.27E-03)
40 Sta - 802.11	8.67E-03 (8.22E-05)	1.23E-02 (1.81E-04)	1.08E+01 (1.92E+00)	2.71E+01 (1.22E+00)
40 Sta - RT-MAC	1.35E-02 (1.01E-04)	1.93E-02 (5.19E-04)	3.89E-02 (1.13E-03)	1.24E-01 (3.13E-03)
50 Sta - 802.11	8.64E-03 (7.14E-05)	1.25E-02 (1.59E-04)	1.47E+01 (1.87E+00)	3.25E+01 (9.70E-01)
50 Sta - RT-MAC	1.47E-02 (7.57E-05)	2.11E-02 (2.95E-04)	4.30E-02 (1.43E-03)	1.29E-01 (7.34E-03)

Table B.13: Avionics Mean Delay - Bursty Error Channel (Figure 6.20)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	1.13E-02 (1.33E-03)	1.72E-02 (1.03E-03)	4.66E-02 (6.75E-03)	5.35E+00 (5.66E-01)
5 Sta - RT-MAC	1.15E-02 (2.84E-04)	1.59E-02 (8.27E-04)	3.13E-02 (2.02E-03)	1.33E-01 (8.58E-03)
10 Sta - 802.11	1.16E-02 (1.09E-03)	1.67E-02 (2.16E-03)	5.84E-02 (8.87E-03)	9.10E+00 (8.58E-01)
10 Sta - RT-MAC	1.23E-02 (6.60E-04)	1.71E-02 (5.10E-04)	3.18E-02 (1.10E-03)	1.27E-01 (8.36E-03)
20 Sta - 802.11	1.19E-02 (8.13E-04)	1.86E-02 (2.31E-03)	5.02E-01 (1.72E+00)	1.66E+01 (1.56E+00)
20 Sta - RT-MAC	1.35E-02 (6.95E-04)	1.86E-02 (4.15E-04)	3.73E-02 (2.40E-03)	1.24E-01 (4.21E-03)
30 Sta - 802.11	1.15E-02 (8.43E-04)	1.91E-02 (2.92E-03)	9.15E+00 (3.48E+00)	2.28E+01 (2.48E+00)
30 Sta - RT-MAC	1.48E-02 (6.19E-04)	2.08E-02 (1.12E-03)	4.11E-02 (7.93E-04)	1.30E-01 (9.26E-03)
40 Sta - 802.11	1.23E-02 (5.97E-04)	1.90E-02 (3.28E-03)	1.37E+01 (7.43E-01)	2.90E+01 (1.62E+00)
40 Sta - RT-MAC	1.62E-02 (5.18E-04)	2.24E-02 (5.35E-04)	4.44E-02 (9.57E-04)	1.31E-01 (4.23E-03)
50 Sta - 802.11	1.16E-02 (1.02E-03)	1.78E-02 (2.84E-03)	1.66E+01 (2.81E+00)	3.67E+01 (2.79E+00)
50 Sta - RT-MAC	1.73E-02 (5.27E-04)	2.44E-02 (8.36E-04)	4.93E-02 (1.62E-03)	1.32E-01 (8.51E-03)

Table B.14: Avionics Missed Deadline Ratio - Ideal Channel (Figure 6.23)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	8.30E-05 (3.05E-05)	3.74E-04 (5.03E-05)	6.19E-03 (1.72E-04)	9.87E-01 (7.69E-04)
5 Sta - RT-MAC	7.47E-05 (2.89E-05)	3.76E-04 (5.04E-05)	3.05E-03 (1.21E-04)	7.69E-02 (7.91E-04)
10 Sta - 802.11	8.73E-05 (3.13E-05)	4.36E-04 (5.43E-05)	1.05E-02 (2.36E-04)	9.73E-01 (1.11E-03)
10 Sta - RT-MAC	9.57E-05 (3.28E-05)	4.51E-04 (5.52E-05)	3.37E-03 (1.27E-04)	8.50E-02 (9.79E-04)
20 Sta - 802.11	7.49E-05 (2.90E-05)	4.77E-04 (5.68E-05)	2.50E-02 (3.43E-04)	9.77E-01 (9.29E-04)
20 Sta - RT-MAC	1.37E-04 (3.93E-05)	6.88E-04 (6.81E-05)	4.51E-03 (1.47E-04)	9.84E-02 (1.07E-03)
30 Sta - 802.11	8.31E-05 (3.06E-05)	4.81E-04 (5.70E-05)	4.19E-01 (1.33E-03)	9.73E-01 (9.32E-04)
30 Sta - RT-MAC	2.66E-04 (5.47E-05)	9.27E-04 (7.90E-05)	6.17E-03 (1.72E-04)	1.08E-01 (1.13E-03)
40 Sta - 802.11	6.23E-05 (2.65E-05)	5.34E-04 (6.00E-05)	5.93E-01 (1.53E-03)	9.78E-01 (8.09E-04)
40 Sta - RT-MAC	3.74E-04 (6.48E-05)	1.13E-03 (8.74E-05)	7.33E-03 (1.87E-04)	1.10E-01 (1.09E-03)
50 Sta - 802.11	1.12E-04 (3.56E-05)	6.01E-04 (6.37E-05)	7.61E-01 (1.67E-03)	9.82E-01 (7.08E-04)
50 Sta - RT-MAC	4.95E-04 (7.46E-05)	1.47E-03 (9.93E-05)	8.72E-03 (2.03E-04)	1.20E-01 (1.06E-03)

Table B.15: Avionics Missed Deadline Ratio - Bursty Error Channel (Figure 6.24)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	1.71E-03 (1.39E-04)	4.53E-03 (1.74E-04)	2.43E-02 (3.47E-04)	9.85E-01 (7.93E-04)
5 Sta - RT-MAC	2.02E-03 (1.51E-04)	3.98E-03 (1.64E-04)	1.12E-02 (2.30E-04)	9.85E-02 (8.90E-04)
10 Sta - 802.11	2.19E-03 (1.57E-04)	4.48E-03 (1.73E-04)	3.59E-02 (4.09E-04)	9.76E-01 (1.03E-03)
10 Sta - RT-MAC	2.87E-03 (1.80E-04)	5.24E-03 (1.87E-04)	1.12E-02 (2.38E-04)	1.05E-01 (1.08E-03)
20 Sta - 802.11	2.75E-03 (1.76E-04)	6.33E-03 (2.06E-04)	1.52E-01 (8.20E-04)	9.81E-01 (8.10E-04)
20 Sta - RT-MAC	3.45E-03 (1.97E-04)	4.56E-03 (1.75E-04)	1.41E-02 (2.81E-04)	1.13E-01 (1.14E-03)
30 Sta - 802.11	2.22E-03 (1.58E-04)	7.00E-03 (2.17E-04)	6.83E-01 (1.57E-03)	9.72E-01 (9.16E-04)
30 Sta - RT-MAC	3.39E-03 (1.95E-04)	5.95E-03 (1.99E-04)	1.58E-02 (2.91E-04)	1.28E-01 (1.21E-03)
40 Sta - 802.11	3.14E-03 (1.88E-04)	6.91E-03 (2.15E-04)	7.84E-01 (1.59E-03)	9.82E-01 (7.06E-04)
40 Sta - RT-MAC	4.09E-03 (2.14E-04)	5.73E-03 (1.96E-04)	1.66E-02 (2.90E-04)	1.34E-01 (1.19E-03)
50 Sta - 802.11	2.31E-03 (1.61E-04)	5.53E-03 (1.93E-04)	8.63E-01 (1.50E-03)	9.83E-01 (6.34E-04)
50 Sta - RT-MAC	4.02E-03 (2.12E-04)	6.74E-03 (2.12E-04)	1.95E-02 (3.06E-04)	1.38E-01 (1.13E-03)

Table B.16: Avionics Collision Ratio - Ideal Channel (Figure 6.27)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	2.14E-03 (1.55E-04)	7.87E-03 (2.29E-04)	2.67E-02 (3.49E-04)	7.96E-02 (1.78E-03)
5 Sta - RT-MAC	8.62E-04 (9.83E-05)	2.75E-03 (1.36E-04)	7.78E-03 (1.92E-04)	1.84E-02 (4.11E-04)
10 Sta - 802.11	2.90E-03 (1.80E-04)	1.12E-02 (2.72E-04)	4.49E-02 (4.70E-04)	1.60E-01 (2.34E-03)
10 Sta - RT-MAC	1.20E-03 (1.16E-04)	3.66E-03 (1.57E-04)	9.82E-03 (2.16E-04)	2.56E-02 (5.72E-04)
20 Sta - 802.11	3.51E-03 (1.98E-04)	1.36E-02 (2.99E-04)	7.11E-02 (5.44E-04)	2.58E-01 (2.40E-03)
20 Sta - RT-MAC	1.05E-03 (1.08E-04)	3.58E-03 (1.55E-04)	9.74E-03 (2.15E-04)	2.71E-02 (6.05E-04)
30 Sta - 802.11	3.75E-03 (2.04E-04)	1.57E-02 (3.20E-04)	2.11E-01 (9.74E-04)	3.24E-01 (2.30E-03)
30 Sta - RT-MAC	1.30E-03 (1.21E-04)	3.48E-03 (1.53E-04)	9.75E-03 (2.15E-04)	2.81E-02 (6.27E-04)
40 Sta - 802.11	4.17E-03 (2.16E-04)	1.63E-02 (3.27E-04)	2.88E-01 (1.19E-03)	3.67E-01 (2.16E-03)
40 Sta - RT-MAC	1.15E-03 (1.13E-04)	3.37E-03 (1.51E-04)	9.45E-03 (2.12E-04)	2.58E-02 (5.76E-04)
50 Sta - 802.11	3.88E-03 (2.08E-04)	1.75E-02 (3.38E-04)	3.57E-01 (1.51E-03)	3.97E-01 (2.04E-03)
50 Sta - RT-MAC	1.19E-03 (1.16E-04)	3.20E-03 (1.47E-04)	8.68E-03 (2.03E-04)	2.29E-02 (5.11E-04)

Table B.17: Avionics Collision Ratio - Bursty Error Channel (Figure 6.28)

Stations - Protocol	Offered Load (G)			
	0.3	0.5	0.7	0.9
5 Sta - 802.11	2.51E-03 (1.64E-04)	8.43E-03 (2.33E-04)	2.88E-02 (3.67E-04)	7.77E-02 (1.74E-03)
5 Sta - RT-MAC	1.21E-03 (1.14E-04)	3.30E-03 (1.47E-04)	8.22E-03 (1.96E-04)	1.87E-02 (4.18E-04)
10 Sta - 802.11	3.54E-03 (1.94E-04)	1.32E-02 (2.90E-04)	5.28E-02 (4.73E-04)	1.55E-01 (2.29E-03)
10 Sta - RT-MAC	1.54E-03 (1.29E-04)	4.23E-03 (1.66E-04)	1.03E-02 (2.26E-04)	2.56E-02 (5.71E-04)
20 Sta - 802.11	4.78E-03 (2.26E-04)	1.81E-02 (3.37E-04)	1.16E-01 (6.81E-04)	2.49E-01 (2.29E-03)
20 Sta - RT-MAC	1.70E-03 (1.36E-04)	4.04E-03 (1.62E-04)	1.10E-02 (2.46E-04)	2.71E-02 (6.07E-04)
30 Sta - 802.11	5.48E-03 (2.42E-04)	2.10E-02 (3.63E-04)	2.70E-01 (1.27E-03)	3.19E-01 (2.21E-03)
30 Sta - RT-MAC	1.38E-03 (1.22E-04)	4.26E-03 (1.66E-04)	1.06E-02 (2.36E-04)	2.79E-02 (6.23E-04)
40 Sta - 802.11	6.60E-03 (2.64E-04)	2.34E-02 (3.82E-04)	3.29E-01 (1.47E-03)	3.59E-01 (2.10E-03)
40 Sta - RT-MAC	1.38E-03 (1.22E-04)	3.51E-03 (1.52E-04)	1.01E-02 (2.25E-04)	2.62E-02 (5.86E-04)
50 Sta - 802.11	6.50E-03 (2.63E-04)	2.25E-02 (3.76E-04)	3.73E-01 (1.65E-03)	3.92E-01 (1.94E-03)
50 Sta - RT-MAC	1.37E-03 (1.22E-04)	3.68E-03 (1.55E-04)	9.40E-03 (2.12E-04)	2.33E-02 (5.22E-04)

B.3 Voice with Non Real-time Traffic Model

B.3.1 1 Mbps Data Rate

Table B.18: Voice Throughput - Ideal Channel (1 Mbps) (Figure 6.29)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	5.45E-02 (2.88E-03)	2.53E-01 (8.58E-03)	4.52E-01 (1.03E-02)	6.48E-01 (1.60E-02)	6.54E-01 (6.30E-03)
4 Sta - RT-MAC	5.41E-02 (2.39E-03)	2.54E-01 (1.11E-02)	4.45E-01 (1.63E-02)	6.32E-01 (1.67E-02)	6.81E-01 (3.73E-03)
10 Sta - 802.11	1.34E-01 (4.75E-03)	3.33E-01 (7.68E-03)	5.29E-01 (4.61E-03)	5.16E-01 (3.00E-03)	5.15E-01 (7.19E-03)
10 Sta - RT-MAC	1.34E-01 (3.83E-03)	3.31E-01 (8.44E-03)	5.20E-01 (1.06E-02)	6.43E-01 (7.09E-03)	6.41E-01 (2.26E-02)
14 Sta - 802.11	1.89E-01 (8.02E-03)	3.92E-01 (7.58E-03)	4.55E-01 (6.77E-03)	4.50E-01 (7.19E-03)	4.54E-01 (6.26E-03)
14 Sta - RT-MAC	1.90E-01 (7.06E-03)	3.82E-01 (5.32E-03)	5.43E-01 (6.79E-03)	6.40E-01 (1.18E-02)	6.46E-01 (6.15E-03)
20 Sta - 802.11	2.61E-01 (8.99E-03)	3.76E-01 (9.48E-03)	3.73E-01 (1.88E-02)	3.71E-01 (9.54E-03)	3.75E-01 (1.09E-02)
20 Sta - RT-MAC	2.66E-01 (1.43E-02)	4.33E-01 (7.97E-03)	5.40E-01 (4.90E-03)	6.38E-01 (8.32E-03)	6.57E-01 (3.43E-03)
24 Sta - 802.11	3.20E-01 (3.63E-03)	3.32E-01 (1.45E-02)	3.31E-01 (1.27E-02)	3.28E-01 (1.85E-02)	3.27E-01 (1.64E-02)
24 Sta - RT-MAC	2.97E-01 (9.38E-03)	4.36E-01 (1.93E-03)	5.36E-01 (7.25E-03)	6.37E-01 (4.04E-03)	6.64E-01 (3.86E-03)
30 Sta - 802.11	2.95E-01 (9.46E-03)	3.04E-01 (3.46E-03)	3.05E-01 (5.28E-03)	3.06E-01 (7.00E-03)	3.05E-01 (7.20E-03)
30 Sta - RT-MAC	3.10E-01 (3.82E-03)	4.30E-01 (3.69E-03)	5.32E-01 (5.26E-03)	6.38E-01 (2.11E-03)	6.65E-01 (3.56E-03)

Table B.19: Voice Throughput - Bursty Error Channel (1 Mbps) (Figure 6.30)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	5.37E-02 (2.23E-03)	2.49E-01 (2.00E-02)	4.46E-01 (1.19E-02)	6.32E-01 (9.28E-03)	6.29E-01 (1.25E-02)
4 Sta - RT-MAC	5.37E-02 (5.19E-03)	2.49E-01 (7.33E-03)	4.40E-01 (9.75E-03)	6.18E-01 (1.65E-02)	6.67E-01 (7.92E-03)
10 Sta - 802.11	1.35E-01 (5.78E-03)	3.29E-01 (1.09E-02)	5.15E-01 (1.24E-02)	5.06E-01 (3.36E-03)	5.05E-01 (9.09E-03)
10 Sta - RT-MAC	1.34E-01 (6.34E-03)	3.27E-01 (1.24E-02)	5.04E-01 (2.19E-02)	6.24E-01 (1.28E-02)	6.21E-01 (1.33E-02)
14 Sta - 802.11	1.91E-01 (7.41E-03)	3.87E-01 (1.21E-02)	4.44E-01 (6.23E-03)	4.41E-01 (8.02E-03)	4.46E-01 (3.97E-03)
14 Sta - RT-MAC	1.82E-01 (5.07E-03)	3.77E-01 (3.99E-03)	5.34E-01 (1.24E-02)	6.28E-01 (5.50E-03)	6.35E-01 (1.26E-02)
20 Sta - 802.11	2.67E-01 (1.28E-02)	3.71E-01 (1.07E-02)	3.65E-01 (1.25E-02)	3.59E-01 (2.06E-02)	3.64E-01 (1.03E-02)
20 Sta - RT-MAC	2.62E-01 (3.69E-03)	4.25E-01 (1.02E-02)	5.29E-01 (1.10E-02)	6.23E-01 (1.18E-02)	6.46E-01 (5.26E-03)
24 Sta - 802.11	3.17E-01 (1.51E-02)	3.20E-01 (1.26E-02)	3.23E-01 (1.79E-02)	3.21E-01 (1.38E-02)	3.26E-01 (1.33E-02)
24 Sta - RT-MAC	2.92E-01 (1.31E-02)	4.25E-01 (1.01E-02)	5.24E-01 (1.48E-02)	6.22E-01 (5.30E-03)	6.49E-01 (1.15E-02)
30 Sta - 802.11	2.88E-01 (2.33E-03)	2.98E-01 (9.60E-03)	2.96E-01 (2.77E-03)	2.97E-01 (6.47E-03)	2.99E-01 (1.19E-02)
30 Sta - RT-MAC	3.05E-01 (3.82E-03)	4.17E-01 (2.59E-03)	5.20E-01 (2.97E-03)	6.18E-01 (1.27E-02)	6.51E-01 (2.26E-03)

Table B.20: Voice Mean Delay - Ideal Channel (1 Mbps) (Figure 6.34)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	2.10E-02 (4.88E-05)	1.44E-02 (3.27E-04)	1.40E-02 (6.02E-04)	1.20E+00 (1.75E+00)	6.19E+00 (6.38E-01)
4 Sta - RT-MAC	2.13E-02 (4.62E-05)	1.47E-02 (6.23E-05)	1.39E-02 (4.91E-04)	1.00E-01 (2.48E-02)	5.70E+00 (4.70E-01)
10 Sta - 802.11	2.12E-02 (4.16E-05)	1.93E-02 (2.07E-04)	9.97E-01 (6.30E-01)	9.84E+00 (5.50E-01)	1.17E+01 (3.16E-01)
10 Sta - RT-MAC	2.23E-02 (1.75E-05)	2.06E-02 (3.40E-04)	6.16E-02 (3.04E-02)	2.80E+00 (6.35E-01)	8.59E+00 (3.73E+00)
14 Sta - 802.11	2.16E-02 (3.48E-04)	4.52E-02 (1.89E-02)	1.03E+01 (1.12E+00)	1.38E+01 (1.66E+00)	1.52E+01 (2.97E-01)
14 Sta - RT-MAC	2.33E-02 (1.35E-04)	3.10E-02 (1.01E-03)	2.28E-01 (2.83E-02)	1.77E+00 (3.48E-01)	8.14E+00 (1.37E+00)
20 Sta - 802.11	2.72E-02 (2.31E-03)	4.31E+00 (1.37E+00)	9.41E+00 (7.59E+00)	8.80E+00 (4.21E+00)	1.15E+01 (5.67E+00)
20 Sta - RT-MAC	3.17E-02 (3.91E-03)	1.04E-01 (1.14E-02)	3.14E-01 (1.51E-02)	1.23E+00 (2.14E-01)	7.46E+00 (6.87E-01)
24 Sta - 802.11	2.36E-01 (2.02E-01)	4.81E+00 (1.03E+00)	5.76E+00 (5.99E-01)	6.43E+00 (7.42E-01)	6.56E+00 (8.34E-01)
24 Sta - RT-MAC	4.95E-02 (6.30E-03)	1.39E-01 (8.99E-03)	3.09E-01 (1.48E-02)	1.04E+00 (2.23E-01)	7.19E+00 (8.63E-01)
30 Sta - 802.11	4.51E+00 (2.28E+00)	6.53E+00 (1.32E+00)	8.03E+00 (6.08E-01)	8.58E+00 (6.00E-01)	8.68E+00 (1.13E+00)
30 Sta - RT-MAC	7.38E-02 (3.42E-03)	1.57E-01 (4.00E-03)	3.13E-01 (1.11E-02)	9.69E-01 (1.27E-01)	7.42E+00 (1.09E+00)

Table B.21: Voice Mean Delay - Bursty Error Channel (1 Mbps) (Figure 6.35)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	2.35E-02 (1.86E-03)	1.78E-02 (2.61E-03)	2.01E-02 (2.43E-03)	1.38E+00 (1.92E+00)	6.15E+00 (2.07E-01)
4 Sta - RT-MAC	2.20E-02 (3.30E-04)	1.61E-02 (6.55E-04)	1.55E-02 (1.06E-03)	1.26E-01 (4.84E-02)	5.44E+00 (5.22E-01)
10 Sta - 802.11	2.44E-02 (1.59E-03)	2.52E-02 (3.50E-03)	2.47E+00 (3.41E+00)	1.04E+01 (1.45E+00)	1.21E+01 (1.70E-01)
10 Sta - RT-MAC	2.30E-02 (2.71E-04)	2.18E-02 (3.53E-04)	6.33E-02 (9.05E-03)	2.36E+00 (1.16E+00)	7.85E+00 (1.55E+00)
14 Sta - 802.11	2.56E-02 (2.32E-03)	6.54E-02 (1.11E-02)	1.14E+01 (4.98E-01)	1.45E+01 (5.76E-01)	1.55E+01 (6.17E-01)
14 Sta - RT-MAC	2.42E-02 (4.90E-04)	3.43E-02 (2.13E-03)	2.32E-01 (5.44E-02)	1.71E+00 (4.33E-01)	8.48E+00 (1.17E+00)
20 Sta - 802.11	4.02E-02 (2.19E-02)	4.92E+00 (3.52E+00)	6.21E+00 (2.19E+00)	8.18E+00 (2.60E+00)	1.16E+01 (8.74E+00)
20 Sta - RT-MAC	3.31E-02 (3.24E-03)	1.04E-01 (1.06E-02)	3.07E-01 (3.03E-02)	1.22E+00 (2.07E-01)	7.97E+00 (1.99E+00)
24 Sta - 802.11	7.63E-01 (1.72E+00)	4.62E+00 (1.00E+00)	5.78E+00 (5.90E-01)	6.29E+00 (9.17E-01)	7.31E+00 (9.94E-01)
24 Sta - RT-MAC	4.86E-02 (5.71E-03)	1.38E-01 (1.15E-02)	3.10E-01 (4.46E-02)	1.06E+00 (1.94E-01)	7.66E+00 (1.43E+00)
30 Sta - 802.11	4.75E+00 (1.11E+00)	7.32E+00 (2.50E+00)	8.57E+00 (1.44E+00)	9.21E+00 (9.20E-01)	9.23E+00 (7.67E-01)
30 Sta - RT-MAC	7.36E-02 (2.98E-03)	1.53E-01 (8.61E-03)	3.14E-01 (1.37E-02)	9.27E-01 (2.35E-01)	7.29E+00 (1.17E+00)

Table B.22: Voice Missed Deadline Ratio - Ideal Channel (1 Mbps) (Figure 6.38)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	7.07E-05 (3.36E-05)	3.26E-02 (7.68E-04)	5.60E-02 (1.25E-03)
4 Sta - RT-MAC	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	8.25E-05 (3.62E-05)
10 Sta - 802.11	0.00E+00 (0.00E+00)	5.53E-04 (5.96E-05)	4.95E-01 (1.25E-03)	8.34E-01 (1.32E-03)	8.49E-01 (1.37E-03)
10 Sta - RT-MAC	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	2.53E-03 (1.26E-04)	3.81E-01 (1.23E-03)	4.76E-01 (1.94E-03)
14 Sta - 802.11	2.13E-04 (3.11E-05)	5.85E-02 (5.17E-04)	9.27E-01 (6.27E-04)	9.40E-01 (6.17E-04)	9.42E-01 (6.16E-04)
14 Sta - RT-MAC	0.00E+00 (0.00E+00)	1.39E-03 (7.91E-05)	1.39E-01 (7.36E-04)	5.89E-01 (1.04E-03)	7.16E-01 (1.78E-03)
20 Sta - 802.11	1.52E-02 (3.41E-04)	9.36E-01 (8.15E-04)	9.80E-01 (3.73E-04)	9.83E-01 (4.11E-04)	9.84E-01 (3.48E-04)
20 Sta - RT-MAC	6.58E-03 (1.60E-04)	1.10E-01 (5.55E-04)	4.21E-01 (8.79E-04)	7.35E-01 (7.86E-04)	8.54E-01 (1.19E-03)
24 Sta - 802.11	2.93E-01 (9.84E-04)	9.68E-01 (8.50E-04)	9.83E-01 (7.05E-04)	9.85E-01 (6.52E-04)	9.90E-01 (5.65E-04)
24 Sta - RT-MAC	5.26E-02 (7.26E-04)	2.55E-01 (7.11E-04)	5.33E-01 (8.11E-04)	7.87E-01 (6.69E-04)	8.96E-01 (9.28E-04)
30 Sta - 802.11	9.36E-01 (1.19E-03)	9.84E-01 (6.52E-04)	9.92E-01 (4.78E-04)	9.93E-01 (4.33E-04)	9.96E-01 (3.34E-04)
30 Sta - RT-MAC	1.89E-01 (1.26E-03)	4.22E-01 (7.20E-04)	6.44E-01 (6.98E-04)	8.47E-01 (5.25E-04)	9.29E-01 (7.04E-04)

Table B.23: Voice Missed Deadline Ratio - Bursty Error Channel (1 Mbps) (Figure 6.39)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	8.84E-03 (3.74E-04)	1.05E-02 (4.05E-04)	1.44E-02 (4.74E-04)	7.16E-02 (1.37E-03)	9.45E-02 (2.11E-03)
4 Sta - RT-MAC	6.59E-03 (3.22E-04)	9.56E-03 (3.86E-04)	8.70E-03 (3.71E-04)	1.20E-02 (4.34E-04)	1.76E-02 (5.26E-04)
10 Sta - 802.11	1.09E-02 (2.61E-04)	1.87E-02 (3.56E-04)	6.21E-01 (1.24E-03)	8.44E-01 (1.29E-03)	8.52E-01 (1.31E-03)
10 Sta - RT-MAC	1.09E-02 (2.62E-04)	1.22E-02 (2.79E-04)	1.77E-02 (3.33E-04)	3.54E-01 (1.25E-03)	4.84E-01 (2.28E-03)
14 Sta - 802.11	1.43E-02 (2.83E-04)	1.01E-01 (6.47E-04)	9.31E-01 (6.04E-04)	9.43E-01 (5.72E-04)	9.42E-01 (6.14E-04)
14 Sta - RT-MAC	1.25E-02 (2.40E-04)	1.51E-02 (3.20E-04)	1.60E-01 (7.83E-04)	5.92E-01 (1.08E-03)	7.16E-01 (1.80E-03)
20 Sta - 802.11	5.70E-02 (5.35E-04)	9.47E-01 (7.16E-04)	9.75E-01 (6.32E-04)	9.82E-01 (4.92E-04)	9.85E-01 (3.21E-04)
20 Sta - RT-MAC	1.97E-02 (3.90E-04)	1.21E-01 (5.82E-04)	4.27E-01 (8.81E-04)	7.42E-01 (8.82E-04)	8.57E-01 (1.13E-03)
24 Sta - 802.11	4.44E-01 (1.31E-03)	9.70E-01 (8.68E-04)	9.85E-01 (6.52E-04)	9.88E-01 (5.93E-04)	9.88E-01 (5.66E-04)
24 Sta - RT-MAC	5.68E-02 (7.34E-04)	2.69E-01 (7.24E-04)	5.34E-01 (8.13E-04)	7.93E-01 (7.49E-04)	8.98E-01 (9.36E-04)
30 Sta - 802.11	9.68E-01 (8.75E-04)	9.88E-01 (5.53E-04)	9.92E-01 (4.31E-04)	9.95E-01 (3.50E-04)	9.97E-01 (2.83E-04)
30 Sta - RT-MAC	2.06E-01 (1.29E-03)	4.25E-01 (7.26E-04)	6.45E-01 (6.98E-04)	8.44E-01 (6.35E-04)	9.30E-01 (7.06E-04)

Table B.24: Voice Collision Ratio - Ideal Channel (1 Mbps) (Figure 6.44)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	1.38E-03 (1.47E-04)	2.53E-03 (1.52E-04)	9.95E-03 (2.51E-04)	5.42E-02 (5.37E-04)	6.09E-02 (6.97E-04)
4 Sta - RT-MAC	5.27E-04 (9.13E-05)	1.41E-03 (1.14E-04)	3.70E-03 (1.55E-04)	1.28E-02 (2.53E-04)	1.85E-02 (2.93E-04)
10 Sta - 802.11	2.54E-03 (1.27E-04)	1.68E-02 (2.84E-04)	1.33E-01 (6.32E-04)	1.69E-01 (9.65E-04)	1.69E-01 (1.04E-03)
10 Sta - RT-MAC	2.97E-03 (1.39E-04)	7.50E-03 (1.92E-04)	1.83E-02 (2.68E-04)	3.23E-02 (3.66E-04)	3.44E-02 (5.85E-04)
14 Sta - 802.11	7.11E-03 (1.78E-04)	6.44E-02 (4.75E-04)	2.18E-01 (7.77E-04)	2.20E-01 (8.39E-04)	2.20E-01 (8.48E-04)
14 Sta - RT-MAC	6.13E-03 (1.65E-04)	1.51E-02 (2.34E-04)	2.74E-02 (3.05E-04)	3.45E-02 (3.81E-04)	3.60E-02 (7.56E-04)
20 Sta - 802.11	3.33E-02 (4.91E-04)	2.65E-01 (1.20E-03)	2.77E-01 (9.72E-04)	2.77E-01 (1.16E-03)	2.78E-01 (1.01E-03)
20 Sta - RT-MAC	1.46E-02 (2.36E-04)	2.59E-02 (2.75E-04)	2.86E-02 (3.16E-04)	3.34E-02 (3.81E-04)	3.87E-02 (8.12E-04)
24 Sta - 802.11	1.45E-01 (7.04E-04)	2.96E-01 (1.81E-03)	3.01E-01 (2.02E-03)	3.02E-01 (2.02E-03)	3.02E-01 (2.07E-03)
24 Sta - RT-MAC	2.14E-02 (4.79E-04)	2.62E-02 (2.76E-04)	2.76E-02 (3.14E-04)	3.17E-02 (3.75E-04)	3.84E-02 (7.99E-04)
30 Sta - 802.11	3.24E-01 (1.88E-03)	3.37E-01 (2.01E-03)	3.40E-01 (2.01E-03)	3.41E-01 (2.01E-03)	3.44E-01 (2.00E-03)
30 Sta - RT-MAC	2.45E-02 (5.47E-04)	2.54E-02 (2.76E-04)	2.68E-02 (3.14E-04)	3.13E-02 (3.78E-04)	3.76E-02 (8.22E-04)

Table B.25: Voice Collision Ratio - Bursty Error Channel (1 Mbps) (Figure 6.45)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
4 Sta - 802.11	9.54E-04 (1.21E-04)	3.20E-03 (1.69E-04)	1.11E-02 (2.63E-04)	5.17E-02 (6.39E-04)	5.91E-02 (9.15E-04)
4 Sta - RT-MAC	6.63E-04 (1.01E-04)	1.64E-03 (1.21E-04)	3.93E-03 (1.59E-04)	1.31E-02 (2.55E-04)	1.82E-02 (2.90E-04)
10 Sta - 802.11	4.64E-03 (1.68E-04)	1.90E-02 (3.09E-04)	1.39E-01 (6.53E-04)	1.62E-01 (9.48E-04)	1.65E-01 (9.91E-04)
10 Sta - RT-MAC	3.25E-03 (1.42E-04)	7.55E-03 (1.91E-04)	1.76E-02 (2.64E-04)	3.12E-02 (3.67E-04)	3.32E-02 (6.84E-04)
14 Sta - 802.11	1.08E-02 (2.42E-04)	6.68E-02 (4.65E-04)	2.13E-01 (7.58E-04)	2.15E-01 (7.92E-04)	2.15E-01 (8.31E-04)
14 Sta - RT-MAC	5.89E-03 (1.64E-04)	1.54E-02 (2.92E-04)	2.69E-02 (3.04E-04)	3.35E-02 (3.90E-04)	3.73E-02 (7.66E-04)
20 Sta - 802.11	4.68E-02 (4.70E-04)	2.63E-01 (1.15E-03)	2.72E-01 (1.45E-03)	2.73E-01 (1.33E-03)	2.71E-01 (9.51E-04)
20 Sta - RT-MAC	1.53E-02 (3.41E-04)	2.54E-02 (2.73E-04)	2.86E-02 (3.15E-04)	3.32E-02 (4.30E-04)	3.87E-02 (7.79E-04)
24 Sta - 802.11	1.78E-01 (9.03E-04)	2.91E-01 (1.88E-03)	2.94E-01 (1.94E-03)	2.96E-01 (1.98E-03)	2.98E-01 (1.95E-03)
24 Sta - RT-MAC	2.02E-02 (4.53E-04)	2.59E-02 (2.75E-04)	2.75E-02 (3.13E-04)	3.19E-02 (4.27E-04)	3.80E-02 (8.18E-04)
30 Sta - 802.11	3.23E-01 (1.89E-03)	3.34E-01 (1.93E-03)	3.34E-01 (1.90E-03)	3.36E-01 (1.92E-03)	3.37E-01 (1.94E-03)
30 Sta - RT-MAC	2.42E-02 (5.41E-04)	2.54E-02 (2.77E-04)	2.63E-02 (3.11E-04)	3.10E-02 (4.50E-04)	3.95E-02 (8.49E-04)

B.3.2 10 Mbps Data Rate

Table B.26: Voice Throughput - Ideal Channel (10 Mbps) (Figure 6.46)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	1.33E-02 (4.05E-04)	2.11E-01 (2.54E-03)	4.08E-01 (8.93E-03)	4.67E-01 (3.44E-03)	4.69E-01 (6.88E-03)
10 Sta - RT-MAC	1.35E-02 (2.42E-04)	2.07E-01 (3.30E-03)	3.88E-01 (3.22E-03)	5.10E-01 (4.43E-03)	5.14E-01 (8.40E-04)
20 Sta - 802.11	2.68E-02 (9.05E-04)	2.26E-01 (2.26E-03)	4.18E-01 (5.48E-03)	3.47E-01 (7.68E-03)	3.46E-01 (3.87E-03)
20 Sta - RT-MAC	2.67E-02 (7.71E-04)	2.20E-01 (2.22E-03)	3.94E-01 (3.66E-03)	4.86E-01 (1.86E-03)	4.86E-01 (7.71E-04)
30 Sta - 802.11	4.03E-02 (1.54E-03)	2.40E-01 (3.66E-03)	3.53E-01 (1.11E-02)	3.11E-01 (4.70E-03)	3.11E-01 (5.30E-03)
30 Sta - RT-MAC	4.01E-02 (1.27E-03)	2.32E-01 (2.15E-03)	3.98E-01 (3.10E-03)	4.61E-01 (8.23E-04)	4.60E-01 (1.46E-03)
40 Sta - 802.11	5.41E-02 (7.08E-04)	2.52E-01 (4.26E-03)	3.03E-01 (9.38E-03)	2.82E-01 (4.32E-03)	2.85E-01 (1.02E-02)
40 Sta - RT-MAC	5.40E-02 (9.16E-04)	2.41E-01 (5.19E-03)	4.01E-01 (2.53E-03)	3.93E-01 (4.48E-03)	3.92E-01 (1.53E-02)
50 Sta - 802.11	6.68E-02 (8.63E-04)	2.65E-01 (5.61E-03)	2.69E-01 (4.27E-03)	2.58E-01 (9.98E-03)	2.57E-01 (5.51E-03)
50 Sta - RT-MAC	6.72E-02 (1.31E-03)	2.53E-01 (4.16E-03)	3.77E-01 (1.04E-02)	3.54E-01 (7.20E-03)	3.32E-01 (8.93E-03)
60 Sta - 802.11	8.08E-02 (8.83E-04)	2.79E-01 (2.06E-03)	2.43E-01 (2.56E-03)	2.37E-01 (5.63E-03)	2.32E-01 (3.77E-03)
60 Sta - RT-MAC	8.07E-02 (1.05E-03)	2.66E-01 (2.97E-03)	3.65E-01 (8.18E-03)	3.50E-01 (7.06E-03)	3.32E-01 (8.85E-03)
70 Sta - 802.11	9.37E-02 (1.86E-03)	2.76E-01 (1.78E-02)	2.14E-01 (4.47E-03)	2.14E-01 (7.13E-03)	2.12E-01 (5.04E-03)
70 Sta - RT-MAC	9.44E-02 (1.14E-03)	2.75E-01 (4.95E-03)	3.62E-01 (5.32E-03)	3.53E-01 (1.05E-02)	3.28E-01 (8.46E-03)
80 Sta - 802.11	1.07E-01 (2.19E-03)	2.28E-01 (4.98E-02)	1.98E-01 (6.45E-03)	1.95E-01 (4.75E-03)	1.96E-01 (7.54E-03)
80 Sta - RT-MAC	1.08E-01 (2.23E-03)	2.72E-01 (7.54E-03)	3.63E-01 (7.91E-03)	3.58E-01 (1.42E-02)	3.37E-01 (8.86E-03)

Table B.27: Voice Throughput - Bursty Error Channel (10 Mbps) (Figure 6.47)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	1.35E-02 (5.34E-04)	2.11E-01 (4.08E-03)	4.04E-01 (1.36E-02)	4.50E-01 (1.04E-02)	4.51E-01 (1.58E-02)
10 Sta - RT-MAC	1.34E-02 (5.54E-04)	2.03E-01 (4.71E-03)	3.80E-01 (4.63E-03)	5.02E-01 (4.41E-03)	5.03E-01 (2.16E-03)
20 Sta - 802.11	2.69E-02 (2.48E-04)	2.23E-01 (2.23E-03)	4.04E-01 (2.77E-02)	3.42E-01 (3.27E-03)	3.42E-01 (7.98E-03)
20 Sta - RT-MAC	2.67E-02 (1.24E-03)	2.13E-01 (8.84E-03)	3.85E-01 (8.40E-03)	4.71E-01 (1.23E-02)	4.69E-01 (7.80E-03)
30 Sta - 802.11	4.05E-02 (6.25E-04)	2.31E-01 (6.51E-03)	3.35E-01 (1.37E-02)	3.10E-01 (9.32E-03)	3.12E-01 (7.07E-03)
30 Sta - RT-MAC	3.87E-02 (7.60E-04)	2.23E-01 (5.60E-03)	3.88E-01 (2.35E-03)	4.29E-01 (2.89E-02)	4.29E-01 (1.81E-02)
40 Sta - 802.11	5.33E-02 (1.91E-03)	2.43E-01 (3.77E-03)	3.01E-01 (1.31E-02)	2.80E-01 (8.41E-03)	2.78E-01 (1.36E-02)
40 Sta - RT-MAC	5.30E-02 (1.37E-03)	2.32E-01 (5.31E-03)	3.81E-01 (1.90E-02)	3.59E-01 (1.03E-02)	3.66E-01 (4.88E-02)
50 Sta - 802.11	6.54E-02 (2.71E-03)	2.56E-01 (3.85E-03)	2.66E-01 (9.23E-03)	2.54E-01 (1.04E-02)	2.51E-01 (7.08E-03)
50 Sta - RT-MAC	6.41E-02 (3.96E-03)	2.41E-01 (1.39E-02)	3.69E-01 (1.24E-02)	3.48E-01 (1.36E-02)	3.20E-01 (7.67E-03)
60 Sta - 802.11	7.74E-02 (3.79E-03)	2.66E-01 (9.87E-03)	2.40E-01 (8.96E-03)	2.29E-01 (4.28E-03)	2.29E-01 (1.01E-02)
60 Sta - RT-MAC	7.44E-02 (2.81E-03)	2.34E-01 (3.91E-02)	3.59E-01 (1.15E-02)	3.48E-01 (1.50E-02)	3.30E-01 (5.67E-03)
70 Sta - 802.11	8.89E-02 (3.36E-03)	2.43E-01 (1.09E-02)	2.10E-01 (8.99E-03)	2.09E-01 (5.70E-03)	2.11E-01 (4.45E-03)
70 Sta - RT-MAC	8.58E-02 (7.76E-03)	2.43E-01 (2.56E-02)	3.57E-01 (1.03E-02)	3.46E-01 (1.70E-02)	3.30E-01 (1.46E-02)
80 Sta - 802.11	9.57E-02 (7.99E-03)	2.08E-01 (1.28E-02)	1.94E-01 (7.22E-03)	1.91E-01 (9.34E-03)	1.91E-01 (5.45E-03)
80 Sta - RT-MAC	9.99E-02 (8.47E-03)	2.57E-01 (2.97E-02)	3.53E-01 (8.64E-03)	3.50E-01 (9.78E-03)	3.33E-01 (1.27E-02)

Table B.28: Voice Mean Delay - Ideal Channel (10 Mbps) (Figure 6.50)

Stations - Protocol	Offered Data Load (G_{NRT}) 0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	1.99E-02 (1.36E-05)	5.59E-03 (2.84E-04)	5.15E-03 (3.01E-04)	2.58E+00 (1.24E-01)	2.85E+00 (4.48E-02)
10 Sta - RT-MAC	2.02E-02 (3.87E-06)	6.06E-03 (2.61E-04)	4.51E-03 (1.85E-04)	4.17E-01 (2.56E-01)	2.19E+00 (4.52E-02)
20 Sta - 802.11	2.00E-02 (1.34E-05)	8.61E-03 (1.24E-04)	3.09E-02 (6.28E-02)	2.99E+00 (6.38E-01)	4.43E+00 (3.29E-01)
20 Sta - RT-MAC	2.06E-02 (5.76E-06)	9.60E-03 (9.30E-05)	8.29E-03 (7.57E-05)	2.90E+00 (4.56E-01)	4.13E+00 (3.15E-02)
30 Sta - 802.11	2.00E-02 (1.29E-05)	1.07E-02 (1.15E-04)	9.46E-01 (7.26E-01)	3.63E+00 (5.07E-01)	5.05E+00 (3.52E-01)
30 Sta - RT-MAC	2.10E-02 (1.18E-05)	1.24E-02 (1.69E-04)	1.38E-02 (6.26E-04)	4.83E+00 (2.39E-01)	5.82E+00 (5.31E-02)
40 Sta - 802.11	2.00E-02 (8.20E-06)	1.22E-02 (1.48E-04)	2.29E+00 (6.19E-01)	4.01E+00 (1.26E-01)	5.10E+00 (2.58E-01)
40 Sta - RT-MAC	2.15E-02 (1.26E-05)	1.46E-02 (2.03E-04)	3.95E-02 (8.55E-03)	2.91E+00 (5.90E-01)	4.98E+00 (7.18E-01)
50 Sta - 802.11	2.00E-02 (1.19E-05)	1.34E-02 (5.77E-05)	2.85E+00 (5.73E-01)	4.02E+00 (3.31E-01)	4.83E+00 (4.62E-01)
50 Sta - RT-MAC	2.20E-02 (1.49E-05)	1.70E-02 (9.31E-05)	3.47E-01 (1.40E-01)	2.16E+00 (3.06E-01)	2.98E+00 (2.87E-01)
60 Sta - 802.11	2.01E-02 (1.24E-05)	1.45E-02 (1.20E-04)	3.00E+00 (3.96E-01)	4.09E+00 (2.95E-01)	4.52E+00 (3.85E-01)
60 Sta - RT-MAC	2.26E-02 (3.61E-05)	2.00E-02 (2.63E-04)	6.35E-01 (1.84E-01)	2.13E+00 (2.93E-01)	3.02E+00 (3.07E-01)
70 Sta - 802.11	2.01E-02 (1.52E-05)	6.87E-02 (2.30E-01)	2.97E+00 (1.02E-01)	3.94E+00 (3.60E-01)	4.35E+00 (2.49E-01)
70 Sta - RT-MAC	2.33E-02 (2.76E-05)	2.56E-02 (1.42E-03)	7.62E-01 (1.32E-01)	2.22E+00 (2.32E-01)	3.02E+00 (1.67E-01)
80 Sta - 802.11	2.02E-02 (1.74E-05)	1.11E+00 (8.44E-01)	3.15E+00 (1.02E-01)	3.97E+00 (3.17E-01)	4.28E+00 (2.55E-01)
80 Sta - RT-MAC	2.43E-02 (7.46E-05)	5.18E-02 (1.29E-02)	7.48E-01 (1.76E-01)	2.28E+00 (2.19E-01)	3.02E+00 (1.27E-01)

Table B.29: Voice Mean Delay - Bursty Error Channel (10 Mbps) (Figure 6.51)

Stations - Protocol	Offered Data Load (G_{NRT}) 0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	2.15E-02 (5.87E-04)	9.62E-03 (3.17E-03)	1.94E-02 (1.31E-02)	2.57E+00 (3.46E-01)	2.87E+00 (6.91E-02)
10 Sta - RT-MAC	2.09E-02 (2.03E-04)	7.28E-03 (1.23E-03)	6.20E-03 (1.03E-03)	5.43E-01 (3.01E-01)	2.18E+00 (1.18E-01)
20 Sta - 802.11	2.26E-02 (1.43E-03)	1.26E-02 (2.25E-03)	1.63E-01 (4.31E-01)	3.61E+00 (4.64E-01)	4.67E+00 (2.62E-01)
20 Sta - RT-MAC	2.13E-02 (1.69E-04)	1.07E-02 (1.28E-04)	1.06E-02 (1.82E-03)	2.73E+00 (6.92E-01)	4.06E+00 (1.14E-01)
30 Sta - 802.11	2.23E-02 (2.08E-03)	1.58E-02 (4.80E-03)	1.53E+00 (4.43E-01)	4.04E+00 (1.99E-01)	5.34E+00 (3.18E-01)
30 Sta - RT-MAC	2.18E-02 (2.58E-04)	1.35E-02 (5.88E-04)	1.68E-02 (2.68E-03)	3.33E+00 (9.86E-01)	5.28E+00 (2.57E-01)
40 Sta - 802.11	2.30E-02 (2.43E-03)	1.83E-02 (8.69E-03)	2.40E+00 (4.21E-01)	4.17E+00 (4.55E-01)	5.28E+00 (6.59E-01)
40 Sta - RT-MAC	2.22E-02 (2.53E-04)	1.59E-02 (6.37E-04)	5.92E-02 (3.22E-02)	2.00E+00 (3.35E-01)	4.09E+00 (1.44E+00)
50 Sta - 802.11	2.22E-02 (1.24E-03)	2.30E-02 (9.59E-03)	3.13E+00 (3.59E-01)	4.07E+00 (2.59E-01)	5.00E+00 (5.49E-01)
50 Sta - RT-MAC	2.27E-02 (5.29E-04)	1.84E-02 (9.67E-04)	3.57E-01 (1.34E-01)	2.19E+00 (3.13E-01)	2.99E+00 (3.10E-01)
60 Sta - 802.11	2.38E-02 (3.85E-03)	3.14E-02 (3.77E-02)	3.14E+00 (2.41E-01)	3.98E+00 (3.83E-01)	4.66E+00 (3.39E-01)
60 Sta - RT-MAC	2.36E-02 (7.10E-04)	2.24E-02 (1.93E-03)	6.91E-01 (2.09E-01)	2.12E+00 (2.62E-01)	3.00E+00 (7.76E-02)
70 Sta - 802.11	2.46E-02 (6.15E-03)	8.05E-01 (5.17E-01)	3.05E+00 (3.56E-01)	4.14E+00 (4.93E-01)	4.50E+00 (3.94E-01)
70 Sta - RT-MAC	2.43E-02 (5.11E-04)	2.92E-02 (4.86E-03)	7.57E-01 (1.00E-01)	2.18E+00 (2.66E-01)	3.20E+00 (1.45E-01)
80 Sta - 802.11	2.41E-02 (2.73E-03)	1.27E+00 (3.15E-01)	3.31E+00 (1.85E-01)	4.18E+00 (4.64E-01)	4.37E+00 (3.33E-01)
80 Sta - RT-MAC	2.53E-02 (1.44E-03)	5.67E-02 (2.63E-02)	7.62E-01 (1.25E-01)	2.15E+00 (1.22E-01)	3.33E+00 (3.96E-01)

Table B.30: Voice Missed Deadline Ratio - Ideal Channel (10 Mbps) (Figure 6.54)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	8.78E-05 (2.38E-05)	5.39E-02 (1.20E-03)	5.32E-02 (1.19E-03)
10 Sta - RT-MAC	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	7.03E-05 (2.11E-05)	1.01E-04 (2.53E-05)
20 Sta - 802.11	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	1.80E-02 (3.45E-04)	2.85E-01 (3.68E-03)	3.09E-01 (3.75E-03)
20 Sta - RT-MAC	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	5.98E-06 (4.40E-06)	8.51E-04 (5.20E-05)	8.19E-04 (5.09E-05)
30 Sta - 802.11	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	4.19E-01 (2.43E-03)	5.62E-01 (3.13E-03)	5.79E-01 (3.12E-03)
30 Sta - RT-MAC	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	7.63E-05 (1.27E-05)	5.46E-03 (1.08E-04)	5.21E-03 (1.05E-04)
40 Sta - 802.11	0.00E+00 (0.00E+00)	0.00E+00 (0.00E+00)	7.17E-01 (2.09E-03)	7.41E-01 (2.38E-03)	7.55E-01 (2.36E-03)
40 Sta - RT-MAC	0.00E+00 (0.00E+00)	1.19E-06 (1.39E-06)	9.38E-04 (3.85E-05)	3.15E-02 (7.05E-04)	3.26E-02 (7.28E-04)
50 Sta - 802.11	0.00E+00 (0.00E+00)	1.41E-06 (1.34E-06)	8.37E-01 (1.60E-03)	8.58E-01 (1.65E-03)	8.56E-01 (1.69E-03)
50 Sta - RT-MAC	0.00E+00 (0.00E+00)	1.46E-05 (4.30E-06)	1.72E-02 (3.63E-04)	1.44E-01 (1.61E-03)	1.69E-01 (2.03E-03)
60 Sta - 802.11	0.00E+00 (0.00E+00)	1.31E-04 (1.18E-05)	8.98E-01 (1.21E-03)	9.12E-01 (1.20E-03)	9.15E-01 (1.18E-03)
60 Sta - RT-MAC	3.93E-07 (6.46E-07)	1.07E-04 (1.06E-05)	1.27E-01 (9.64E-04)	3.40E-01 (2.12E-03)	3.66E-01 (2.49E-03)
70 Sta - 802.11	0.00E+00 (0.00E+00)	8.93E-02 (5.94E-04)	9.36E-01 (9.82E-04)	9.42E-01 (9.44E-04)	9.46E-01 (9.09E-04)
70 Sta - RT-MAC	1.17E-05 (3.27E-06)	8.66E-04 (2.81E-05)	2.79E-01 (1.23E-03)	4.87E-01 (2.02E-03)	5.14E-01 (2.44E-03)
80 Sta - 802.11	0.00E+00 (0.00E+00)	6.20E-01 (1.40E-03)	9.55E-01 (7.98E-04)	9.63E-01 (7.19E-04)	9.61E-01 (7.37E-04)
80 Sta - RT-MAC	1.47E-05 (3.42E-06)	7.64E-03 (1.51E-04)	3.95E-01 (1.27E-03)	5.94E-01 (1.87E-03)	6.27E-01 (2.21E-03)

Table B.31: Voice Missed Deadline Ratio - Bursty Error Channel (10 Mbps) (Figure 6.55)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	5.96E-03 (1.94E-04)	1.22E-02 (2.82E-04)	1.50E-02 (3.40E-04)	6.93E-02 (1.55E-03)	6.86E-02 (1.53E-03)
10 Sta - RT-MAC	6.94E-03 (2.09E-04)	9.66E-03 (2.55E-04)	8.69E-03 (2.36E-04)	9.68E-03 (2.47E-04)	1.25E-02 (2.82E-04)
20 Sta - 802.11	8.92E-03 (1.68E-04)	1.17E-02 (2.45E-04)	7.26E-02 (8.76E-04)	3.24E-01 (3.70E-03)	3.40E-01 (3.73E-03)
20 Sta - RT-MAC	1.03E-02 (1.80E-04)	8.69E-03 (1.84E-04)	9.91E-03 (2.15E-04)	1.23E-02 (2.69E-04)	1.40E-02 (3.12E-04)
30 Sta - 802.11	7.83E-03 (1.37E-04)	1.55E-02 (2.86E-04)	5.18E-01 (2.62E-03)	5.90E-01 (3.10E-03)	5.71E-01 (3.15E-03)
30 Sta - RT-MAC	1.08E-02 (1.84E-04)	1.22E-02 (2.67E-04)	1.02E-02 (2.21E-04)	1.98E-02 (4.41E-04)	2.09E-02 (4.66E-04)
40 Sta - 802.11	9.53E-03 (1.66E-04)	2.21E-02 (3.58E-04)	7.28E-01 (2.08E-03)	7.71E-01 (2.24E-03)	7.77E-01 (2.19E-03)
40 Sta - RT-MAC	1.07E-02 (1.99E-04)	1.12E-02 (2.46E-04)	1.45E-02 (3.04E-04)	5.37E-02 (1.18E-03)	4.60E-02 (1.01E-03)
50 Sta - 802.11	6.94E-03 (1.37E-04)	2.71E-02 (3.13E-04)	8.51E-01 (1.46E-03)	8.57E-01 (1.65E-03)	8.63E-01 (1.60E-03)
50 Sta - RT-MAC	8.76E-03 (1.75E-04)	1.13E-02 (2.40E-04)	3.13E-02 (4.97E-04)	1.74E-01 (1.71E-03)	2.02E-01 (2.27E-03)
60 Sta - 802.11	1.18E-02 (2.15E-04)	5.51E-02 (4.90E-04)	9.03E-01 (1.17E-03)	9.18E-01 (1.15E-03)	9.14E-01 (1.19E-03)
60 Sta - RT-MAC	1.49E-02 (3.00E-04)	1.63E-02 (3.62E-04)	1.51E-01 (9.87E-04)	3.55E-01 (2.07E-03)	3.97E-01 (2.62E-03)
70 Sta - 802.11	1.31E-02 (2.57E-04)	7.03E-01 (1.37E-03)	9.40E-01 (9.45E-04)	9.47E-01 (8.77E-04)	9.46E-01 (9.00E-04)
70 Sta - RT-MAC	1.23E-02 (2.60E-04)	1.97E-02 (4.13E-04)	2.89E-01 (1.25E-03)	5.08E-01 (1.98E-03)	5.45E-01 (2.39E-03)
80 Sta - 802.11	1.37E-02 (3.01E-04)	8.42E-01 (1.33E-03)	9.59E-01 (7.43E-04)	9.63E-01 (6.98E-04)	9.65E-01 (6.79E-04)
80 Sta - RT-MAC	9.37E-03 (1.77E-04)	2.34E-02 (3.60E-04)	4.10E-01 (1.27E-03)	6.02E-01 (1.91E-03)	6.41E-01 (2.10E-03)

Table B.32: Voice Collision Ratio - Ideal Channel (10 Mbps) (Figure 6.60)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	1.14E-03 (8.54E-05)	7.92E-03 (1.13E-04)	4.78E-02 (2.02E-04)	1.71E-01 (6.48E-04)	1.72E-01 (6.35E-04)
10 Sta - RT-MAC	2.36E-03 (1.22E-04)	1.20E-02 (1.39E-04)	3.23E-02 (1.72E-04)	9.05E-02 (2.40E-04)	9.64E-02 (2.45E-04)
20 Sta - 802.11	2.40E-03 (8.75E-05)	1.44E-02 (1.35E-04)	1.20E-01 (4.00E-04)	2.78E-01 (1.55E-03)	2.80E-01 (1.55E-03)
20 Sta - RT-MAC	6.05E-03 (1.38E-04)	2.03E-02 (1.60E-04)	5.10E-02 (1.99E-04)	1.22E-01 (2.62E-04)	1.23E-01 (2.62E-04)
30 Sta - 802.11	4.24E-03 (9.45E-05)	2.16E-02 (1.49E-04)	3.17E-01 (1.13E-03)	3.41E-01 (1.50E-03)	3.42E-01 (1.50E-03)
30 Sta - RT-MAC	9.71E-03 (1.43E-04)	2.79E-02 (1.70E-04)	6.80E-02 (2.13E-04)	1.35E-01 (2.65E-04)	1.35E-01 (2.65E-04)
40 Sta - 802.11	6.34E-03 (9.96E-05)	3.02E-02 (1.62E-04)	3.79E-01 (1.22E-03)	3.86E-01 (1.44E-03)	3.86E-01 (1.44E-03)
40 Sta - RT-MAC	1.43E-02 (1.48E-04)	3.52E-02 (1.76E-04)	8.85E-02 (2.27E-04)	1.41E-01 (8.40E-04)	1.41E-01 (8.54E-04)
50 Sta - 802.11	8.84E-03 (1.06E-04)	4.23E-02 (1.77E-04)	4.16E-01 (1.23E-03)	4.21E-01 (1.35E-03)	4.21E-01 (1.37E-03)
50 Sta - RT-MAC	1.91E-02 (1.53E-04)	4.41E-02 (1.82E-04)	1.16E-01 (6.01E-04)	1.43E-01 (1.07E-03)	1.44E-01 (1.28E-03)
60 Sta - 802.11	1.23E-02 (1.13E-04)	6.05E-02 (1.95E-04)	4.44E-01 (1.19E-03)	4.48E-01 (1.27E-03)	4.48E-01 (1.28E-03)
60 Sta - RT-MAC	2.42E-02 (1.56E-04)	5.59E-02 (1.90E-04)	1.26E-01 (6.93E-04)	1.44E-01 (1.16E-03)	1.45E-01 (1.34E-03)
70 Sta - 802.11	1.60E-02 (1.19E-04)	1.61E-01 (5.88E-04)	4.69E-01 (1.25E-03)	4.71E-01 (1.25E-03)	4.73E-01 (1.25E-03)
70 Sta - RT-MAC	3.00E-02 (1.60E-04)	6.77E-02 (1.97E-04)	1.26E-01 (7.20E-04)	1.41E-01 (1.14E-03)	1.44E-01 (1.40E-03)
80 Sta - 802.11	2.09E-02 (1.27E-04)	4.03E-01 (9.54E-04)	4.90E-01 (1.21E-03)	4.94E-01 (1.20E-03)	4.94E-01 (1.20E-03)
80 Sta - RT-MAC	3.63E-02 (1.64E-04)	8.28E-02 (3.99E-04)	1.22E-01 (7.21E-04)	1.39E-01 (1.15E-03)	1.40E-01 (1.39E-03)

Table B.33: Voice Collision Ratio - Bursty Error Channel (10 Mbps) (Figure 6.61)

Stations - Protocol	Offered Data Load (G_{NRT})				
	0.0	0.2	0.4	0.6	0.8
10 Sta - 802.11	1.46E-03 (9.35E-05)	1.15E-02 (1.36E-04)	5.74E-02 (2.41E-04)	1.68E-01 (7.31E-04)	1.71E-01 (7.43E-04)
10 Sta - RT-MAC	2.58E-03 (1.25E-04)	1.24E-02 (1.45E-04)	3.21E-02 (1.72E-04)	9.14E-02 (2.40E-04)	9.59E-02 (2.46E-04)
20 Sta - 802.11	3.94E-03 (1.09E-04)	2.05E-02 (2.02E-04)	1.58E-01 (5.70E-04)	2.76E-01 (1.50E-03)	2.76E-01 (1.51E-03)
20 Sta - RT-MAC	6.37E-03 (1.39E-04)	2.04E-02 (1.78E-04)	5.17E-02 (2.43E-04)	1.22E-01 (3.59E-04)	1.23E-01 (3.90E-04)
30 Sta - 802.11	7.37E-03 (1.30E-04)	3.17E-02 (2.81E-04)	3.26E-01 (1.21E-03)	3.37E-01 (1.48E-03)	3.39E-01 (1.49E-03)
30 Sta - RT-MAC	1.01E-02 (1.76E-04)	2.81E-02 (2.82E-04)	6.93E-02 (3.22E-04)	1.34E-01 (5.73E-04)	1.35E-01 (5.92E-04)
40 Sta - 802.11	1.17E-02 (1.79E-04)	4.75E-02 (3.80E-04)	3.78E-01 (1.22E-03)	3.82E-01 (1.41E-03)	3.77E-01 (1.38E-03)
40 Sta - RT-MAC	1.49E-02 (2.32E-04)	3.63E-02 (3.30E-04)	9.17E-02 (4.63E-04)	1.39E-01 (1.08E-03)	1.39E-01 (1.00E-03)
50 Sta - 802.11	1.41E-02 (1.90E-04)	6.34E-02 (3.57E-04)	4.12E-01 (1.17E-03)	4.13E-01 (1.34E-03)	4.14E-01 (1.33E-03)
50 Sta - RT-MAC	1.93E-02 (2.55E-04)	4.55E-02 (3.70E-04)	1.16E-01 (6.14E-04)	1.43E-01 (1.06E-03)	1.45E-01 (1.33E-03)
60 Sta - 802.11	2.08E-02 (2.76E-04)	1.14E-01 (5.20E-04)	4.42E-01 (1.17E-03)	4.44E-01 (1.27E-03)	4.44E-01 (1.27E-03)
60 Sta - RT-MAC	2.50E-02 (3.80E-04)	5.58E-02 (5.29E-04)	1.26E-01 (6.61E-04)	1.44E-01 (1.12E-03)	1.46E-01 (1.38E-03)
70 Sta - 802.11	2.74E-02 (3.58E-04)	4.04E-01 (9.56E-04)	4.64E-01 (1.22E-03)	4.63E-01 (1.21E-03)	4.67E-01 (1.23E-03)
70 Sta - RT-MAC	3.06E-02 (3.99E-04)	6.82E-02 (6.11E-04)	1.25E-01 (7.19E-04)	1.42E-01 (1.12E-03)	1.45E-01 (1.36E-03)
80 Sta - 802.11	3.36E-02 (4.50E-04)	4.57E-01 (1.17E-03)	4.86E-01 (1.17E-03)	4.85E-01 (1.15E-03)	4.89E-01 (1.17E-03)
80 Sta - RT-MAC	3.67E-02 (3.38E-04)	8.43E-02 (5.51E-04)	1.21E-01 (7.20E-04)	1.38E-01 (1.17E-03)	1.41E-01 (1.34E-03)

B.4 Other Simulations

B.4.1 RT-MAC Enhancements Study

Table B.34: RT-MAC Enhancements Study Results (Figure 6.64)

Enabled Portion of RT-MAC Algorithm	Normalized Throughput (S)	Mean Delay (D)	Missed Deadline Ratio (F)	Collision Ratio (C)
None (802.11)	6.42E-01 (2.08E-02)	1.08E+01 (1.92E+00)	5.93E-01 (1.53E-03)	2.88E-01 (1.19E-03)
ECA only	6.95E-01 (1.28E-03)	4.10E-02 (1.08E-03)	7.91E-03 (2.07E-04)	9.56E-03 (2.26E-04)
EDF only	6.33E-01 (2.83E-02)	1.13E+01 (4.40E+00)	6.88E-01 (1.63E-03)	3.14E-01 (1.35E-03)
TC only	6.86E-01 (3.19E-03)	3.13E-02 (2.05E-03)	1.27E-02 (2.84E-04)	7.74E-02 (6.55E-04)
TC/ECA	6.92E-01 (4.97E-03)	3.84E-02 (1.23E-03)	6.90E-03 (1.82E-04)	9.10E-03 (2.08E-04)
TC/EDF	6.87E-01 (5.48E-3)	3.10E-02 (1.78E-03)	1.20E-02 (2.69E-04)	7.56E-02 (6.31E-04)
ECA/EDF	6.98E-01 (4.03E-03)	4.15E-02 (1.34E-03)	7.45E-03 (1.89E-04)	9.22E-03 (2.09E-04)
TC/ECA/EDF	6.94E-01 (4.23E-03)	3.88E-02 (1.52E-03)	6.23E-03 (1.73E-04)	9.13E-03 (@.08E-04)

B.4.2 Contention Window Expansion Study

B.4.2.1 1 Mbps Channel

Table B.35: Contention Window Study Results - Collision Ratio (1 Mbps) (Figure 6.69)

Enabled Portion of RT-MAC Algorithm	Stations	
	10	50
Transmit Next Backoff Value and CW Expansion	3.30E-02 (1.07E-03)	4.78E-02 (1.08E-03)
CW Expansion Only	8.93E-02 (1.60E-03)	11.82E-02 (1.17E-03)
IEEE 802.11	1.61E-01 (1.88E-03)	3.96E-01 (1.81E-03)

B.4.2.2 10 Mbps Channel

Table B.36: Contention Window Study Results - Collision Ratio (10 Mbps)

Enabled Portion of RT-MAC Algorithm	Stations	
	10	50
Transmit Next Backoff Value and CW Expansion	3.28E-02 (1.07E-03)	5.09E-02 (1.14E-03)
CW Expansion Only	8.85E-02 (1.59E-03)	1.21E-01 (1.79E-03)
IEEE 802.11	1.60E-01 (1.87E-03)	3.97E-01 (1.81E-03)

B.4.3 Service Disciplines

Table B.37: Service Disciplines Study Results (Figure 6.70)

Service Discipline	Normalized Throughput (S)	Mean Delay (D)	Missed Deadline Ratio (F)	Collision Ratio (C)
EDF	5.20E-01 (3.69E-03)	3.22E+01 (2.24E+00)	9.85E-01 (5.97E-04)	3.61E-01 (2.03E-03)
FCFS	5.19E-01 (5.07E-03)	3.17E+01 (2.75E+00)	9.84E-01 (6.33E-04)	3.61E-01 (2.03E-03)
Random	5.18E-01 (2.37E-03)	2.55E+01 (8.70E-01)	9.67E-01 (8.95E-04)	3.62E-01 (2.03E-03)
LCFS	5.18E-01 (5.77E-03)	3.17E+00 (2.70E-01)	6.90E-01 (2.31E-03)	3.62E-01 (2.03E-03)
SJF	5.03E-01 (4.48E-03)	6.59E+00 (3.15E-01)	7.71E-01 (2.25E-03)	3.59E-01 (2.06E-03)
LJF	5.57E-01 (4.86E-03)	2.65E+01 (2.39E+00)	8.90E-01 (1.31E-03)	3.63E-01 (1.95E-03)

B.4.4 RT-MAC/Non RT-MAC Networks

Table B.38: Mixed RT-MAC/IEEE 802.11 Network, $G = 0.9$ (Figure 6.71)

Network	Normalized Throughput (S)	Mean Delay (D)	Missed Deadline Ratio (F)	Collision Ratio (C)
RT-MAC	3.00E-01 (6.53E-04)	7.82E-03 (2.42E-05)	6.10E-01 (1.81E-03)	3.77E-02 (1.11E-03)
20/80%	2.99E-01 (2.46E-04)	8.48E-03 (6.61E-05)	6.29E-01 (1.66E-03)	6.67E-02 (1.34E-03)
40/60%	3.59E-01 (5.29E-03)	1.93E-02 (3.13E-03)	7.26E-01 (9.65E-04)	1.21E-01 (1.02E-03)
60/40%	3.18E-01 (1.38E-03)	6.70E+00 (9.14E-02)	9.95E-01 (2.57E-04)	1.90E-01 (1.94E-03)
80/20%	3.13E-01 (4.80E-04)	1.04E+01 (8.45E-02)	9.98E-01 (1.56E-04)	2.31E-01 (1.99E-03)
100%	3.08E-01 (1.28E-03)	7.11E+00 (4.46E-02)	1.00E+00 (0.00E+00)	2.56E-01 (1.99E-03)

Table B.39: Mixed RT-MAC/IEEE 802.11 Network, $G = 0.3$ (Figure 6.72)

Network	Normalized Throughput (S)	Mean Delay (D)	Missed Deadline Ratio (F)	Collision Ratio (C)
RT-MAC	2.85E-01 (7.37E-05)	1.74E-02 (7.65E-05)	3.08E-04 (6.23E-05)	3.32E-02 (6.26E-04)
20/80%	2.85E-01 (7.04E-05)	1.87E-02 (6.12E-05)	4.89E-04 (7.85E-05)	5.45E-02 (7.84E-04)
40/60%	2.85E-01 (1.16E-04)	1.88E-02 (8.28E-05)	5.45E-04 (8.29E-05)	8.08E-02 (9.28E-04)
60/40%	2.85E-01 (7.05E-05)	1.91E-02 (4.79E-05)	7.27E-04 (9.57E-05)	1.04E-01 (1.03E-03)
80/20%	2.85E-01 (8.24E-05)	1.94E-02 (9.29E-05)	1.14E-03 (1.20E-04)	1.32E-01 (1.12E-03)
100%	2.85E-01 (1.93E-05)	1.99E-02 (1.11E-04)	1.49E-03 (1.37E-04)	1.48E-01 (1.16E-03)

Table B.40: Mixed RT-MAC/IEEE 802.11 Network, Avionics Traffic Model (Figure 6.73)

Network	Normalized Throughput (S)	Mean Delay (D)	Missed Deadline Ratio (F)	Collision Ratio (C)
RT-MAC	8.08E-01 (9.54E-04)	1.24E-01 (3.13E-03)	1.10E-01 (1.09E-03)	2.58E-02 (5.76E-04)
20/80%	8.09E-01 (3.83E-03)	1.07E-01 (6.48E-03)	9.77E-02 (1.17E-03)	3.20E-02 (7.15E-04)
40/60%	8.06E-01 (2.18E-03)	9.32E-02 (2.04E-03)	1.01E-01 (1.14E-03)	4.02E-02 (7.69E-04)
60/40%	8.02E-01 (2.05E-03)	8.08E-02 (3.40E-03)	1.14E-01 (1.05E-03)	5.55E-02 (7.76E-04)
80/20%	7.02E-01 (9.73E-03)	5.99E+00 (1.50E+00)	8.28E-01 (1.19E-03)	2.20E-01 (1.30E-03)
100%	6.02E-01 (1.56E-03)	2.71E+01 (1.22E+00)	9.78E-01 (8.09E-04)	3.67E-01 (2.16E-03)

Table B.41: Mixed RT-MAC/IEEE 802.11 Network, Avionics Traffic Model, 5 Stations (Figure 6.74)

Network	Normalized Throughput (S)	Mean Delay (D)	Missed Deadline Ratio (F)	Collision Ratio (C)
RT-MAC	8.25E-01 (1.88E-03)	1.22E-01 (3.58E-03)	7.42E-02 (7.82E-04)	1.85E-02 (4.14E-04)
20/80%	8.21E-01 (4.23E-03)	1.16E-01 (5.05E-03)	8.02E-02 (8.86E-04)	2.21E-02 (4.94E-04)
40/60%	8.15E-01 (2.10E-03)	1.07E-01 (5.89E-03)	8.42E-02 (1.01E-03)	2.75E-02 (6.14E-04)
60/40%	8.05E-01 (2.40E-03)	1.04E-01 (5.80E-03)	9.75E-02 (1.24E-03)	3.63E-02 (8.05E-04)
80/20%	7.95E-01 (4.68E-03)	2.86E-01 (2.12E-01)	3.20E-01 (1.82E-03)	5.86E-02 (9.36E-04)
100%	7.55E-01 (8.15E-03)	5.92E+00 (1.61E+00)	9.79E-01 (9.55E-04)	7.90E-02 (1.73E-03)

B.4.5 Static BER

Table B.42: Static BER, BERs (Figure 6.75)

Offered Data Load (G_{NRT})	IEEE 802.11 (1×10^{-5})	RT-MAC (1×10^{-5})	IEEE 802.11 Bursty	RT-MAC Bursty	IEEE 802.11 (1×10^{-3})	RT-MAC (1×10^{-3})
0	1.68E-05	1.62E-05	3.61E-02	3.05E-02	1.66E-03	1.68E-03
0.2	1.38E-05	1.40E-05	2.86E-02	1.84E-02	1.65E-03	1.42E-03
0.4	1.34E-05	1.30E-05	2.44E-02	1.93E-02	1.65E-03	1.28E-03
0.6	1.36E-05	1.24E-05	2.15E-02	1.68E-02	1.65E-03	1.20E-03
0.8	1.36E-05	1.16E-05	2.29E-02	1.67E-02	1.65E-03	1.19E-03

Table B.43: Static BER, Packet Error Rate (Figure 6.76)

Offered Data Load (G_{NRT})	IEEE 802.11 (1×10^{-5})	RT-MAC (1×10^{-5})	IEEE 802.11 Bursty	RT-MAC Bursty	IEEE 802.11 (1×10^{-3})	RT-MAC (1×10^{-3})
0	1.05E-02	1.02E-02	2.68E-02	2.25E-02	6.30E-01	6.51E-01
0.2	1.38E-02	1.45E-02	1.91E-02	1.74E-02	6.30E-01	6.97E-01
0.4	1.26E-02	1.80E-02	1.81E-02	1.81E-02	6.31E-01	7.52E-01
0.6	1.26E-02	2.54E-02	1.59E-02	1.73E-02	6.30E-01	8.23E-01
0.8	1.26E-02	2.68E-02	1.69E-02	1.77E-02	6.30E-01	8.37E-01

Table B.44: Static BER, Throughput (Figure 6.77)

Offered Data Load (G_{NRT})	IEEE 802.11 (1×10^{-5})	RT-MAC (1×10^{-5})	IEEE 802.11 Bursty	RT-MAC Bursty	IEEE 802.11 (1×10^{-3})	RT-MAC (1×10^{-3})
0	1.88E-01 (8.88E-03)	1.89E-01 (5.03E-03)	1.91E-01 (7.41E-03)	1.82E-01 (5.07E-03)	1.31E-01 (8.95E-04)	9.44E-02 (2.25E-03)
0.2	3.86E-01 (2.14E-02)	3.77E-01 (6.95E-03)	3.87E-01 (1.21E-02)	3.77E-01 (3.99E-03)	1.31E-01 (9.96E-04)	7.87E-02 (1.08E-03)
0.4	4.44E-01 (5.14E-03)	5.26E-01 (6.11E-03)	4.44E-01 (6.23E-03)	5.34E-01 (1.24E-02)	1.31E-01 (1.55E-03)	6.09E-02 (1.90E-03)
0.6	4.40E-01 (5.98E-03)	6.15E-01 (1.14E-02)	4.41E-01 (8.02E-03)	6.28E-01 (5.50E-03)	1.31E-01 (9.32E-04)	4.08E-02 (5.18E-04)
0.8	4.43E-01 (5.30E-03)	6.27E-01 (7.15E-03)	4.46E-01 (3.97E-03)	6.35E-01 (1.26E-02)	1.31E-01 (6.95E-04)	3.75E-02 (1.60E-03)

Table B.45: Static BER, Mean Delay (Figure 6.78)

Offered Data Load (G_{NRT})	IEEE 802.11 (1×10^{-5})	RT-MAC (1×10^{-5})	IEEE 802.11 Bursty	RT-MAC Bursty	IEEE 802.11 (1×10^{-3})	RT-MAC (1×10^{-3})
0	2.17E-02 (2.69E-04)	2.35E-02 (5.47E-05)	2.56E-02 (2.32E-03)	2.42E-02 (4.90E-04)	3.27E+01 (7.31E-01)	9.66E-02 (3.62E-04)
0.2	4.67E-02 (2.13E-02)	3.29E-02 (2.70E-03)	6.54E-02 (1.11E-02)	3.43E-02 (2.13E-03)	3.35E+01 (4.17E-01)	1.06E-01 (2.27E-03)
0.4	1.14E+01 (8.50E-01)	2.19E-01 (1.42E-02)	1.14E+01 (4.98E-01)	2.32E-01 (5.44E-02)	3.36E+01 (5.93E-01)	1.33E-01 (2.04E-03)
0.6	1.46E+01 (6.24E-01)	1.75E+00 (4.03E-01)	1.45E+01 (5.76E-01)	1.71E+00 (4.33E-01)	3.36E+01 (8.43E-01)	5.36E-01 (2.35E-01)
0.8	1.55E+01 (5.11E-01)	8.45E+00 (1.20E+00)	1.55E+01 (6.17E-01)	8.48E+00 (1.17E+00)	3.36E+01 (1.48E+00)	3.39E+00 (1.30E-01)

Table B.46: Static BER, Missed Deadline Ratio (Figure 6.79)

Offered Data Load (G_{NRT})	IEEE 802.11 (1×10^{-5})	RT-MAC (1×10^{-5})	IEEE 802.11 Bursty	RT-MAC Bursty	IEEE 802.11 (1×10^{-3})	RT-MAC (1×10^{-3})
0	1.63E-04 (2.73E-05)	1.18E-05 (7.31E-06)	1.43E-02 (2.83E-04)	1.25E-02 (2.40E-04)	1.00E+00 (4.49E-05)	5.59E-01 (9.96E-04)
0.2	6.53E-02 (5.60E-04)	2.49E-03 (1.06E-04)	1.01E-01 (6.47E-04)	1.51E-02 (3.20E-04)	1.00E+00 (4.90E-06)	6.44E-01 (9.75E-04)
0.4	9.32E-01 (5.89E-04)	1.39E-01 (7.43E-04)	9.31E-01 (6.04E-04)	1.60E-01 (7.83E-04)	1.00E+00 (1.28E-05)	7.52E-01 (8.86E-04)
0.6	9.42E-01 (5.78E-04)	5.98E-01 (1.22E-03)	9.43E-01 (5.72E-04)	5.92E-01 (1.08E-03)	1.00E+00 (9.74E-06)	8.67E-01 (7.14E-04)
0.8	9.44E-01 (5.89E-04)	7.19E-01 (1.73E-03)	9.42E-01 (6.14E-04)	7.16E-01 (1.80E-03)	1.00E+00 (2.80E-06)	8.89E-01 (6.61E-04)

Table B.47: Static BER, Collision Ratio (Figure 6.80)

Offered Data Load (G_{NRT})	IEEE 802.11 (1×10^{-5})	RT-MAC (1×10^{-5})	IEEE 802.11 Bursty	RT-MAC Bursty	IEEE 802.11 (1×10^{-3})	RT-MAC (1×10^{-3})
0	7.86E-03 (1.87E-04)	6.14E-03 (1.65E-04)	1.08E-02 (2.42E-04)	5.89E-03 (1.64E-04)	3.28E-02 (2.75E-04)	8.61E-03 (1.63E-04)
0.2	6.39E-02 (4.84E-04)	1.55E-02 (2.36E-04)	6.68E-02 (4.65E-04)	1.54E-02 (2.92E-04)	3.30E-02 (2.75E-04)	1.20E-02 (1.99E-04)
0.4	2.13E-01 (7.48E-04)	2.66E-02 (3.02E-04)	2.13E-01 (7.58E-04)	2.69E-02 (3.04E-04)	3.25E-02 (2.73E-04)	1.72E-02 (2.52E-04)
0.6	2.16E-01 (7.97E-04)	3.40E-02 (4.46E-04)	2.15E-01 (7.92E-04)	3.35E-02 (3.90E-04)	3.27E-02 (2.75E-04)	2.80E-02 (3.48E-04)
0.8	2.15E-01 (8.20E-04)	3.66E-02 (7.37E-04)	2.15E-01 (8.31E-04)	3.73E-02 (7.66E-04)	3.25E-02 (2.74E-04)	3.07E-02 (3.69E-04)

Appendix C

Statistical Comparison Method and Regression Tables

This appendix contains a discussion of the statistical method used to compare the performance of IEEE 802.11 and RT-MAC. It also contains the output tables from SAS [SAS] obtained while developing the regression models.

C.1 Statistical Comparison for Unpaired Observations

The following explanation and Figure C.1 are due to [Jai91]. In order to determine the relative performance of two systems during this research, two methods are used. The first is a visual test of the means and confidence intervals (CIs) of two unpaired samples. From this test one can conclude either, (a) one system performs better than the other, (b) the systems performance is not different, or (c) the relative performance of the systems is indeterminate. These visual tests are shown graphically in Figure C.1. If the comparison shows that the CIs overlap but either mean is not contained in the CI of the other (case (c)), then the *t*-test must be performed to make the comparison. The *t*-test is the commonly used method to

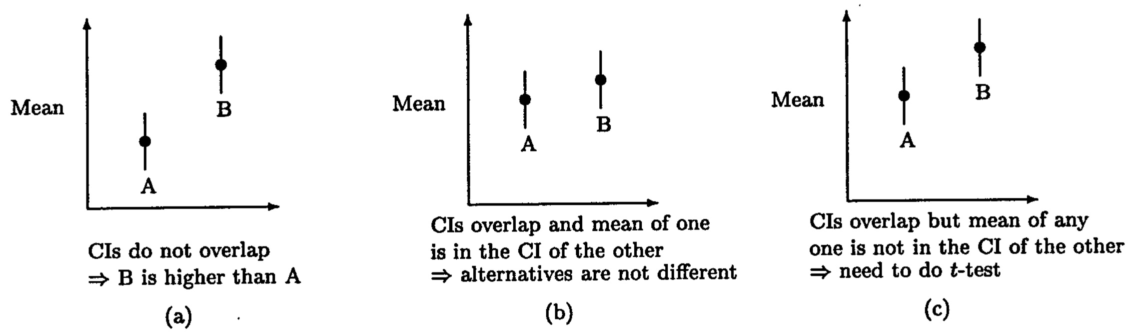

Figure C.1: Visual Performance Comparison Tests

compare the means of two different samples [All90]. Details on the mechanics of the *t*-test can be found in almost any statistics book.

Conclusions that are made regarding system performance, unless explicitly noted, are based on the preceding statistical comparison method.

C.2 Glossary of SAS Output Table Terms

A glossary of abbreviations used in the following figures is provided in Table C.1. The explanation of statistical terms that follow are from [SAS85] and [Jai91]. It may be helpful to refer to Figure C.2 during the following paragraphs.

The *DF*, degrees of freedom, statistic is the number of independent observations in the sample. The *Sum of Squares* is the sum of i samples minus the sample mean squared or $\sum_{i=1}^{n}(y_i - \overline{y})^2$, where n is the degrees of freedom. The *Mean Square* is the Sum of Squares divided by DF. The F Value is the ratio produced by dividing the Mean Square of the Model by the Mean Square of the Error. It is a measure of how well the model accounts

Table C.1: Abbreviations used in Appendix C

Abbreviation	Meaning
C.V.	Coefficient of variation
DF	Degrees of freedom
F	F value
MSE	Mean square error
PR	Significance probability
SS	Sum of Squares
S[1,2,3]	Number of stations (i.e., N^1, N^2, N^3)
L[1,2,3]	Offered Load (i.e., G^1, G^2, G^3)
C1	Channel Model: Ideal ($C1 = 0$) or Bursty ($C1 = 1$)
X*Y	Interaction of factor X and Y

for the dependent variables behavior. An F Value much greater than 1 indicates the model is assumed to explain a significant fraction of the variance. Conversely, an F Value of less than 1 indicates that the experimental error contributes more to the variance than does the model. A small significance probability, $PR > F$, indicates that some linear combination of the model parameters are significantly different from zero. The $PR > |T|$ term is the probability of getting a larger value of t if the parameter is actually zero. A small value for this probability means that the independent variable contributes significantly to the model.

The *R-Square* or R^2 term measures how much variation of the samples is accounted for by the model. R^2, which varies from 0 to 1, is the ratio of the model *Sum of Squares* divided by the Corrected Total *Sum of Squares.* The larger the R^2 value, the better the fit of the regression model. *C.V.* is the coefficient of variation. It is the sample standard deviation divided by the sample mean. It measures the amount of variation of the sample population with respect to the mean. *Root MSE* is the square root of the *Mean Square* of the Error. *Mean* is the mean of the dependent variable.

Type III SS is the sum of squares that results when the variable (i.e., L1, L2, etc.) is added last to the model.

C.3 SAS Output Tables

C.3.1 Telemetry Regression Model

```
                            The SAS System                                  2
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                      General Linear Models Procedure

Dependent Variable: XPUT_STD

                                      Sum of            Mean
Source                  DF           Squares          Square   F Value     Pr > F

Model                    4        0.07067380      0.01766845    691.62     0.0001
Error                  235        0.00600338      0.00002555
Corrected Total        239        0.07667718

                  R-Square              C.V.        Root MSE           XPUT_STD Mean
                  0.921706          1.694505        0.005054                0.298278

Source                  DF       Type III SS     Mean Square   F Value     Pr > F

L1                       1        0.01434199      0.01434199    561.41     0.0001
L2                       1        0.00797098      0.00797098    312.02     0.0001
L2*S1                    1        0.01385279      0.01385279    542.26     0.0001
S1*L3                    1        0.00704789      0.00704789    275.89     0.0001

                                          T for H0:    Pr > |T|    Std Error of
Parameter                   Estimate    Parameter=0                  Estimate

INTERCEPT               0.2222851045          73.48      0.0001      0.00302500
L1                      0.3047182332          23.69      0.0001      0.01286050
L2                      -.2035693374         -17.66      0.0001      0.01152446
L2*S1                   -.0061562848         -23.29      0.0001      0.00026437
S1*L3                   0.0052916762          16.61      0.0001      0.00031859
```

Figure C.2: IEEE 802.11 Telemetry Throughput Regression GLM Results

```
                            The SAS System                                  8
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                      General Linear Models Procedure
Dependent Variable: XPUT_ENH
                                      Sum of            Mean
Source                  DF           Squares          Square   F Value     Pr > F

Model                    6        0.08023846      0.01337308    392.72     0.0001
Error                  233        0.00793423      0.00003405
Corrected Total        239        0.08817268

                  R-Square              C.V.        Root MSE           XPUT_ENH Mean
                  0.910015          1.897859        0.005835                0.307475

Source                  DF       Type III SS     Mean Square   F Value     Pr > F
L1                       1        0.02175863      0.02175863    638.97     0.0001
L2                       1        0.01688540      0.01688540    495.86     0.0001
L3                       1        0.01343084      0.01343084    394.42     0.0001
L1*S1                    1        0.00121620      0.00121620     35.72     0.0001
L1*S2                    1        0.00227585      0.00227585     66.83     0.0001
L1*S3                    1        0.00246907      0.00246907     72.51     0.0001

                                          T for H0:    Pr > |T|    Std Error of
Parameter                   Estimate    Parameter=0                  Estimate
INTERCEPT               -0.040556542          -3.35      0.0009      0.01211420
L1                       1.795760590          25.28      0.0001      0.07104067
L2                      -2.821170833         -22.27      0.0001      0.12669167
L3                       1.393958333          19.86      0.0001      0.07018956
L1*S1                   -0.003091120          -5.98      0.0001      0.00051723
L1*S2                    0.000178233           8.18      0.0001      0.00002180
L1*S3                   -0.000002215          -8.52      0.0001      0.00000026
```

Figure C.3: RT-MAC Telemetry Throughput Regression GLM Results

```
                              The SAS System                                13
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                       General Linear Models Procedure

Dependent Variable: TD_STD
                                    Sum of             Mean
Source                  DF         Squares           Square   F Value      Pr > F

Model                    7      3.34750704       0.47821529   6627.49      0.0001

Error                  232      0.01674026       0.00007216

Corrected Total        239      3.36424730

                  R-Square            C.V.         Root MSE              TD_STD Mean

                  0.995024        0.822422         0.008494                 1.032862

Source                  DF     Type III SS      Mean Square   F Value      Pr > F

L1                       1      0.31712396       0.31712396   4394.96      0.0001
L2                       1      0.21977839       0.21977839   3045.87      0.0001
L3                       1      0.16391160       0.16391160   2271.62      0.0001
L2*S1                    1      0.02029706       0.02029706    281.29      0.0001
L1*S1                    1      0.03309829       0.03309829    458.70      0.0001
L1*S2                    1      0.00695957       0.00695957     96.45      0.0001
L1*S3                    1      0.00396429       0.00396429     54.94      0.0001

                                          T for H0:    Pr > |T|    Std Error of
Parameter                  Estimate      Parameter=0                 Estimate

INTERCEPT               -0.49896029           -28.29      0.0001     0.01763426
L1                       6.86623055            66.29      0.0001     0.10357166
L2                     -10.18697581           -55.19      0.0001     0.18458222
L3                       4.86970867            47.66      0.0001     0.10217278
L2*S1                   -0.00500497           -16.77      0.0001     0.00029842
L1*S1                    0.01681630            21.42      0.0001     0.00078517
L1*S2                   -0.00031168            -9.82      0.0001     0.00003174
L1*S3                    0.00000281             7.41      0.0001     0.00000038
```

Figure C.4: IEEE 802.11 Telemetry Mean Delay Regression GLM Results

```
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                       General Linear Models Procedure

Dependent Variable: D_ENH
                                    Sum of             Mean
Source                  DF         Squares           Square   F Value      Pr > F

Model                    2      0.02888294       0.01444147  32185.40      0.0001

Error                  237      0.00010634       0.00000045

Corrected Total        239      0.02898928

                R-Square            C.V.         Root MSE               D_ENH Mean

                0.996332        4.256099         0.000670                 0.015739

Source                  DF     Type III SS      Mean Square   F Value      Pr > F

S1                       1      0.02381699       0.02381699  53080.43      0.0001
S1*L1                    1      0.00715697       0.00715697  15950.58      0.0001

                                          T for H0:    Pr > |T|    Std Error of
Parameter                  Estimate      Parameter=0                 Estimate

INTERCEPT              0.0003002479             3.64      0.0003     0.00008241
S1                     0.0010804862           230.39      0.0001     0.00000469
S1*L1                  -.0008047914          -126.30      0.0001     0.00000637
```

Figure C.5: RT-MAC Telemetry Mean Delay Regression GLM Results

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General Linear Models Procedure

Dependent Variable: F_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	82.81440773	16.56288155	4045.92	0.0001
Error	234	0.95793137	0.00409372		
Corrected Total	239	83.77233910			

R-Square	C.V.	Root MSE	F_STD Mean
0.988565	5.211435	0.063982	1.227727

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	10.63817242	10.63817242	2598.65	0.0001
L2	1	7.15039688	7.15039688	1746.67	0.0001
L3	1	5.25554063	5.25554063	1283.80	0.0001
S1	1	0.05830770	0.05830770	14.24	0.0002
S3	1	0.09427090	0.09427090	23.03	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-7.18626201	-53.95	0.0001	0.13319989
L1	39.67010098	50.98	0.0001	0.77819612
L2	-58.05488232	-41.79	0.0001	1.38909819
L3	27.57444844	35.83	0.0001	0.76958644
S1	-0.00262456	-3.77	0.0002	0.00069543
S3	0.00000118	4.80	0.0001	0.00000025

Figure C.6: IEEE 802.11 Telemetry Missed Deadline Ratio Regression GLM Results

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General Linear Models Procedure

Dependent Variable: F_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	12.83292638	6.41646319	23473.07	0.0001
Error	237	0.06478495	0.00027335		
Corrected Total	239	12.89771133			

R-Square	C.V.	Root MSE	F_ENH Mean
0.994977	4.810867	0.016533	0.343668

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	1.03586946	1.03586946	3789.48	0.0001
L2	1	0.25023662	0.25023662	915.43	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-0.520974744	-59.08	0.0001	0.00881756
L1	1.992694893	61.56	0.0001	0.03237063
L2	-0.807253280	-30.26	0.0001	0.02668070

Figure C.7: RT-MAC Telemetry Missed Deadline Ratio Regression GLM Results

```
                                  The SAS System                             31
                                              13:10 Monday, January 18, 1999

                          General Linear Models Procedure

Dependent Variable: C_STD
                                        Sum of            Mean
Source                  DF             Squares          Square   F Value     Pr > F

Model                    4          3.34141999      0.83535500   2648.97     0.0001

Error                  235          0.07410748      0.00031535

Corrected Total        239          3.41552747

                  R-Square                C.V.        Root MSE            C_STD Mean

                  0.978303            7.249707        0.017758              0.244950


Source                  DF         Type III SS     Mean Square   F Value     Pr > F

S1                       1          0.48863668      0.48863668   1549.50     0.0001
S2                       1          0.09857324      0.09857324    312.58     0.0001
L1                       1          0.10272891      0.10272891    325.76     0.0001
L2                       1          0.07331947      0.07331947    232.50     0.0001

                                          T for H0:    Pr > |T|   Std Error of
Parameter                  Estimate     Parameter=0                 Estimate

INTERCEPT              -.1837051097          -18.31      0.0001     0.01003573
S1                     0.0125729336           39.36      0.0001     0.00031940
S2                     -.0001015490          -17.68      0.0001     0.00000574
L1                     0.6275302119           18.05      0.0001     0.03476845
L2                     -.4369623820          -15.25      0.0001     0.02865705
```

Figure C.8: IEEE 802.11 Telemetry Collision Ratio Regression GLM Results

```
                                  The SAS System                             36
                                              13:10 Monday, January 18, 1999

                          General Linear Models Procedure

Dependent Variable: C_ENH
                                        Sum of            Mean
Source                  DF             Squares          Square   F Value     Pr > F

Model                    3          0.01353711      0.00451237    751.66     0.0001

Error                  236          0.00141676      0.00000600

Corrected Total        239          0.01495386

                  R-Square                C.V.        Root MSE            C_ENH Mean

                  0.905258            7.174704        0.002450              0.034150


Source                  DF         Type III SS     Mean Square   F Value     Pr > F

S1                       1          0.00175609      0.00175609    292.53     0.0001
S2                       1          0.00068420      0.00068420    113.97     0.0001
S3                       1          0.00036410      0.00036410     60.65     0.0001

                                          T for H0:    Pr > |T|   Std Error of
Parameter                  Estimate     Parameter=0                 Estimate

INTERCEPT              0.0098980589           11.82      0.0001     0.00083739
S1                     0.0023783638           17.10      0.0001     0.00013906
S2                     -.0000625751          -10.68      0.0001     0.00000586
S3                     0.0000005445            7.79      0.0001     0.00000007
```

Figure C.9: RT-MAC Telemetry Collision Ratio Regression GLM Results

C.3.2 Avionics Traffic Model

The SAS System 2
14:12 Monday, January 18, 1999

General Linear Models Procedure

Dependent Variable: XPUT_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	5.46584182	1.82194727	10187.92	0.0001
Error	236	0.04220483	0.00017883		
Corrected Total	239	5.50804665			

R-Square	C.V.	Root MSE	XPUT_STD Mean
0.992338	2.537001	0.013373	0.527114

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L2	1	1.90738080	1.90738080	10665.65	0.0001
L3	1	1.14264581	1.14264581	6389.42	0.0001
L3*S1	1	0.26036808	0.26036808	1455.92	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.116252470	38.88	0.0001	0.00299040
L2	2.658142719	103.27	0.0001	0.02573858
L3	-2.087847466	-79.93	0.0001	0.02611969
L3*S1	-0.005072211	-38.16	0.0001	0.00013293

Figure C.10: IEEE 802.11 Avionics Throughput Regression GLM Results

The SAS System 7
14:12 Monday, January 18, 1999

General Linear Models Procedure

Dependent Variable: XPUT_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	8.98056601	4.49028300	99999.99	0.0001
Error	237	0.00747447	0.00003154		
Corrected Total	239	8.98804048			

R-Square	C.V.	Root MSE	XPUT_ENH Mean
0.999168	0.980445	0.005616	0.572786

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L2	1	1.26537154	1.26537154	40122.32	0.0001
L3	1	0.59734852	0.59734852	18940.69	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.143037012	113.90	0.0001	0.00125580
L2	2.165053458	200.31	0.0001	0.01080875
L3	-1.496478667	-137.63	0.0001	0.01087358

Figure C.11: RT-MAC Avionics Throughput Regression GLM Results

The SAS System 13
14:12 Monday, January 18, 1999
General Linear Models Procedure

Dependent Variable: TD_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	6.09878834	0.87125548	1233.44	0.0001
Error	232	0.16387553	0.00070636		
Corrected Total	239	6.26266387			

R-Square	C.V.	Root MSE	TD_STD Mean
0.973833	2.835675	0.026577	0.937253

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	0.05622925	0.05622925	79.60	0.0001
L2	1	0.07305131	0.07305131	103.42	0.0001
L3	1	0.09840993	0.09840993	139.32	0.0001
L1*S1	1	0.26487609	0.26487609	374.99	0.0001
L2*S1	1	0.31344992	0.31344992	443.75	0.0001
L3*S1	1	0.34496900	0.34496900	488.38	0.0001
S1	1	0.22056143	0.22056143	312.25	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-0.04261292	-0.41	0.6857	0.10516196
L1	5.49713332	8.92	0.0001	0.61612408
L2	-11.18440792	-10.17	0.0001	1.09979582
L3	7.19188822	11.80	0.0001	0.60930750
L1*S1	-0.39317508	-19.36	0.0001	0.02030382
L2*S1	0.76347104	21.07	0.0001	0.03624278
L3*S1	-0.44373428	-22.10	0.0001	0.02007918
S1	0.06123784	17.67	0.0001	0.00346552

Figure C.12: IEEE 802.11 Avionics Mean Delay Regression GLM Results

The SAS System 18
14:12 Monday, January 18, 1999
General Linear Models Procedure

Dependent Variable: D_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.50636755	0.12659189	6577.79	0.0001
Error	235	0.00452266	0.00001925		
Corrected Total	239	0.51089021			

R-Square	C.V.	Root MSE	D_ENH Mean
0.991147	9.048490	0.004387	0.048483

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	0.00409056	0.00409056	212.55	0.0001
L2	1	0.00612351	0.00612351	318.18	0.0001
L3	1	0.01061700	0.01061700	551.67	0.0001
C1	1	0.00119283	0.00119283	61.98	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-0.103170719	-11.32	0.0001	0.00911157
L1	0.777895521	14.58	0.0001	0.05335717
L2	-1.698923958	-17.84	0.0001	0.09524378
L3	1.239364583	23.49	0.0001	0.05276684
C1	0.004458750	7.87	0.0001	0.00056635

Figure C.13: RT-MAC Avionics Mean Delay Regression GLM Results

The SAS System 28
11:27 Tuesday, April 6, 1999

General Linear Models Procedure

Dependent Variable: F_STDA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.07929267	0.02643089	657.82	0.0001
Error	115	0.00462065	0.00004018		
Corrected Total	118	0.08391333			

R-Square	C.V.	Root MSE	F_STDA Mean
0.944935	16.38438	0.006339	0.038688

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L3	1	0.00263943	0.00263943	65.69	0.0001
L1*C1	1	0.02307750	0.02307750	574.36	0.0001
C1*S1	1	0.00090321	0.00090321	22.48	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.0079268455	6.81	0.0001	0.00116391
L3	0.1025261160	8.10	0.0001	0.01264977
L1*C1	0.0996714804	23.97	0.0001	0.00415891
C1*S1	0.0002369303	4.74	0.0001	0.00004997

Figure C.14: IEEE 802.11 Avionics Missed Deadline Ratio Regression GLM Results, $G \leq 0.5$

The SAS System 24
11:27 Tuesday, April 6, 1999
General Linear Models Procedure

Dependent Variable: F_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	67.92939587	13.58587917	1282.42	0.0001
Error	174	1.84335154	0.01059397		
Corrected Total	179	69.77274741			

R-Square	C.V.	Root MSE	F_STD Mean
0.973581	14.83460	0.102927	0.693831

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	3.93765417	3.93765417	371.69	0.0001
L3	1	7.02230889	7.02230889	662.86	0.0001
L1*S1	1	4.85654594	4.85654594	458.43	0.0001
S1*L2	1	5.70639346	5.70639346	538.65	0.0001
L3*S1	1	6.09965023	6.09965023	575.77	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	4.29963097	17.11	0.0001	0.25136064
L1	-10.88781318	-19.28	0.0001	0.56474362
L3	9.50727404	25.75	0.0001	0.36927126
L1*S1	-0.41139045	-21.41	0.0001	0.01921409
S1*L2	1.28164250	23.21	0.0001	0.05522243
L3*S1	-0.91630267	-24.00	0.0001	0.03818704

Figure C.15: IEEE 802.11 Avionics Missed Deadline Ratio Regression GLM Results, $G > 0.5$

```
                              The SAS System                          28
                                          14:12 Monday, January 18, 1999
                      General Linear Models Procedure

Dependent Variable: F_ENH
                                      Sum of            Mean
Source                    DF         Squares          Square   F Value     Pr > F

Model                      4      0.50714420      0.12678605   2432.43     0.0001

Error                    235      0.01224894      0.00005212

Corrected Total          239      0.51939314

                  R-Square            C.V.        Root MSE            F_ENH Mean
                  0.976417        23.14554        0.007220              0.031192

Source                    DF     Type III SS     Mean Square   F Value     Pr > F
L1                         1      0.01030621      0.01030621    197.73     0.0001
L2                         1      0.01507812      0.01507812    289.28     0.0001
L3                         1      0.02264596      0.02264596    434.47     0.0001
L2*S1                      1      0.01091612      0.01091612    209.43     0.0001

                                          T for H0:    Pr > |T|   Std Error of
Parameter               Estimate         Parameter=0                Estimate
INTERCEPT           -0.179583347              -11.98     0.0001     0.01498772
L1                   1.234750942               14.06     0.0001     0.08781022
L2                  -2.666048947              -17.01     0.0001     0.15675084
L3                   1.810062124               20.84     0.0001     0.08683872
L2*S1                0.000861638               14.47     0.0001     0.00005954
```

Figure C.16: RT-MAC Avionics Missed Deadline Ratio Regression GLM Results

```
                              The SAS System                          34
                                          14:12 Monday, January 18, 1999

                      General Linear Models Procedure

Dependent Variable: C_STD
                                      Sum of            Mean
Source                    DF         Squares          Square   F Value     Pr > F

Model                      5     11.90639479      2.38127896   1673.58     0.0001

Error                    234      0.33294970      0.00142286

Corrected Total          239     12.23934448

                  R-Square            C.V.        Root MSE             C_STD Mean

                  0.972797        13.44101        0.037721              0.280640

Source                    DF     Type III SS     Mean Square   F Value     Pr > F

S1                         1      0.60865329      0.60865329    427.77     0.0001
L3                         1      0.61345198      0.61345198    431.14     0.0001
S1*L1                      1      0.72252145      0.72252145    507.79     0.0001
S1*L2                      1      0.85484724      0.85484724    600.79     0.0001
S1*L3                      1      0.89791979      0.89791979    631.07     0.0001

                                          T for H0:    Pr > |T|   Std Error of
Parameter               Estimate         Parameter=0                Estimate

INTERCEPT           0.0335898764                4.79     0.0001     0.00701916
S1                  0.0535273221               20.68     0.0001     0.00258805
L3                  0.3573288897               20.76     0.0001     0.01720914
S1*L1               -.3406941287              -22.53     0.0001     0.01511892
S1*L2               0.6614962939               24.51     0.0001     0.02698762
S1*L3               -.3757964579              -25.12     0.0001     0.01495944
```

Figure C.17: IEEE 802.11 Avionics Collision Ratio Regression GLM Results

The SAS System 39
14:12 Monday, January 18, 1999

General Linear Models Procedure

Dependent Variable: C_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.02025802	0.00506451	2167.27	0.0001
Error	235	0.00054915	0.00000234		
Corrected Total	239	0.02080717			

R-Square	C.V.	Root MSE	C_ENH Mean
0.973608	15.60663	0.001529	0.009795

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S1	1	0.00019736	0.00019736	84.46	0.0001
S3	1	0.00017813	0.00017813	76.23	0.0001
L2	1	0.00018609	0.00018609	79.63	0.0001
L3	1	0.00095879	0.00095879	410.30	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.0002013095	0.48	0.6296	0.00041689
S1	0.0001526956	9.19	0.0001	0.00001662
S3	-.0000000515	-8.73	0.0001	0.00000001
L2	-.0262552785	-8.92	0.0001	0.00294220
L3	0.0599539347	20.26	0.0001	0.00295984

Figure C.18: RT-MAC Avionics Collision Ratio Regression GLM Results

C.3.3 Voice with Non Real-time Traffic Model

C.3.3.1 1 Mbps Data Rate

```
                              The SAS System                                2
                                                14:12 Monday, January 18, 1999
                         General Linear Models Procedure
Dependent Variable: XPUT_STD
Source                  DF        Squares          Square   F Value     Pr > F
Model                    6     4.65610463      0.77601744   1308.01     0.0001
Error                  293     0.17383147      0.00059328
Corrected Total        299     4.82993610

                  R-Square           C.V.        Root MSE         XPUT_STD Mean
                  0.964010       6.748327        0.024357              0.360939

Source                  DF    Type III SS     Mean Square   F Value     Pr > F

L1                       1     2.12745519      2.12745519   3585.91     0.0001
L2                       1     0.63673989      0.63673989   1073.25     0.0001
S1                       1     0.41281503      0.41281503    695.82     0.0001
S2                       1     0.19918847      0.19918847    335.74     0.0001
L1*S1                    1     1.23776799      1.23776799   2086.31     0.0001
L2*S3                    1     0.34124747      0.34124747    575.19     0.0001

                                      T for H0:    Pr > |T|   Std Error of
Parameter                 Estimate   Parameter=0                Estimate

INTERCEPT             -0.069123778        -7.68      0.0001     0.00900171
L1                     1.647478201        59.88      0.0001     0.02751185
L2                    -0.794481197       -32.76      0.0001     0.02425119
S1                     0.026937741        26.38      0.0001     0.00102121
S2                    -0.000489423       -18.32      0.0001     0.00002671
L1*S1                 -0.056975199       -45.68      0.0001     0.00124737
L2*S3                  0.000033114        23.98      0.0001     0.00000138
```

Figure C.19: IEEE 802.11 Voice Throughput (1 Mbps) Regression GLM Results

```
                              The SAS System                                8
                                                14:12 Monday, January 18, 1999
                         General Linear Models Procedure
Dependent Variable: XPUT_ENH
Source                  DF        Squares          Square   F Value     Pr > F
Model                    3     8.85440919      2.95146973   2529.66     0.0001
Error                  296     0.34535710      0.00116675
Corrected Total        299     9.19976630

                  R-Square           C.V.        Root MSE         XPUT_ENH Mean
                  0.962460       7.187126        0.034158              0.475262

Source                  DF    Type III SS     Mean Square   F Value     Pr > F

L1                       1     5.24658823      5.24658823   4496.77     0.0001
S1                       1     0.85066977      0.85066977    729.10     0.0001
S1*L3                    1     0.60933704      0.60933704    522.25     0.0001

                                      T for H0:    Pr > |T|   Std Error of
Parameter                 Estimate   Parameter=0                Estimate

INTERCEPT             0.0918203748        14.34      0.0001     0.00640228
L1                    0.7907049484        67.06      0.0001     0.01179137
S1                    0.0072707945        27.00      0.0001     0.00026927
S1*L3                 -.0207514195       -22.85      0.0001     0.00090804
```

Figure C.20: RT-MAC Voice Throughput (1 Mbps) Regression GLM Results

The SAS System 13
14:12 Monday, January 18, 1999

General Linear Models Procedure

Dependent Variable: TD_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	4.15283078	0.59326154	402.67	0.0001
Error	292	0.43020747	0.00147331		
Corrected Total	299	4.58303825			

R-Square	C.V.	Root MSE	TD_STD Mean
0.906131	3.751390	0.038384	1.023188

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S3	1	0.62439980	0.62439980	423.81	0.0001
L1	1	0.10573315	0.10573315	71.77	0.0001
L2	1	0.19737502	0.19737502	133.97	0.0001
L1*S1	1	0.61183500	0.61183500	415.28	0.0001
L2*S1	1	0.36762827	0.36762827	249.52	0.0001
L1*S2	1	0.60537168	0.60537168	410.89	0.0001
S3*L3	1	0.24544717	0.24544717	166.60	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.794079408	125.53	0.0001	0.00632592
S3	0.000009880	20.59	0.0001	0.00000048
L1	-0.571519084	-8.47	0.0001	0.06746410
L2	1.003420189	11.57	0.0001	0.08669305
L1*S1	0.143942777	20.38	0.0001	0.00706351
L2*S1	-0.117288161	-15.80	0.0001	0.00742501
L1*S2	-0.003240158	-20.27	0.0001	0.00015985
S3*L3	0.000073089	12.91	0.0001	0.00000566

Figure C.21: IEEE 802.11 Voice Mean Delay (1 Mbps) Regression GLM Results

The SAS System 18
14:12 Monday, January 18, 1999

General Linear Models Procedure

Dependent Variable: TD_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2.95817664	1.47908832	1804.42	0.0001
Error	297	0.24345145	0.00081970		
Corrected Total	299	3.20162808			

R-Square	C.V.	Root MSE	TD_ENH Mean
0.923960	3.034980	0.028630	0.943348

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S1	1	0.17738534	0.17738534	216.40	0.0001
L2	1	2.78079130	2.78079130	3392.44	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.7979032501	199.51	0.0001	0.00399934
S1	0.0027954127	14.71	0.0001	0.00019003
L2	0.4080129592	58.24	0.0001	0.00700515

Figure C.22: RT-MAC Voice Mean Delay (1 Mbps) Regression GLM Results

The SAS System 33
08:13 Thursday, April 8, 1999
General Linear Models Procedure
Dependent Variable: TF_STDA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	41.66380304	5.95197186	499.49	0.0001
Error	112	1.33461185	0.01191618		
Corrected Total	119	42.99841488			

R-Square	C.V.	Root MSE	TF_STDA Mean
0.968961	18.76416	0.109161	0.581754

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	0.52891452	0.52891452	44.39	0.0001
S2	1	0.25504071	0.25504071	21.40	0.0001
S3	1	1.19260835	1.19260835	100.08	0.0001
L1*S1	1	1.45823477	1.45823477	122.37	0.0001
S2*L3	1	2.86564990	2.86564990	240.48	0.0001
S3*L3	1	3.65802155	3.65802155	306.98	0.0001
C1	1	0.22425160	0.22425160	18.82	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.023516026	0.71	0.4769	0.03294933
L1	3.264021886	6.66	0.0001	0.48992409
S2	-0.001344791	-4.63	0.0001	0.00029068
S3	0.000093813	10.00	0.0001	0.00000938
L1*S1	-1.244461077	-11.06	0.0001	0.11249574
S2*L3	2.966175196	15.51	0.0001	0.19127302
S3*L3	-0.067116804	-17.52	0.0001	0.00383069
C1	0.086458391	4.34	0.0001	0.01993003

Figure C.23: IEEE 802.11 Voice Missed Deadline Ratio (1 Mbps) Regression GLM Results, $G < 0.2$

The SAS System 23
08:13 Thursday, April 8, 1999
General Linear Models Procedure
Dependent Variable: TF_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	65.95100109	9.42157158	562.18	0.0001
Error	232	3.88807261	0.01675893		
Corrected Total	239	69.83907370			

R-Square	C.V.	Root MSE	TF_STD Mean
0.944328	12.21010	0.129456	1.060240

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L2	1	2.70202295	2.70202295	161.23	0.0001
S1	1	1.79089284	1.79089284	106.86	0.0001
S2	1	3.07775051	3.07775051	183.65	0.0001
S3	1	3.03021357	3.03021357	180.81	0.0001
S1*L1	1	6.65684986	6.65684986	397.21	0.0001
S2*L1	1	5.75109512	5.75109512	343.17	0.0001
S3*L1	1	4.53158896	4.53158896	270.40	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.191825695	2.63	0.0091	0.07288338
L2	-2.022363745	-12.70	0.0001	0.15927145
S1	-0.255287236	-10.34	0.0001	0.02469548
S2	0.023509626	13.55	0.0001	0.00173481
S3	-0.000469670	-13.45	0.0001	0.00003493
S1*L1	0.828369327	19.93	0.0001	0.04156357
S2*L1	-0.055152958	-18.52	0.0001	0.00297726
S3*L1	0.000997917	16.44	0.0001	0.00006069

Figure C.24: IEEE 802.11 Voice Missed Deadline Ratio (1 Mbps) Regression GLM Results, $G \geq 0.2$

The SAS System 38
08:13 Thursday, April 8, 1999

General Linear Models Procedure

Dependent Variable: TF_ENHA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	5.77332692	1.92444231	809.75	0.0001
Error	116	0.27568463	0.00237659		
Corrected Total	119	6.04901155			

R-Square	C.V.	Root MSE	TF_ENHA Mean
0.954425	21.42296	0.048750	0.227561

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S3	1	1.76418044	1.76418044	742.32	0.0001
L2*S2	1	0.93367576	0.93367576	392.86	0.0001
C1	1	0.10672614	0.10672614	44.91	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.0032342975	-0.43	0.6704	0.00758058
S3	0.0000152214	27.25	0.0001	0.00000056
L2*S2	0.0092482215	19.82	0.0001	0.00046659
C1	0.0596451017	6.70	0.0001	0.00890055

Figure C.25: RT-MAC Voice Missed Deadline Ratio (1 Mbps) Regression GLM Results, $G < 0.2$

The SAS System 28
08:13 Thursday, April 8, 1999

General Linear Models Procedure

Dependent Variable: TF_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	43.13026954	14.37675651	1281.05	0.0001
Error	236	2.64854481	0.01122265		
Corrected Total	239	45.77881435			

R-Square	C.V.	Root MSE	TF_ENH Mean
0.942145	16.70335	0.105937	0.634226

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S2	1	7.33415279	7.33415279	653.51	0.0001
L2*S1	1	12.57641121	12.57641121	1120.63	0.0001
S2*L3	1	6.07672914	6.07672914	541.47	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.0740655838	-5.00	0.0001	0.01482774
S2	0.0006925052	25.56	0.0001	0.00002709
L2*S1	0.1682941148	33.48	0.0001	0.00502734
S2*L3	-.0055193144	-23.27	0.0001	0.00023719

Figure C.26: RT-MAC Voice Missed Deadline Ratio (1 Mbps) Regression GLM Results, $G \geq 0.2$

The SAS System 34
14:12 Monday, January 18, 1999

General Linear Models Procedure

Dependent Variable: TC_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	11.28182147	2.82045537	977.16	0.0001
Error	295	0.85147856	0.00288637		
Corrected Total	299	12.13330003			

R-Square	C.V.	Root MSE	TC_STD Mean
0.929823	13.33020	0.053725	0.403032

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S2	1	3.65758967	3.65758967	1267.19	0.0001
L1*S1	1	3.05281423	3.05281423	1057.67	0.0001
S2*L1	1	2.27315537	2.27315537	787.55	0.0001
S1*L2	1	0.35318059	0.35318059	122.36	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.0232201199	3.16	0.0017	0.00734041
S2	0.0006188754	35.60	0.0001	0.00001739
L1*S1	0.0874724172	32.52	0.0001	0.00268966
S2*L1	-.0022744447	-28.06	0.0001	0.00008105
S1*L2	-.0266956878	-11.06	0.0001	0.00241334

Figure C.27: IEEE 802.11 Voice Collision Ratio (1 Mbps) Regression GLM Results

The SAS System 39
14:12 Monday, January 18, 1999

General Linear Models Procedure

Dependent Variable: TC_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.69096570	0.17274142	1568.09	0.0001
Error	295	0.03249722	0.00011016		
Corrected Total	299	0.72346292			

R-Square	C.V.	Root MSE	TC_ENH Mean
0.955081	7.319374	0.010496	0.143396

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	0.26579228	0.26579228	2412.78	0.0001
S1	1	0.13676015	0.13676015	1241.47	0.0001
S2	1	0.03239127	0.03239127	294.04	0.0001
L1*S2	1	0.04728170	0.04728170	429.21	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.0288647072	-10.77	0.0001	0.00267956
L1	0.1645189097	49.12	0.0001	0.00334932
S1	0.0109560622	35.23	0.0001	0.00031095
S2	-.0001603244	-17.15	0.0001	0.00000935
L1*S2	-.0001462608	-20.72	0.0001	0.00000706

Figure C.28: RT-MAC Voice Collision Ratio (1 Mbps) Regression GLM Results

C.3.3.2 10 Mbps Data Rate

The SAS System 2
08:16 Monday, March 29, 1999
General Linear Models Procedure

Dependent Variable: XPUT_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	4.61604762	0.92320952	1562.24	0.0001
Error	394	0.23283534	0.00059095		
Corrected Total	399	4.84888296			

R-Square	C.V.	Root MSE	XPUT_STD Mean
0.951982	10.39458	0.024310	0.233867

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	1.92424441	1.92424441	3256.17	0.0001
L2	1	0.75922727	0.75922727	1284.75	0.0001
S2	1	0.11721108	0.11721108	198.34	0.0001
L2*S1	1	0.68766351	0.68766351	1163.65	0.0001
S1*L3	1	0.46795187	0.46795187	791.86	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.024168195	6.59	0.0001	0.00366601
L1	1.426298418	57.06	0.0001	0.02499520
L2	-1.114375722	-35.84	0.0001	0.03109010
S2	0.000012804	14.08	0.0001	0.00000091
L2*S1	-0.035761546	-34.11	0.0001	0.00104835
S1*L3	0.036139554	28.14	0.0001	0.00128428

Figure C.29: IEEE 802.11 Voice Throughput (10 Mbps) Regression GLM Results

The SAS System 8
08:16 Monday, March 29, 1999
General Linear Models Procedure

Dependent Variable: XPUT_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	7.54285192	1.88571298	4204.41	0.0001
Error	395	0.17716098	0.00044851		
Corrected Total	399	7.72001289			

R-Square	C.V.	Root MSE	XPUT_ENH Mean
0.977052	7.224668	0.021178	0.293135

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	3.77726815	3.77726815	8421.84	0.0001
L2	1	1.37988700	1.37988700	3076.61	0.0001
S2	1	0.19479747	0.19479747	434.32	0.0001
L1*S1	1	0.59644986	0.59644986	1329.85	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.013244280	4.31	0.0001	0.00307336
L1	1.372295326	91.77	0.0001	0.01495354
L2	-0.877511384	-55.47	0.0001	0.01582036
S2	0.000017298	20.84	0.0001	0.00000083
L1*S1	-0.005696398	-36.47	0.0001	0.00015621

Figure C.30: RT-MAC Voice Throughput (10 Mbps) Regression GLM Results

The SAS System 24
13:38 Thursday, April 15, 1999
General Linear Models Procedure

Dependent Variable: TD_STDL

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.06028425	0.01507106	511.76	0.0001
Error	125	0.00368119	0.00002945		
Corrected Total	129	0.06396543			

R-Square	C.V.	Root MSE	TD_STDL Mean
0.942450	4.072793	0.005427	0.133244

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L3	1	0.03339535	0.03339535	1133.99	0.0001
C1*S1	1	0.00242392	0.00242392	82.31	0.0001
L3*C1	1	0.00378083	0.00378083	128.38	0.0001
S1*L1	1	0.01053865	0.01053865	357.85	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.142230137	183.45	0.0001	0.00077529
L3	-9.264027721	-33.67	0.0001	0.27510337
C1*S1	0.000194612	9.07	0.0001	0.00002145
L3*C1	2.357284475	11.33	0.0001	0.20804501
S1*L1	0.005232188	18.92	0.0001	0.00027659

Figure C.31: IEEE 802.11 Voice Mean Delay (10 Mbps) Regression GLM Results, $G < 0.2; G = 0.2, N \leq 50$

The SAS System 29
13:38 Thursday, April 15, 1999
General Linear Models Procedure

Dependent Variable: TD_ENHL

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.05253188	0.01050638	1363.40	0.0001
Error	154	0.00118672	0.00000771		
Corrected Total	159	0.05371860			

R-Square	C.V.	Root MSE	TD_ENHL Mean
0.977909	0.337896	0.002776	0.821545

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L2	1	0.00893582	0.00893582	1159.59	0.0001
S2	1	0.00050239	0.00050239	65.19	0.0001
L2*S1	1	0.00265182	0.00265182	344.12	0.0001
S2*L3	1	0.00188529	0.00188529	244.65	0.0001
L3*S3	1	0.00214909	0.00214909	278.88	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.823805686	1693.32	0.0001	0.00048650
L2	-1.887421136	-34.05	0.0001	0.05542634
S2	0.000001186	8.07	0.0001	0.00000015
L2*S1	0.090768448	18.55	0.0001	0.00489302
S2*L3	-0.009602999	-15.64	0.0001	0.00061395
L3*S3	0.000075187	16.70	0.0001	0.00000450

Figure C.32: RT-MAC Voice Mean Delay (10 Mbps) Regression GLM Results, $G < 0.2; G = 0.2, N < 40$

The SAS System 14

13:38 Thursday, April 15, 1999

General Linear Models Procedure

Dependent Variable: TD_STDH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	145.7066421	20.8152346	507.74	0.0001
Error	282	11.5609204	0.0409962		
Corrected Total	289	157.2675625			

R-Square	C.V.	Root MSE	TD_STDH Mean
0.926489	13.22326	0.202475	1.531205

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S2	1	7.28562622	7.28562622	177.71	0.0001
S3	1	5.55841643	5.55841643	135.58	0.0001
L2	1	16.88844374	16.88844374	411.95	0.0001
S1*L1	1	25.04588095	25.04588095	610.93	0.0001
L2*S1	1	18.06859538	18.06859538	440.74	0.0001
S3*L2	1	9.67455284	9.67455284	235.99	0.0001
S3*L3	1	8.47668395	8.47668395	206.77	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-1.124789470	-14.11	0.0001	0.07970245
S2	-0.001092000	-13.33	0.0001	0.00008191
S3	0.000010686	11.64	0.0001	0.00000092
L2	4.193011080	20.30	0.0001	0.20658693
S1*L1	0.338463153	24.72	0.0001	0.01369351
L2*S1	-0.344519765	-20.99	0.0001	0.01641057
S3*L2	-0.000054676	-15.36	0.0001	0.00000356
S3*L3	0.000060941	14.38	0.0001	0.00000424

Figure C.33: IEEE 802.11 Voice Mean Delay (10 Mbps) Regression GLM Results, $G = 0.2, N > 50; G \geq 0.2$

The SAS System 19

13:38 Thursday, April 15, 1999

General Linear Models Procedure

Dependent Variable: TD_ENHH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	175.1381198	29.1896866	702.49	0.0001
Error	313	13.0057283	0.0415518		
Corrected Total	319	188.1438481			

R-Square	C.V.	Root MSE	TD_ENHH Mean
0.930873	20.66264	0.203843	0.986528

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	4.97596537	4.97596537	119.75	0.0001
L2	1	5.21801147	5.21801147	125.58	0.0001
L3	1	4.29279756	4.29279756	103.31	0.0001
L2*S1	1	11.75048187	11.75048187	282.79	0.0001
L3*S2	1	7.25552078	7.25552078	174.61	0.0001
L3*S3	1	4.13049991	4.13049991	99.41	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	1.84724809	9.76	0.0001	0.18931051
L1	-15.84165319	-10.94	0.0001	1.44762807
L2	36.05221916	11.21	0.0001	3.21717479
L3	-21.90612826	-10.16	0.0001	2.15521495
L2*S1	0.13189120	16.82	0.0001	0.00784302
L3*S2	-0.00376083	-13.21	0.0001	0.00028461
L3*S3	0.00002355	9.97	0.0001	0.00000236

Figure C.34: RT-MAC Voice Mean Delay (10 Mbps) Regression GLM Results, $G = 0.2, N \geq 40; G > 0.2$

The SAS System 24
08:16 Monday, March 29, 1999

General Linear Models Procedure

Dependent Variable: TF_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	108.1582440	18.0263740	791.59	0.0001
Error	393	8.9494935	0.0227722		
Corrected Total	399	117.1077375			

R-Square	C.V.	Root MSE	TF_STD Mean
0.923579	23.62806	0.150905	0.638668

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1*S1	1	1.35436861	1.35436861	59.47	0.0001
L1*S3	1	4.11663744	4.11663744	180.77	0.0001
S1*L2	1	4.39942804	4.39942804	193.19	0.0001
S3*L2	1	4.43195730	4.43195730	194.62	0.0001
S1*L3	1	4.79115434	4.79115434	210.39	0.0001
S3*L3	1	3.85439363	3.85439363	169.26	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.0158477265	1.10	0.2702	0.01435391
L1*S1	-.0718517704	-7.71	0.0001	0.00931691
L1*S3	0.0000252442	13.45	0.0001	0.00000188
S1*L2	0.4443964763	13.90	0.0001	0.03197242
S3*L2	-.0000931867	-13.95	0.0001	0.00000668
S1*L3	-.3899073316	-14.50	0.0001	0.02688093
S3*L3	0.0000737375	13.01	0.0001	0.00000567

Figure C.35: IEEE 802.11 Voice Missed Deadline Ratio (10 Mbps) Regression GLM Results

The SAS System 30
08:16 Monday, March 29, 1999

General Linear Models Procedure

Dependent Variable: TF_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	29.44906966	14.72453483	3162.31	0.0001
Error	397	1.84853490	0.00465626		
Corrected Total	399	31.29760456			

R-Square	C.V.	Root MSE	TF_ENH Mean
0.940937	28.94758	0.068237	0.235725

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L2*S2	1	7.80881022	7.80881022	1677.06	0.0001
S2*L3	1	3.99487764	3.99487764	857.96	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.0194680530	4.39	0.0001	0.00443166
L2*S2	0.0009202051	40.95	0.0001	0.00002247
S2*L3	-.0008502653	-29.29	0.0001	0.00002903

Figure C.36: RT-MAC Voice Missed Deadline Ratio (10 Mbps) Regression GLM Results

The SAS System 35
08:16 Monday, March 29, 1999
General Linear Models Procedure

Dependent Variable: TC_STD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	27.07172141	4.51195357	1138.34	0.0001
Error	393	1.55770048	0.00396361		
Corrected Total	399	28.62942189			

R-Square	C.V.	Root MSE	TC_STD Mean
0.945591	13.62426	0.062957	0.462096

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S2	1	0.33593742	0.33593742	84.76	0.0001
L1*S3	1	2.38612686	2.38612686	602.01	0.0001
L2*S1	1	5.09399218	5.09399218	1285.19	0.0001
S2*L2	1	3.21722771	3.21722771	811.69	0.0001
S1*L3	1	3.26999161	3.26999161	825.00	0.0001
S2*L3	1	2.26451093	2.26451093	571.32	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.0339349510	4.37	0.0001	0.00776966
S2	0.0000231597	9.21	0.0001	0.00000252
L1*S3	0.0000070285	24.54	0.0001	0.00000029
L2*S1	0.2527400409	35.85	0.0001	0.00705002
S2*L2	-.0042030215	-28.49	0.0001	0.00014753
S1*L3	-.2363340239	-28.72	0.0001	0.00822808
S2*L3	0.0035733362	23.90	0.0001	0.00014950

Figure C.37: IEEE 802.11 Voice Collision Ratio (10 Mbps) Regression GLM Results

The SAS System 41
08:16 Monday, March 29, 1999
General Linear Models Procedure

Dependent Variable: TC_ENH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	4.48860186	1.12215047	3425.82	0.0001
Error	395	0.12938482	0.00032756		
Corrected Total	399	4.61798668			

R-Square	C.V.	Root MSE	TC_ENH Mean
0.971982	6.584050	0.018099	0.274884

Source	DF	Type III SS	Mean Square	F Value	Pr > F
L1	1	1.53737155	1.53737155	4693.45	0.0001
L3	1	0.12650930	0.12650930	386.22	0.0001
S1	1	0.70467855	0.70467855	2151.32	0.0001
L2*S3	1	0.12465898	0.12465898	380.57	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	0.0075600054	2.50	0.0128	0.00302277
L1	0.5222033572	68.51	0.0001	0.00762243
L3	-.2248675541	-19.65	0.0001	0.01144218
S1	0.0024502637	46.38	0.0001	0.00005283
L2*S3	-.0000004074	-19.51	0.0001	0.00000002

Figure C.38: RT-MAC Voice Collision Ratio (10 Mbps) Regression GLM Results

Vita

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Rusty O. Baldwin is a Major (select) in the U.S. Air Force. He earned his B.S. degree in Electrical Engineering (with honors) from New Mexico State University in 1987 and his M.S. degree in Computer Engineering from the Air Force Institute of Technology in 1992. His assignments in the Air Force include: Instructor of Software Engineering, Air Force Institute of Technology, Wright-Patterson AFB, OH, Chief Computer Support Branch, Wright Laboratory, Wright-Patterson AFB, OH, Project Officer, Defense Meteorological Satellite Program, Los Angeles AFB, CA, and Instrumentation Mechanic, Guidance Division, Holloman AFB, NM. His professional memberships include IEEE and Eta Kappa Nu. His research interests are computer communication protocols, software engineering, and wireless networking.

His publications include:

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