Multiple Access Schemes for Data Communications

by

Rana Ejaz Ahmed

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

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Dean, College of Graduate Studies

Date June 4, 1985

Department Chairman

THESIS COMMITTEE

Chairman

Member

Member

This thesis is dedicated to my lovely parents

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ABSTRACT

We propose four new multiple access schemes for a broadcast channel shared by a finite number of users in packet communications. Random access schemes (e.g., slotted ALOHA) are efficient at low values of throughput while the performance of fixed assignment TDMA is better when throughput is high.

Scheme I has static mixing of S-ALOHA and TDMA slots. In Schemes II, III & IV, the normal accessing mode is S-ALOHA until a collision is detected. Upon detecting a collision, a TDMA frame is reserved in Scheme II; while in Schemes III & IV slots are reserved for collided users only.Scheme IV is just the extension of Scheme III with the additional capability of sending queue length information of each collided user. Schemes II, III & IV adapt smoothly to traffic variations and the maximum throughput may approach unity in these schemes. Detailed delay and buffer analyses are performed and the results are verified by simulation.

ملخص البحث

نقوم في هذه البحث باقتراح اربعة انظمه جديدة متعددة المداخل لقنوات الارسال المستعمله بين عدد محدود من المستخدمين في الاتصالات الرزميه • ان الانظمه ذات المداخل العشوائيه مثل (S-ALOHA)

تكون فعاله لقيم صغيره من الانتاجيه بينما فعالية نظام (TDMA) ذو النصاب المحدد يكون افضل عندما يكون الانتاجيه عاليه •

النظام المقترح رقم (I)له مزج ثابت من (S-ALOHA) واجزاء من (TDMA) اما الانظمه رقم (IV - III - II) فتكون حاله الادخال العاديه هي (S - ALOHA) حتى يتم حدوث تصادم • وفي حالة اكتشاف هذا التصادم نقوم بحجز اطار من (TDMA) في النظام رقم(II) بينما في رقم (IV, III)نقوم بحجز الاجزاء للمستخدمين المتصادمين فقط • اما النظام رقم (IV) فهو امتداد لنظام رقم (III) بقدرة اضافيه لارسال صف من المعلومات لكل مستخدم متصادم •

ومن خواص الانظمه رقم (IV, III, II) انها تتكيف بسهوله مع تغيرات السير وانتاجيتهما قد تصل الواحد صحيح • ولقد تم في هذه الدراسه تحليل التاخير الحاملات في هذه الانظمه وتم التحقق من النتائج باستخدام الحاسب الالـــــــى

Chapter 1

INTRODUCTION

1.1 PACKET COMMUNICATION

The progress in the field of computer communications began in the early sixties, when we witnessed the problem of connecting remote user terminals to central computer facilities. The solutions to that problem were then based on asynchronous low-speed lines organized in either a star topology with a line dedicated to each terminal, or a tree topology with multidrop lines. By the end of the sixties, the field had made a major leap with the advent of distributed resource sharing networks. The goal was to interconnect computers and their users at various geographically distributed sites in order to allow the sharing, by all users connected to network, of hardware and software resources developed at any of the sites. The prominent example of such a network is ARPANET, which began implementation in 1969. Such a network comprises:

a) the collection of computing resources called hosts,

b) the collection of users connected to the hosts via terminal access networks, and

c) a communication subnetwork which interconnects the hosts.

The communications subnet itself consists of two basic components: the relatively high speed communication channel and the switching nodes. The switching nodes are computers with processing and storage capabilities, which perform what is called <u>packet switching</u>. In packet-switching, a message to be transmitted between a source and destination is broken into blocks of fixed length. Each block of data is combined with a header containing source and destination addresses as well as control information, and a check sum which is used for error control purposes, thus forming a packet. The packets travel independently from source to destination, through (in general) a sequence of intermediate nodes. When a packet reaches some intermediate node, the node receives the entire packet into a buffer, checks its correctness, determines the outgoing channel on which to transmit it, and puts it on the corresponding queue for transmission. The destination node delivers the packet to the appropriate host.

Packet-switching is favored over the conventional circuit-switching for computer communications because of the bursty nature of computer traffic (e.g. interactive terminal traffic, and inquiry response systems etc).

Burstiness is a result of the high degree of randomness encountered in the message generation process and message size distribution, combined with a low delay constraint required by the user. For bursty users, packet-switching and the store-and-forward transmission technique offer a more cost-effective solution, since a packet occupies a particular communication link only for the duration of its transmission on that link; the rest of the time it is stored at some intermediate switch, and the link is available for other transmissions [1].

1.2 MULTIPLE ACCESS SCHEMES

In a packet-broadcasting network, a large number of packet-switched network users are interconnected via a broadcast channel. A communication channel is said to have braodcast capabilities if every user can receive and listen to the messages transmitted by any user, including itself. Typical examples of broadcast channels are satellites, ground radio and coaxial cable. A multiple access scheme is required to appropriately allocate the channel capacity among the users in order to achieve efficient utilization of expensive channel and to provide high degree of connectivity for communication among users.

A large number of multiaccess schemes have been developed

and implemented. These schemes can be grouped into five classes [2].

The first class, labelled fixed-assignment techniques, consists of allocating the channel to the users, independently of their activity, by partitioning the time-bandwidth space into slots which are assigned in a static predetermined fashion.

The second class is that of random access schemes. In this class, the entire bandwidth is available to the users as a single channel to be accessed randomly. Since collisions may result which degrade the performance of the channel, improved performance can be achieved by either synchronizing users so that their transmission coincide with the boundaries of time slots or by sensing carrier prior to transmission or both.

The third and fourth classes correspond to demand assignment techniques. These techniques require that explicit control information regarding the user's need for the communication resource be exchanged. A distinction is made between those techniques in which the decision making is centralized (constituting the third class), and those techniques in which all users individually execute a distributed algorithm based on control information exchanged among them.

The fifth class is "adaptive strategies and mixed modes". This includes those schemes which consist of several distinct modes, and those strategies in which the choice of an access scheme is itself adaptive to the varying need, in the hope that near-optimum performance will be achieved at all times [2].

These schemes (or protocols) are devised in a variety of traffic environments; consequently, the situation in which one protocol performs well differ from that of another protocol. The performance of a multiple access protocol is strongly dependent upon the traffic model and network loading [3].

1.3 THESIS OBJECTIVES

The broad objectives of this study are as follows:

1) To develop new multiple access schemes for broadcast channel (under distributed management) which give better and stable performance as compared with either random access or fixed assignment techniques and

2) Simulation and analytical modelling for these schemes.

Chapter 2

LITERATURE REVIEW

2.1 FIXED-ASSIGNMENT TECHNIQUES

The problem of multiple access (M.A.) has been solved in the past with voice communication in mind. The design objective is to maximize the number of voice-grade channels for given constraints of power and bandwidth. The common fixed assignment techniques are frequency division multiple access (FDMA), time-division multiple access (TDMA), and code- division multiple access (CDMA) (also called spread-spectrum multiple access) [4].

FDMA consists of assigning to each user a fraction of the bandwidth and confining its access to the allocated sub band. FDMA is relatively simple to implement and requires no real time coordination among the users.

TDMA consists of assigning fixed predetermined channel time slots to each users; the user has access to the entire channel bandwidth, but only during its allocated slots.

CDMA allows overlap in transmission both in the frequency

and time coordinates. It uses different signalling code and matched filters at receivers [2].

It has been established that TDMA is superior to FDMA in many practical cases. Rubin [5] has shown that the random variable representing packet delay is always larger in FDMA than in TDMA for comparable systems. Both FDMA and TDMA station buffer queue sizes are essentially the same.

If the message traffic at each user is steady, these techniques are very efficient. In computer communication, much traffic is characterized as bursty, low duty cycle with a high ratio of peak-to-average traffic intensity. Under this kind of traffic, fixed assignment schemes are inefficient [2].

With the decrease in cost of processing and processors, attention has shifted to packet-switching forms of multiple access. Most of the work that has been done on this form of multiple access is reviewed in the next sections.

2.2 RANDOM ACCESS TECHNIQUES

Abramson [6], [7] studied the pure ALOHA protocol. This protocol was first used in the ALOHA system, a single hop terminal

access network developed in 1970 at the University of Hawaii, employing packet-switching on a radio channel. Pure ALOHA permits a user to transmit any time it desires. If two or more packets collide (i.e. overlap in time), each user involved realizes this after round trip propagation delay and retransmits his packet after a randomized delay. Pure ALOHA is unstable and has a maximum throughput of 1/2e.

Roberts improved the maximum throughput of the channel to 1/e by slotting the channel time. Users are now required to synchronize their packet transmissions into fixed-length channel time slots. It is called the slotted ALOHA scheme [2], [8].

Metcalfe tried to stabilize the ALOHA and slotted ALOHA systems by two methods. First, he introduced blocking, i.e., a source may not generate another packet until the present packet has been transmitted successfully. Second, he varied the transmission probabilities [8].

Kleinrock and Lam [9], [10] extended Metcalfe's work. They showed that even by blocking, if the population of sources is infinite and independent, the system is unstable. If the population of sources is finite, then the system is stable. However, due to traffic fluctuations, the system sways between two points, one with

a small number of retransmitted packets and another with a large number of retransmitted packets [8].

Rubin [11] proposed group random access (GRA) schemes. A GRA scheme uses only certain channel time periods during which some network terminals attempt to transmit their packets on a random access basis. The channel can thus be utilized at other times to grant access to other terminals or message type. To stabilize the GRA channel, a dynamic control procedure was applied. The GRA scheme was shown to have a maximum throughput of 1/e.

Capetanakis [12] proposed tree algorithm. It is stable and the maximum throughput is 0.43 for an infinite population of sources. The sources are assigned to the leaves of a tree graph. Packet collisions are resolved by systematically moving from node to node through the tree, trying to determine the branches containing the conflicting users.

Capetanakis [13] also showed that the tree protocol was a generalization of TDMA and that an optimum dynamic tree adaptively changed from an essentially random access protocol in light traffic to TDMA in heavy traffic.

Rubin and Louie [8], [14] developed a hybrid TRDMA/random

access scheme. Under this scheme, the system sources are divided into groups. Each group is associated with one portion of the channel time frame. Hence, the groups can be served in a cyclic manner. Collisions among sources in each group are resolved by the tree search technique. By varying the number of groups, a family of hybrid access schemes are obtained, with fixed assignment TDMA and the pure tree search scheme as extreme members of the family.

So far, under the schemes we have discussed, if more than one packet is transmitted simultaneously, then a collision occurs and all the packets are destroyed. However, Roberts showed that this need not be true because FM receivers can track the strongest of many signals if the next strongest is down by 1.5 to 3 dB. In a ground radio system, he increased the maximum channel throughput to 0.6 by taking the advantage of this FM capture [8].

There are other schemes developed which can improve the channel throughput by requiring each source to obtain more information about the other sources. However, these schemes are efficient only if the round trip propagation delay of channel is small (e.g., ground radio or coaxial cable).

Kleinrock and Tobagi [15], [16], [17] examined CSMA (carrier sense multiple access). In CSMA, a source with a packet to transmit

first listens for the carrier of other sources to determine if the channel is busy. If it is busy then source holds the packet. Otherwise, it transmits the packet with certain probability. Unavoidable collisions are resolved by the ALOHA technique. This scheme gives better throughput-delay characteristics as compared to the slotted ALOHA.

Kleinrock and Yemini [18] suggested URN protocol under which sources which have packets to transmit are required to send signals in mini slots. Hence, every source can acquire information about the other sources by listening to these minislots. Then based on this information, transmission rights in each slot are assigned among the sources by following a certain rule. The URN protocol adapts smoothly to network load fluctuations. The maximum channel throughput of URN protocol is unity.

2.3 RESERVATION TECHNIQUES

The traffic environment suitable for ALOHA and slotted ALOHA is that of a large population of low-rate bursty users with short messages (one packet per message). The R-ALOHA (Reservation ALOHA) protocol was originally proposed by Crowther et al. [4], [8] and is suitable for users who generate long multipacket messages or users with steady input traffic and queueing capability. Under R-ALOHA

the channel slots are grouped into frames that are at least one propagation delay long. A source that has successfully used a slot retains transmission right in that slot in the following frame. Unused slots can be captured by any source through the slotted ALOHA technique.

Roberts [9] suggested interleaved Reservation ALOHA schemes under which the channel is divided into two states, Reservation and ALOHA. On the Reservation state, the source tries to reserve the ALOHA state by the slotted ALOHA technique.

Binder introduced reservation schemes under which slots are grouped into frames such that each source is allocated a slot in every frame. A slot which is not used by its owner is available to the other sources on a Round Robin basis [2], [8].

Rubin [20] offered Fixed Reservation schemes under which the channel frame is divided into two portions, one portion for sending reservation information and the other portion for actual message transmission. By changing the frame duration and the ratio of the two portions, Dynamic and Fixed Reservation schemes are obtained which are capable of adapting to traffic fluctuations.

Other important reservation schemes have been proposed by

Kleinrock and Scholl [21], Hansen and Schwartz [22], and Jacobs et al. [23], [24].

Satellite systems with on-board processing capability have recently received increased attention and are being considered as a means to increase the capacity of packet satellite channels [25]. One example is typified by the integration of slotted ALOHA on several uplink channels, with TDMA on one or several downlink channels. The on-board processing capability is used to filter out all collisions and thus improve the utilization of the downlink channels [2], [26].

Chapter 3

PROPOSED SCHEMES AND SIMULATION RESULTS

In this chapter, the sharing of a slotted broadcast channel by a finite number of geographically distributed data users is considered. We shall propose four multiple access schemes and give the simulation results for each scheme. But, first of all, we shall discuss some definitions regarding the channel performance measures.

3.1 CHANNEL PERFORMANCE MEASURES [12]

The measures which will be relevant to our study are as follows.

Average Throughput - S

The ratio of the number of packets that are successfully transmitted in a very long interval to the maximum number of packets that could have been transmitted with continuous transmission on the channel.

Average Delay - E(D)

The ratio of the total delay of the packets in a very long interval to the number of packets in the interval. The delay is the time from the instant

a packet arrives at a source to the instant that it is successfully received.

Stability

The system is kth order stable if the first k moments of the delay of a randomly chosen packet are finite. Otherwise, it is unstable.

A desirable multiple access scheme is one that is at least first order stable, has high average throughput, and has low average delay.

3.2 SCHEME I

The following is a description of the channel model and Poisson source model used in the scheme. The proposed multiple access scheme, henceforth called Scheme I, is then discussed and the simulation results are presented.

Channel Model

The channel is assumed to be slotted; i.e., the channel time is divided into equal segments called slots. Let τ be the slot length in seconds. For all schemes considered in this thesis, we assume τ = 20 msec. This is the time required to transmit a packet of length 1000 bits at a speed of 50 k-bits/second. The channel is to be shared by a finite number of sources (or users), N. These sources are assumed to be synchronized to slot boundaries.

Problems of modulation, synchronization, coding and the like are assumed to have been solved.

Each source can listen to the transmission of packets from all the sources, including itself. A slot is said to be empty if no packet is transmitted in it by any source. If only one source transmits a packet in a slot, the transmission is regarded as a successful transmission. If two or more sources transmit packets in the same slot, a collision occurs and none of the packets can be correctly received. In the latter case, it is necessary then to arrange for these sources to retransmit the collided packets. Every source has the ability to distinguish if a previously received slot was an empty slot or whether it was a successful transmission or a collision; and based on this information and a multiple access scheme, decides whether or not to transmit in a given slot.

Poisson Source Model

Single packets are assumed to be arriving at the sources which share the communication channel. All of the N sources are assumed to be alike. Each source generates k packets/sec., where k is a Poisson random variable with mean λ. Furthermore, the number of arrivals in any one slot is independent of the arrivals in other slot. Two infinite buffers are available at each source; one to store the newly arriving packets and the other to store collided packets from the previous slots which are to be retransmitted.

Motivation

Random access schemes (e.g., slotted ALOHA) are efficient at low values of throughput while the performance of fixed assignment TDMA is better when throughput is high. The mixing of slotted ALOHA and TDMA modes can be done either statically or dynamically in a search to achieve better delay-throughput tradeoffs. Our first strategy is to use static mixing.

Working of Scheme I

We have a static superframe structure which repeats itself. In a superframe we have α number of slots used in random accessing (i.e. S-ALOHA mode) and β number of contiguous TDMA frames. Fig. 3.1 shows a typical superframe structure for $\alpha = 2$ & $\beta = 2$ and $N = 4$. The Scheme I works as follows.

Each user maintains two buffers, one for storing newly arriving packets and the other to accomodate collided packets. Newly arriving packets can be transmitted in either S-ALOHA mode or in TDMA mode (i.e. in the reserved slots), while the collided packets are retransmitted only in a user's assigned slot in a TDMA frame. So a packet can have at most one collision before it received successfully. If a user's retransmission buffer is empty, then it can transmit any waiting newly generated packet from main buffer in its assigned slot. This scheme is also stable.

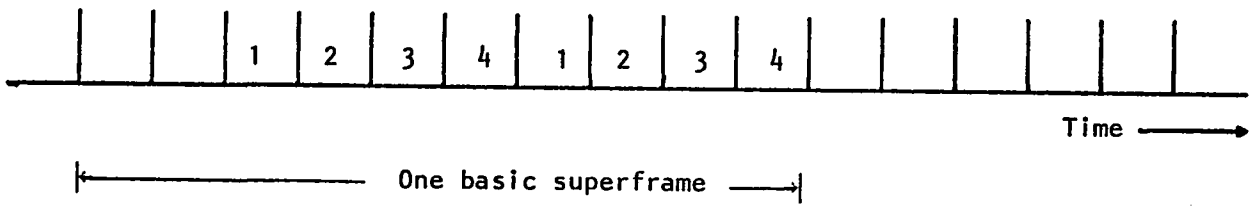


Figure 3.1. Basic superframe structure for Scheme I for $N = 4$, $\alpha = 2$ & $\beta = 2$. A number k in a slot denotes a kth user assigned slot.

Simulation Results

Scheme I was simulated for 50,000 slots using a FORTRAN program. The basic block diagram for the program and the listing are given in the appendix A.1 & B.1 respectively. Delay throughput tradeoffs are tabulated in Tables 3.1 & 3.2. Figures 3.2 & 3.3 show the delay - throughput performances for $N = 10$, $\alpha = 1$ and various values of β for the cases where $R\tau = 0.0$ & $R\tau = 0.27$ sec.

3.3 SCHEME II

The channel model and Poisson source model in this scheme are same as in Scheme I.

Motivation

Every source has the capability to detect a collision. Whenever a collision is detected then collided packets are queued in the retransmission buffer at each colliding source, but all sources do not know which sources are involved in that collision (unless there is some arrangement to detect a user's identification). Approaching on a pessimistic way, we say that all N sources are involved in any collision and a slot is reserved for each of N sources upon detecting a collision.

TABLE 3.1. Delay - Throughput Tradeoffs for Scheme I,

$R\tau = 0$, $N = 10$ and $\alpha = 1$.

Total Traffic Intensity	Throughput (Delay (sec))						
	$\beta=0$ (S-ALOHA)	$\beta=1$	$\beta=2$	$\beta=3$	$\beta=4$	$\beta=5$	TDMA
0.01	0.0093 (0.03)	0.0093 (0.0953)	0.0093 0.1042)	0.0093 (0.1112)	0.0093 (0.1139)	0.0093 (0.1156)	0.0093 (0.1205)
0.04	0.0399 (0.0305)	0.0399 (0.0975)	0.0399 (0.1094)	0.0399 (0.1161)	0.0399 (0.1186)	0.0399 (0.1181)	0.0399 (0.1249)
0.1	0.0993 (0.032)	0.993 (0.1122)	0.0993 (0.122)	0.0993 (0.1253)	0.0993 (0.1266)	0.0993 (0.1264)	0.0993 (0.1322)
0.2	0.1995 (0.0354)	0.1995 (0.1379)	0.1994 (0.1405)	0.1994 (0.1416)	0.1994 (0.1431)	0.1994 (0.143)	0.1994 (0.1456)
0.3	0.2995 (0.100)	0.2996 (0.1680)	0.2996 (0.1652)	0.2996 (0.1636)	0.2996 (0.1626)	0.2996 (0.1631)	0.2996 (0.1625)
0.4	-	0.4003 (0.2085)	0.4003 (0.1955)	0.4003 (0.1930)	0.4003 (0.1910)	0.4003 (0.1907)	0.4 (0.1861)
0.5	-	0.4987 (0.2591)	0.4987 (0.2377)	0.4987 (0.2309)	0.4987 (0.2283)	0.4987 (0.226)	0.4987 (0.2182)
0.7	-	0.6987 (0.5057)	0.6988 (0.4215)	0.6988 (0.3977)	0.6988 (0.3861)	0.6988 (0.3813)	0.6988 (0.3562)
0.9	-	0.8928 (5.1269	0.898 (1.8099)	0.8986 (1.4633)	0.8988 (1.3229)	0.8989 (1.256)	0.8991 (1.041)

TABLE 3.2. Delay - Throughput Tradeoffs for Scheme I,

$R\tau = 0.27$, $N = 10$ and $\alpha = 1$.

Total Traffic Intensity	Throughput (Delay (sec))						
	$\beta=0$ (S-ALOHA)	$\beta=1$	$\beta=2$	$\beta=3$	$\beta=4$	$\beta=5$	TDMA
0.01	0.0093 (0.3037)	0.0093 (0.3751)	0.0093 (0.3796)	0.0093 (0.3877)	0.0093 (0.3865)	0.0093 (0.3865)	0.0093 (0.3906)
0.04	0.0399 (0.3079)	0.0399 (0.3919)	0.0399 (0.395)	0.0399 (0.396)	0.0399 (0.3976)	0.0399 (0.3955)	0.0399 (0.3949)
0.1	0.0993 (0.3335)	0.0993 (0.4452)	0.0993 (0.4285)	0.0993 (0.4205)	0.0993 (0.4142)	0.0993 (0.4095)	0.0993 (0.4021)
0.2	0.1995 (0.3767)	0.1994 (0.5104)	0.1994 (0.4747)	0.1994 (0.4616)	0.1994 (0.4447)	0.1994 (0.4392)	0.1994 (0.4152)
0.3	0.2995 (0.4648)	0.2995 (0.5683)	0.2996 (0.5168)	0.2996 (0.5017)	0.2996 (0.4779)	0.2996 (0.4689)	0.2996 (0.4307)
0.4	-	0.4002 (0.6203)	0.4003 (0.5591)	0.4003 (0.5391)	0.4003 (0.514)	0.4003 (0.5017)	0.4 (0.4538)
0.5	-	0.4986 (0.6742)	0.4987 (0.6080)	0.4986 (0.5833)	0.4987 (0.5583)	0.4987 (0.5415)	0.4987 (0.4864)
0.7	-	0.6987 (0.9222)	0.6987 (0.7943)	0.6988 (0.7621)	0.6987 (0.7234)	0.6987 (0.7041)	0.6988 (0.6254)
0.9	-	0.8927 (5.4917)	0.8979 (2.1636)	0.8985 (1.8044)	0.8987 (1.6495)	0.8988 (1.5769)	0.8991 (1.3104)

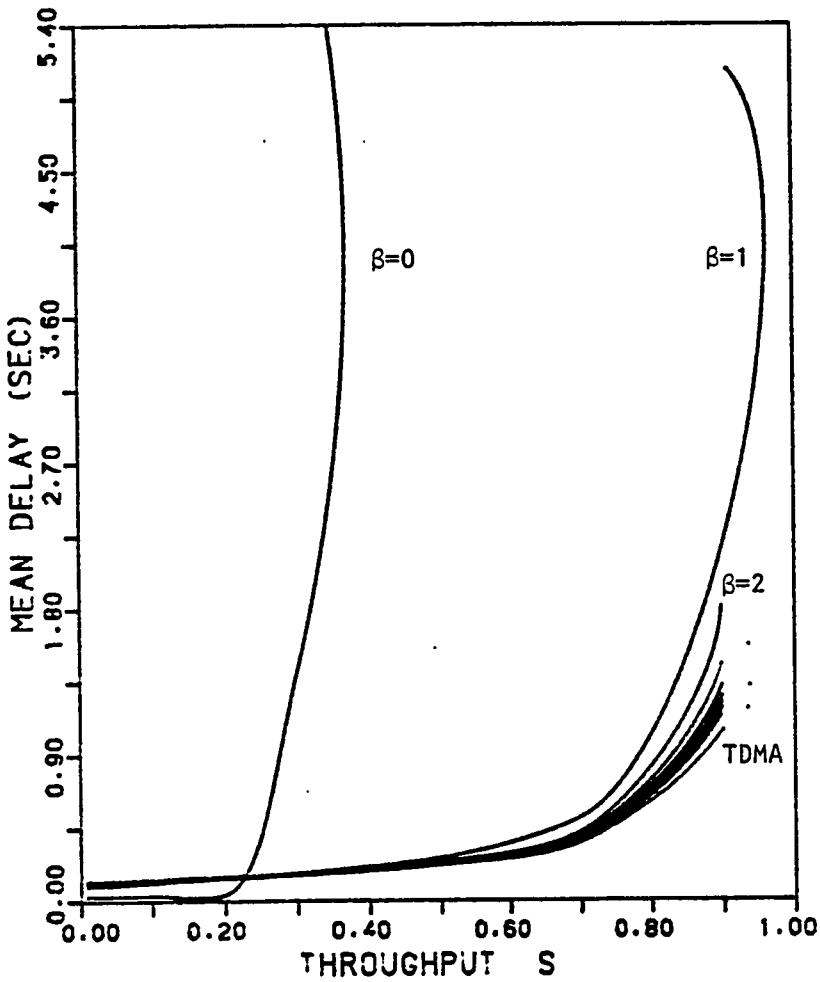


Figure 3.2. Delay-throughput tradeoffs for Scheme I,

$N = 10$, $R = 0$, $\alpha = 1$.

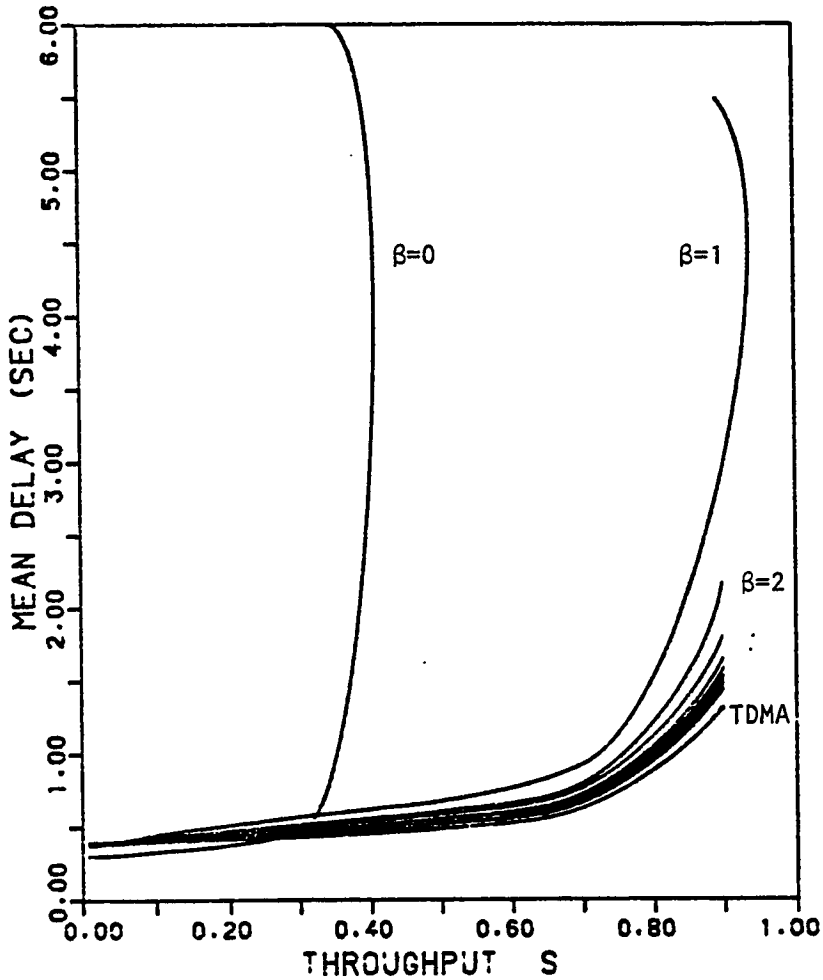


Figure 3.3. Delay throughput tradeoffs for Scheme I,

$N = 10$, $R\tau = 0.27$, $\alpha = 1$.

Working of Scheme II

The system can be in one of the following two states:

(1) State # 1 (slotted - ALOHA). The users transmit in a slot whenever they have packets ready to send.

(2) State # 2 (TDMA) mode). A slot is reserved for each source connected to the broadcast channel. If a source has a collided packet waiting to be retransmitted, it transmits in its assigned slot; otherwise it can transmit any newly generated waiting packet in its assigned slot. Each source maintains a Reservation Table (R.T.) which identifies the reserved slots and their assigned users. This RT is updated at each user whenever a collision is detected.

Scheme II works as follows. The system remains in state # 1 until a collision is detected. Upon detecting a collision, RT at each source is updated and the system goes to state # 2. System remains in state # 2 for N slots (when R = 0) and all collided packets are retransmitted.

Figure 3.4 shows a possible epoch developed when there is a collision for the cases when N = 4 and R = 0 & R = 3, where R is the round trip propagation delay measured in units of channel slots. Examples for the

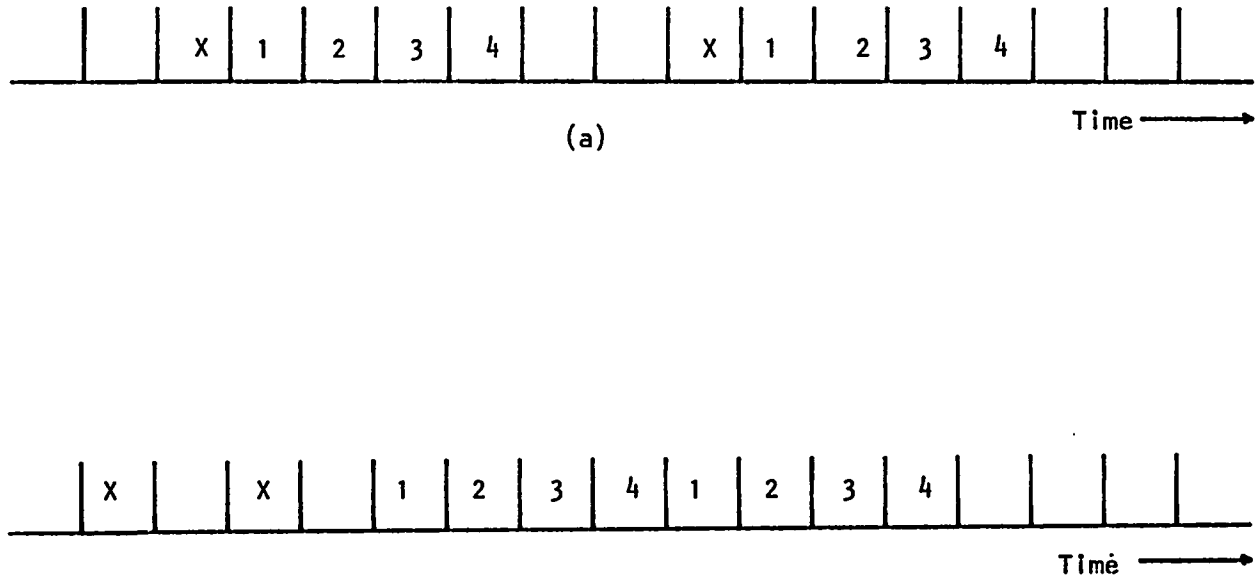


Figure 3.4. A typical epoch developed in Scheme II collision when

(a) N = 4, R = 0 (b) N = 4, R = 3.

('X' denotes a collision in that slot and a number 'k' in a slot denotes the kth user assigned slot, k = 1,2,.. N).

channels for which $R \to 0$ are coaxial cable (in case of local area network) and ground radio. The propagation delay in a satellite system is 0.27 sec., equivalent to $R = 13.5$ for $\tau = 20$ ms.

The most attractive feature of this scheme is that the maximum number of collided packets at a source is upper bounded by R. If R is an integer, there are at most $R + 1$ number of collided packets at a user's retransmission buffer; if R is not an integer, then this number is $[R]^{\dagger}$, where $[R]^{\dagger}$ is the largest integer which is not larger than $(R + 1)$. This is the main reason for the stability of this scheme.

Simulation Results

The system for scheme II was simulated on computer for 50,000 slots. A FORTRAN program was written for simulation [see appendix B.2]. The basic block diagram for program is shown in appendix (A.2). Delay throughput results are tabulated in Tables 3.3 and 3.4. Figure 3.5 shows the delay - throughput performance curves for $R = 0$ and $N = 10$, $N = 100$, while Fig. 3.6 shows the performance for $R\tau = 0.27$ sec.

3.4 SCHEME III

The channel model and Poisson source model in this scheme are same as in Scheme I except for the following additions in the channel model.

TABLE 3.3. Delay-Throughput Tradeoffs for Scheme II

Wher $R\tau = 0$ sec.

Total Traffic Intensity ρ	N = 10		N = 100	
	S	E(D) (sec)	S	E(D) (sec)
0.01	0.0092	0.0304	0.0102	0.0349
0.04	0.00395	0.0338	0.0391	0.2581
0.1	0.0985	0.044	0.0965	1.0422
0.2	0.1978	0.0701	0.1957	1.2635
0.3	0.2971	0.1201	0.2928	1.4332
0.4	0.397	0.1836	0.3917	1.6744
0.5	0.4943	0.2452	0.4893	1.9703
0.7	0.6933	0.4859	0.6844	3.1313
0.9	0.8873	3.9583	0.8791	7.8771

TABLE 3.4. Delay-Throughput Tradeoffs for Scheme II

Wher $R\tau$ = 0.27 sec.

Total Traffic Intensity ρ	N = 10		N = 100	
	S	E(D) (sec)	S	E(D) (sec)
0.01	0.0092	0.3014	0.0102	0.3059
0.04	0.0395	0.4335	0.0391	0.5706
0.1	0.0985	0.3792	0.0965	1.3421
0.2	0.1978	0.4142	0.1955	1.5335
0.3	0.2971	0.4713	0.2931	1.7215
0.4	0.3969	0.5287	0.392	1.9722
0.5	0.4942	0.5924	0.4901	2.2517
0.7	0.6933	0.8378	0.6852	3.4414
0.9	0.8871	4.3126	0.878	8.2686

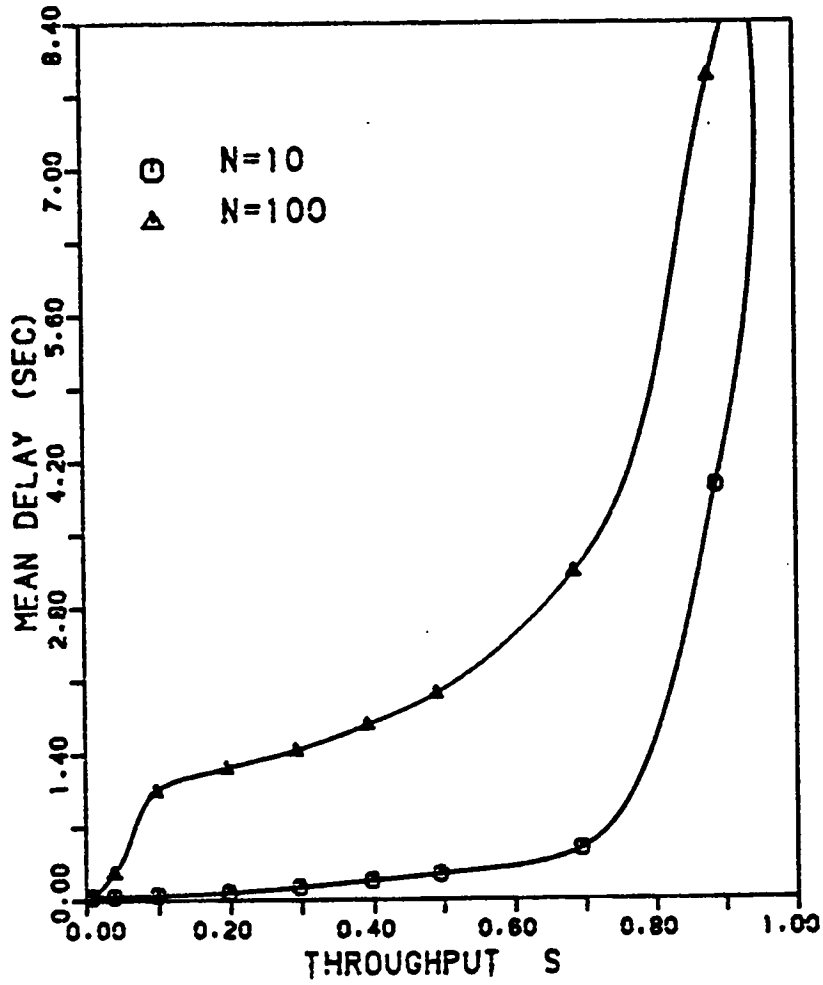


Figure 3.5. Delay-throughput performance for Scheme II when R = 0.

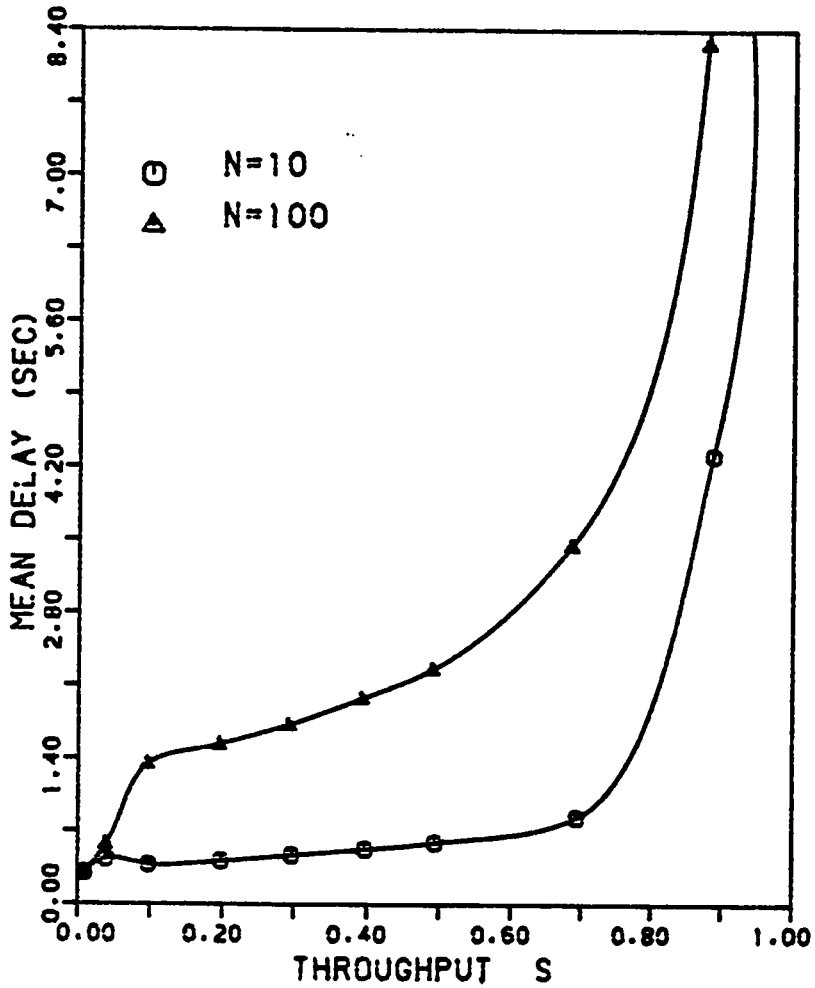


Figure 3.6. Delay-throughput performance for Scheme II when $R\tau = 0.27$ sec.

Each time slot of length τ sec is further divided into two main parts. One part of length τ_1 sec is for actual packet transmission and the other part of length $\tau_2 = \tau - \tau_1$ sec is further slotted into N mini-slots. This situation is depicted in Fig. 3.7. One mini slot is assigned to each user. When a user transmits a packet in a slot, he puts a '1' in his assigned slot, otherwise he puts a '0'. In case of a collision there are two or more '1's in the mini slots. R slots after the transmission, all users know about the origins of packets.

Scheme III is also feasible in satellite multiple access. In this report, we are considering a system with a capacity of 50 packets/sec. If the packets are 1000 bits long, then capacity is 50 Kbps. For N = 100, we have τ_1 = 18 msec and τ_2 = 2 msec. The situation can worsen for the systems with very high number of users because of large overhead.

<u>Working of Scheme III</u>

Like Scheme II, in this scheme the reservation is made only on a collision detection. The system can be in one of the following two states:

(1) State # 1 (slotted ALOHA). The users transmit in a slot whenever they have packets ready to send, and they also give their own identifications by sending signals in assigned mini slots.

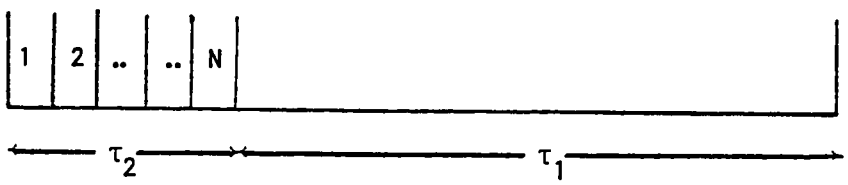


Figure 3.7. Slot subdivision in Scheme III.

(2) State # 2 (Reserved Mode). A slot is reserved for a user to retransmit a previously collided packet.

Each user maintains a Reservation Table (RT) which identifies the reserved slots and their assigned users. RT is updated at each user whenever a collision is detected. Now Scheme III works as follows.

The channel remains in state # 1 until a collision is detected. Upon detecting a collision, RT at each user is updated and the system goes to state # 2. Let the users be labelled 1, 2, ..., N. Slots are reserved for collided users with highest priority to user # 1 and the lowest to user # N (i.e. user # 1 has higher priority than user # 2 and so on). After resolving all collisions, system returns to state # 1.

Figure 3.8 shows a typical epoch developed when there is a collision for N = 4 and R = 3.

In this scheme there are at most $[R]^{\dagger}$ number of collided packets at a user's retransmission buffer, where $[R]^{\dagger}$ is the largest integer which is not larger than (R + 1). This is the main reason for the stability of this scheme.

Simulation Results

The system for Scheme III was simulated on computer for 50,000

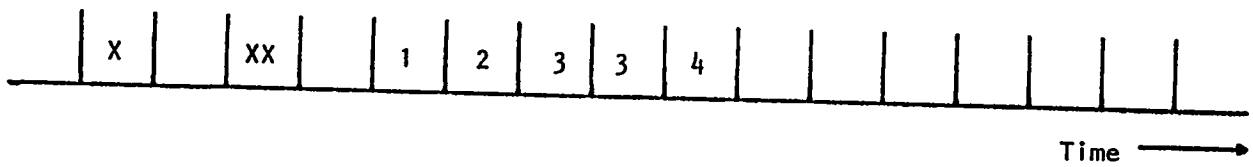


Figure 3.8. A typical epoch developed on a collision when N = 4 and R = 3 in Scheme III ('X' denotes a collision among users # 1, # 2 & # 3, and 'XX' denotes a collision between users # 3 & # 4. A number 'k' (k = 1,2,.. N) in a slot denotes the kth user assigned slot).

slots using a FORTRAN program. The block diagram for the program is given in appendix A.3 and the listing is shown in appendix B.3. Delay-throughput results are given in Tables 3.5 & 3.6. Figures 3.9 and 3.10 show the delay-throughput performance for N = 10, N = 100 for $R\tau = 0$ & $R\tau = 0.27$ sec respectively.

Scheme III is stable and changes adaptively from pure slotted ALOHA in low traffic to reserved mode in high traffic intensity. It also gives better delay-throughput performance than Scheme II. Significantly, for a wide range of throughput, system performance does not degrade with increase in the number of users. However, the actual throughput decreases with increasing N, because of greater overhead in each packet.

3.5 SCHEME IV

Motivation

An obvious drawback of Scheme III is that at very high traffic intensity ($\rho \rightarrow 1$) almost every user's packet collide first before it is retransmitted successfully in a reserved slot. When in the reservation mode of Scheme III, all users know that a particular future slot is reserved for a particular user, so there is no need to send identification signal in a user's assigned mini slot. Instead a user can give other information in those mini slots.

TABLE 3.5. Delay- Throughput Tradeoffs for Scheme III

When $R\tau$ = 0.0 sec.

Total Traffic Intensity ρ	N = 10		N = 100	
	S	E(D) (sec)	S	E(D) (sec)
0.01	0.00911	0.03	0.00918	0.03
0.04	0.03911	0.0309	0.0352	0.0306
0.1	0.09752	0.0327	0.08685	0.033
0.2	0.1958	0.0366	0.17604	0.0369
0.3	0.2941	0.0423	0.2637	0.0427
0.4	0.3930	0.0501	0.3529	0.0499
0.5	0.4894	0.0614	0.4415	0.0615
0.7	0.6865	0.1185	0.6176	0.1041
0.9	0.8824	1.0361	0.7963	0.2827

TABLE 3.6. Delay- Throughput Tradeoffs for Scheme III

When $R\tau = 0.27$ sec.

Total Traffic Intensity ρ	N = 10		N = 100	
	S	E(D) (sec)	S	E(D) (sec)
0.01	0.00911	0.3011	0.0092	0.3004
0.04	0.03911	0.3086	0.0352	0.3092
0.1	0.0975	0.3248	0.0869	0.3295
0.2	0.1957	0.3509	0.17604	0.3584
0.3	0.2941	0.3806	0.264	0.3912
0.4	0.3930	0.4191	0.3529	0.4303
0.5	0.4893	0.4742	0.4414	0.4879
0.7	0.6794	0.7487	0.6175	0.7199
0.9	0.8806	2.9872	0.7948	1.8325

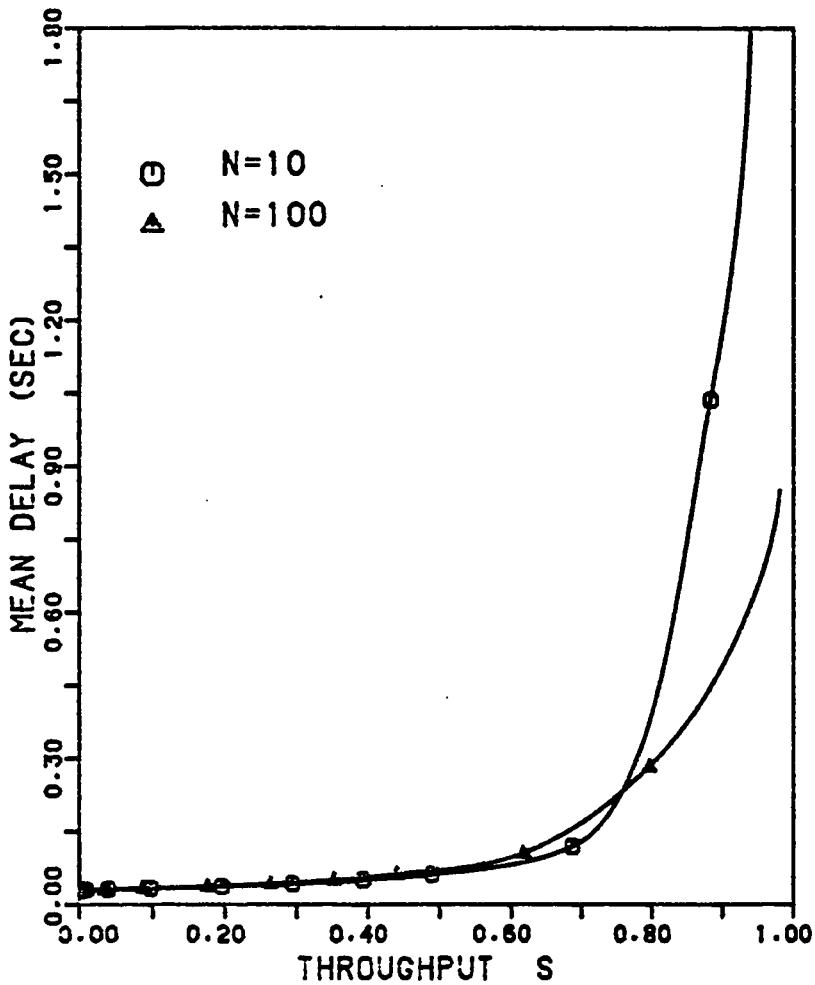


Figure 3.9. Delay throughput curves for Scheme III when R = 0.

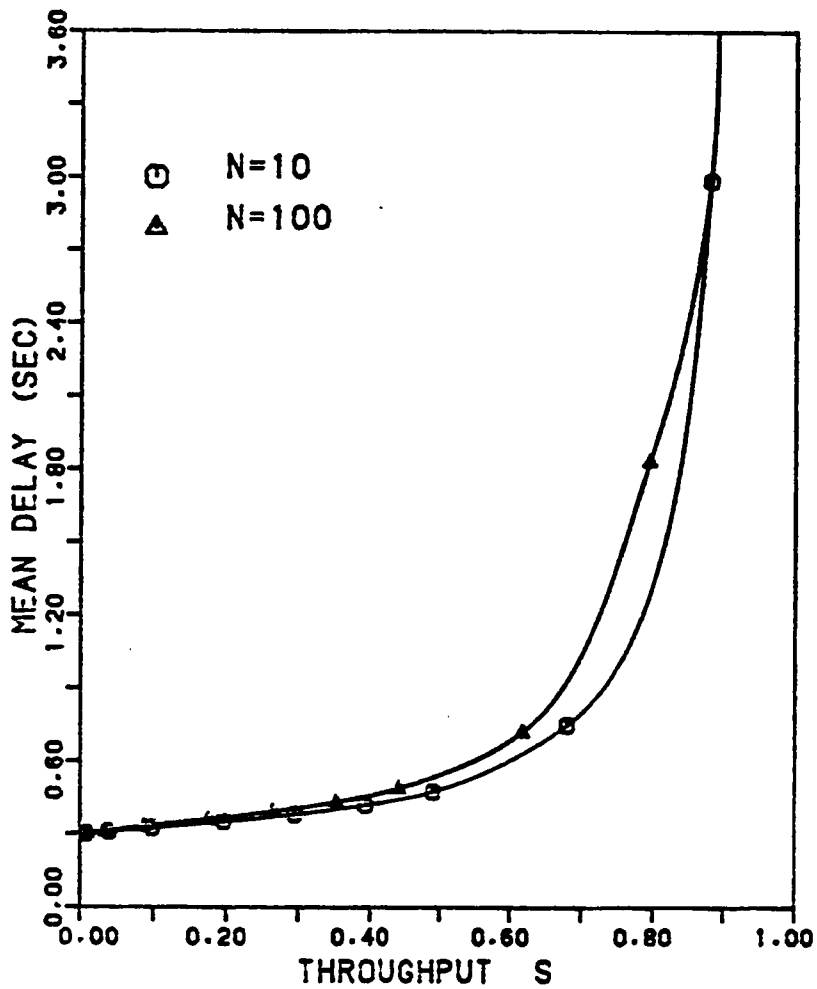


Figure 3.10. Delay throughput curves for Scheme III when $R\tau = 0.27$ sec.

Working of Scheme IV

The channel and source models for this scheme are the same as those of Scheme III except that a user can also send its queue length (of main buffer with newly arriving packets at its input) information in mini slots.

System can be in one of three states:

(1) State # 1 (slotted ALOHA). The users transmit in a slot whenever they have packets ready to send and they also give their own identifications by sending signals in their assigned mini slots.

(2) State # 2 (Reserved mode I). A slot is reserved for a user to retransmit a previously collided packet and that particular user gives its queue length information of main buffer in mini slots (excluding the packet being transmitted currently).

(3) State # 3 (Reserved mode II). Upon detecting queue length information 'r' number of slots are reserved for a user if he reports its queue length = r in state # 2.

Each user maintains a Reservation Table (RT) and a queue length table (QLT) for all users connected to the channel. RT identifies the reserved slots and

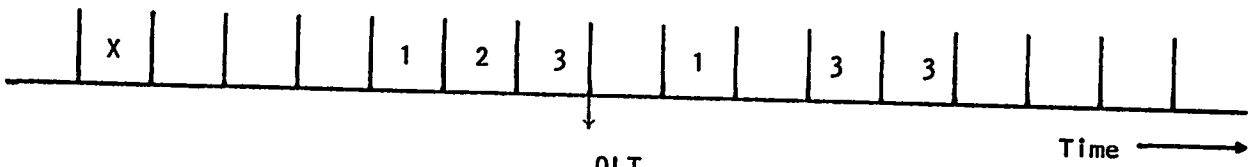
their assigned users. RT and QLT are updated and modified upon a collision detection, collision resolution and executing state # 3. Scheme IV works as follows.

The system remains in state # 1 until a collision is detected and system goes to state # 2 and collisions are resolved just like state # 2 of Scheme II. [Once a user reports its queue length it will not attempt transmission on slotted ALOHA slots (thus decreasing the probability of collision for other users) until all its reported packets are transmitted on reserved mode III slots]. Upon detecting reported queue length of a user, the system switches to state # 3. After transmitting reported packets in state # 3, system will switch to state # 1 or # 2 depending upon any collided packets waiting to be retransmitted at any source.

Figure 3.11 shows a typical situation upon detecting a collision when N = 4 and R = 3.

Simulation Results

The system for Scheme IV was simulated on computer for 50,000 slots using a FORTRAN program. The basic block diagram for the program and the listing are given in appendix A.4 & B.4 respectively. Delay- throughput tradeoffs are tabulated in Tables 3.7 and 3.8. Figures 3.12 & 3.13 show the delay- throughput performance for N = 10 & N = 100 for the cases $R\tau = 0.0$,



QLT

User	Queue Length
1	1
2	0
3	2
4	0

Figure 3.11. An example when a collision is detected in Scheme IV when N = 4 and R = 3. ('X' denotes a collision between user # 1, # 2 & # 3, and a number 'k' in a slot represents a kth user assigned slot).

TABLE 3.7. Delay- Throughput Tradeoffs for Scheme IV

When $R\tau = 0$ sec.

Total Traffic Intensity ρ	N = 10		N = 100	
	S	E(D) (sec)	S	E(D) (sec)
0.01	0.0091	0.03	0.009	0.03
0.04	0.0391	0.0309	0.0357	0.0307
0.1	0.0975	0.0326	0.0871	0.0329
0.2	0.1958	0.0364	0.1766	0.0371
0.3	0.2941	0.0417	0.2644	0.0432
0.4	0.3903	0.0487	0.3524	0.0502
0.5	0.4894	0.058	0.4402	0.0606
0.7	0.6865	0.0975	0.6186	0.1029
0.9	0.883	0.2717	0.7959	0.2611

TABLE 3.8. Delay- Throughput Tradeoffs for Scheme IV

When $R\tau = 0.27$ sec.

Total Traffic Intensity ρ	N = 10		N = 100	
	S	E(D) (sec)	S	E(D) (sec)
0.01	0.0091	0.3011	0.009	0.3
0.04	0.0391	0.3086	0.0357	0.3084
0.1	0.0975	0.3256	0.0871	0.3288
0.2	0.1957	0.3514	0.1766	0.3589
0.3	0.2941	0.3816	0.2644	0.3951
0.4	0.393	0.4182	0.3524	0.4344
0.5	0.4893	0.4695	0.4401	0.4853
0.7	0.6864	0.6264	0.6181	0.6824
0.9	0.8813	2.2646	0.7947	1.5036

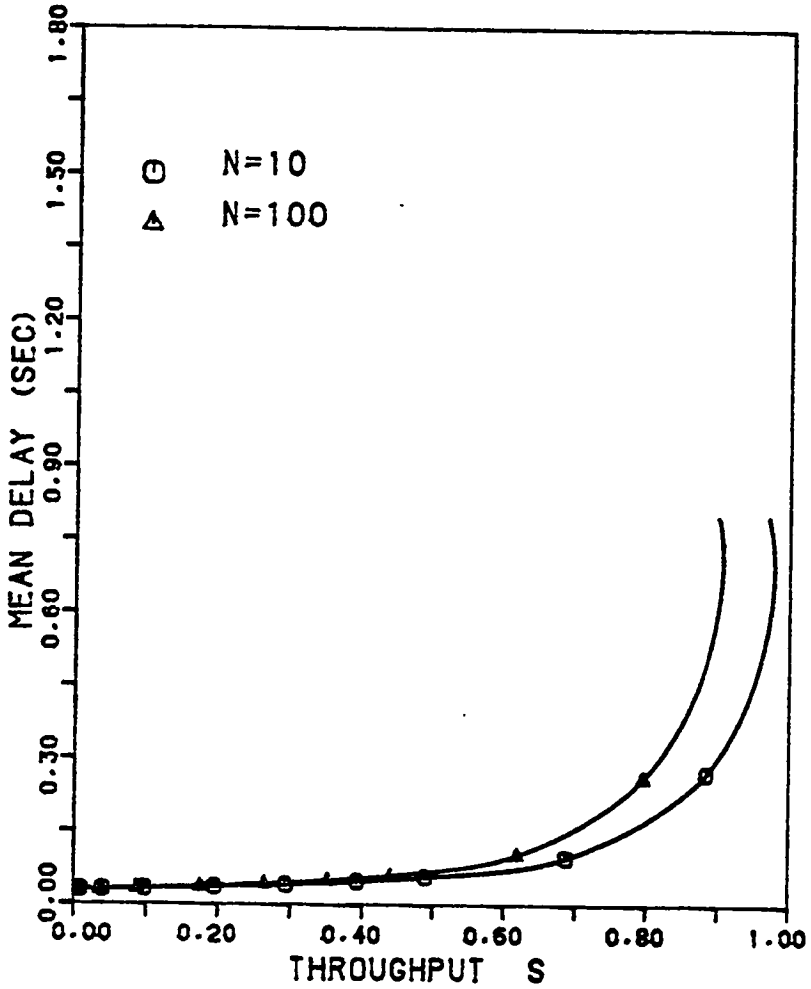


Figure 3.12. Delay throughput curves for Scheme IV when $R\tau = 0$.

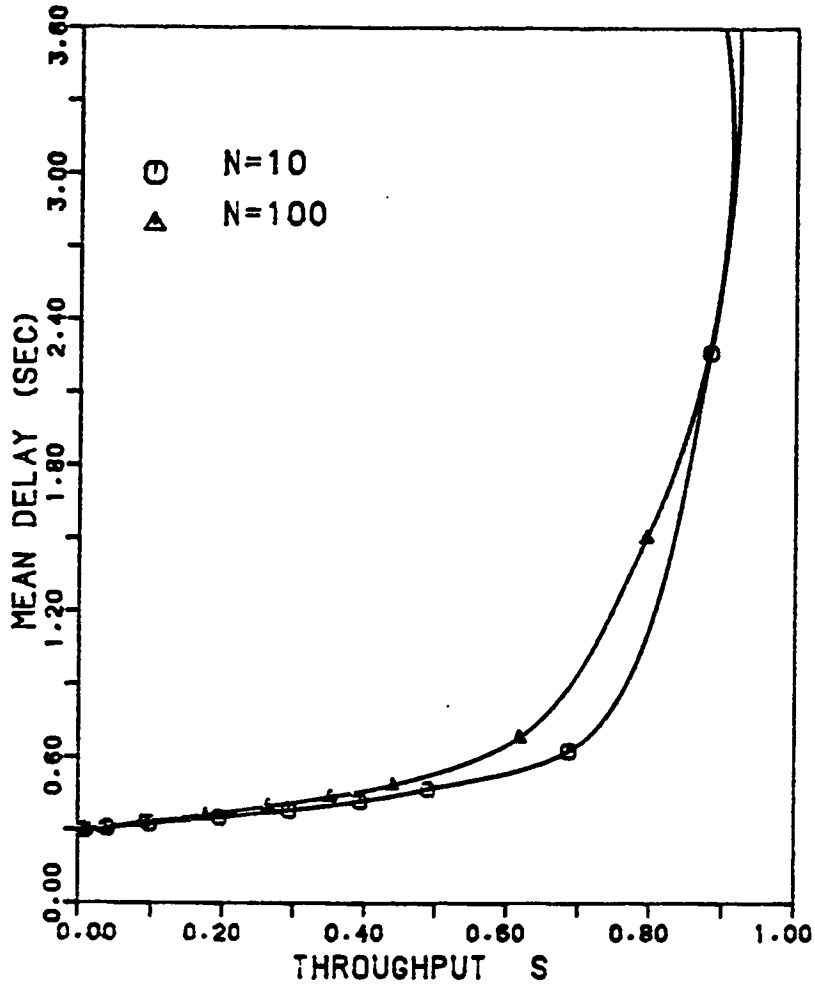


Figure 3.13. Delay throughput curves for Scheme IV when $R\tau = 0.27$ sec.

and $R\tau = 0.27$ sec respectively. In this scheme also, there are at most $[R]^{\dagger}$ number of collided packets at a user's retransmission buffer. The delay throughput performance has improved significantly; however this has been achieved at the expense of greater system complexity. The system is stable and is immune to the number of users over a large range of throughput, unlike TDMA in which delay increases with N, even if total traffic is maintained constant.

Chapter 4

DELAY ANALYSES

4.1 INTRODUCTION

In this chapter, we shall present the delay analyses for the four proposed multiple access schemes (see chapter 3 for the details of schemes). We shall find expression for average delay of a packet in each scheme in which infinite buffers are assumed at each source. The simulation results will be compared with analytical ones.

The following notations will be used throughout this chapter:

N = no. of identical users

τ = slot width (sec.)

λ = Average no. of packets generated per sec by a single source (Poisson distributed)

$E(D)$ = average delay of an accepted packet (sec.)

p = P [a source transmits a newly generated packet in a given slot in a pure S-ALOHA situation]

= $\lambda\tau$ [28], [29]

p_s = P [of finding system in slotted ALOHA mode]

ρ_t = total traffic intensity of newly generated packets in the system

$= N\lambda\tau$ packets/slot

$R =$ round trip propagation delay in slots.

4.2 SCHEME I - DELAY ANALYSIS

We shall present the delay analysis for $R \approx 0$ channels first, then we shall extend the results for $R > 0$ cases.

Let the packets arriving at each source obey Poisson statistics with a mean of λ packets/sec, and further let:

$G_{SAL} =$ total traffic intensity in S-ALOHA slots (packets/slot)

$S_{SAL} =$ throughput in S-ALOHA slots (packets/slot)

$\therefore \quad G_{SAL} = S_{SAL} +$ average no. of retransmission to be required per slot

$$G_{SAL} = S_{SAL} + G_{SAL}(1 - e^{-G_{SAL}})$$

Thus

$$\frac{G_{SAL}}{S_{SAL}} = e^{G_{SAL}} = E + 1 \qquad (4.1)$$

where E is the average number of retransmissions required per successful packet transmitted in S-ALOHA slots. Now

$$p_s = \left(\frac{\alpha}{\alpha+\beta N}\right)$$

$$\therefore \qquad G_{SAL} = N\lambda\tau \cdot \left(\frac{\alpha}{\alpha+\beta N}\right) \qquad (4.2)$$

The total input traffic rate to each TDMA frame will be higher than $N\lambda\tau$ (packets/slot) due to collisions in the previous S-ALOHA slot (as we retransmit all our collided packets in TDMA slots only). Let the total traffic to TDMA slots form an independent Poisson process with mean $N\lambda'\tau$ where

$N\lambda'\tau = N\lambda\tau + E \cdot N\lambda\tau$

or

$$\lambda' = \lambda\,(1 + E)$$

From Eqns. (4.1) and (4.2)

$$\lambda' = \lambda\, e^{N\lambda\tau\left(\frac{\alpha}{\alpha+\beta N}\right)} \qquad (4.3)$$

There are three contributions to the average delay of an accepted packet, E(D).

The first contribution is the average delay which a newly generated packet suffers in S-ALOHA mode. In this mode, system is equivalent to M/D/1 queue and the delay formula (see [30]) can be used. Furthermore, we have an additional delay of $\tau/2$ sec due to slotting of the broadcast channel. Thus the first contribution is

$$\left(\frac{\alpha}{\alpha+\beta N}\right)\left[1.5\tau + \frac{\lambda\tau^2}{2(1-\lambda\tau)}\right]$$

The second contribution is the average time a packet spends in TDMA mode. Lam [31] has analyzed a TDMA system with infinite buffer. Applying his results to our case in which average input rate is $N\lambda'\tau$ (packets/slot), we have

$$\left(\frac{\beta N}{\alpha+\beta N}\right)\left[\frac{N\tau}{2} + \tau + \frac{\lambda' N^2\tau^2}{2(1-N\lambda'\tau)}\right]$$

The third contribution is the passive waiting time of a collided packet. For each retransmission we have an average delay of $(\frac{\alpha}{2})$ slots. Thus from Eqns. (4.1) & (4.2), the third contribution is

$$\left[e^{N\lambda\tau\left(\frac{\alpha}{\alpha+\beta N}\right)} - 1\right] . \left[\frac{\alpha\tau}{2}\right]$$

Therefore, the total packet delay is

$$E(D)\Big|_{R=0} = \left(\frac{\alpha}{\alpha+\beta N}\right) . \left[1.5\tau + \frac{\lambda\tau^2}{2(1-\lambda\tau)}\right] +$$

$$+ \left(\frac{\beta N}{\alpha+\beta N}\right)\left[\frac{N\tau}{2} + \tau + \frac{\lambda' N^2\tau^2}{2(1-N\lambda'\tau)}\right]$$

$$+ \left[e^{N\lambda\tau\left(\frac{\alpha}{\alpha+\beta N}\right)} - 1\right] . \left[\frac{\alpha\tau}{2}\right] \text{ sec} \qquad (4.4)$$

For $R > 0$, a packet needs at least $R\tau$ sec to get transmitted through the channel in each mode. In addition, for each retransmission we have a delay of $(\frac{\alpha}{2} + R)$ slots. Thus for $R > 0$,

$$E(D)\Big|_{R>0} = E(D)\Big|_{R=0} + R\tau + [e^{N\lambda\tau(\frac{\alpha}{\alpha+\beta N})} - 1] \cdot [R\tau] \text{ sec} \quad (4.5)$$

Simulation and analytical results are compared in Table 4.1 for $N = 10$, $\alpha = 1$ and $\beta = 2$. These results are also shown in Fig. 4.1.

4.3 DELAY ANALYSIS - SCHEME II

We shall first describe a procedure to find p_s. When the system is in slotted ALOHA mode continuously, the system capacity is obviously $1/\tau$ sec packets/sec, and a user transmits a packet in a slot with probability $p = \lambda\tau$. When $p_s < 1$, the effective system capacity decreases because a user is blocked with probability $(1 - p_s)$. The effective system capacity is thus $p_s \cdot \frac{1}{\tau}$. Thus the probability with which a user transmits a newly generated packet in a slot is

$$p_t = \frac{\lambda\tau}{p_s} \quad (4.6)$$

Let p_c be the probability of collision in S-ALOHA mode, then

TABLE 4.1. Comparison Between Simulation & Analytical Results for Scheme I for N = 10, α = 1 and β = 2.

Total Traffic Intensity	$R\tau$ = 0.0 sec		$R\tau$ = 0.27 sec	
	Analytical E(D) sec	Simulated E(D) sec	Analytical E(D) sec	Simulated E(D) sec
0.01	0.1165	0.1042	0.3866	0.3796
0.04	0.1197	0.1094	0.3902	0.395
0.1	0.1264	0.122	0.3977	0.4285
0.2	0.140	0.1405	0.4126	0.4747
0.3	0.1576	0.1652	0.4315	0.5168
0.4	0.1815	0.1955	0.4567	0.5591
0.5	0.216	0.2377	0.4925	0.608
0.7	0.366	0.4215	0.6452	0.7943
0.9	1.593	1.8099	1.875	2.1636

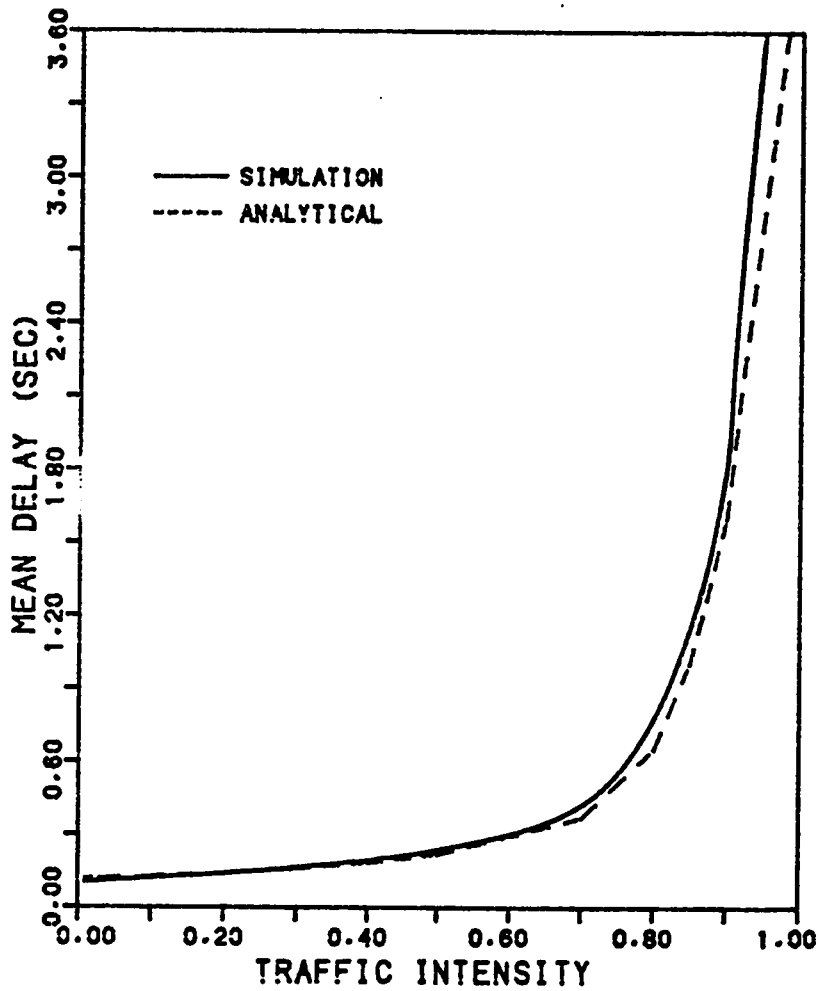


Figure 4.1(a). Comparison between analytical and simulation results for Scheme I for $N = 10$, $\alpha = 1$, $\beta = 2$ and $R\tau = 0$.

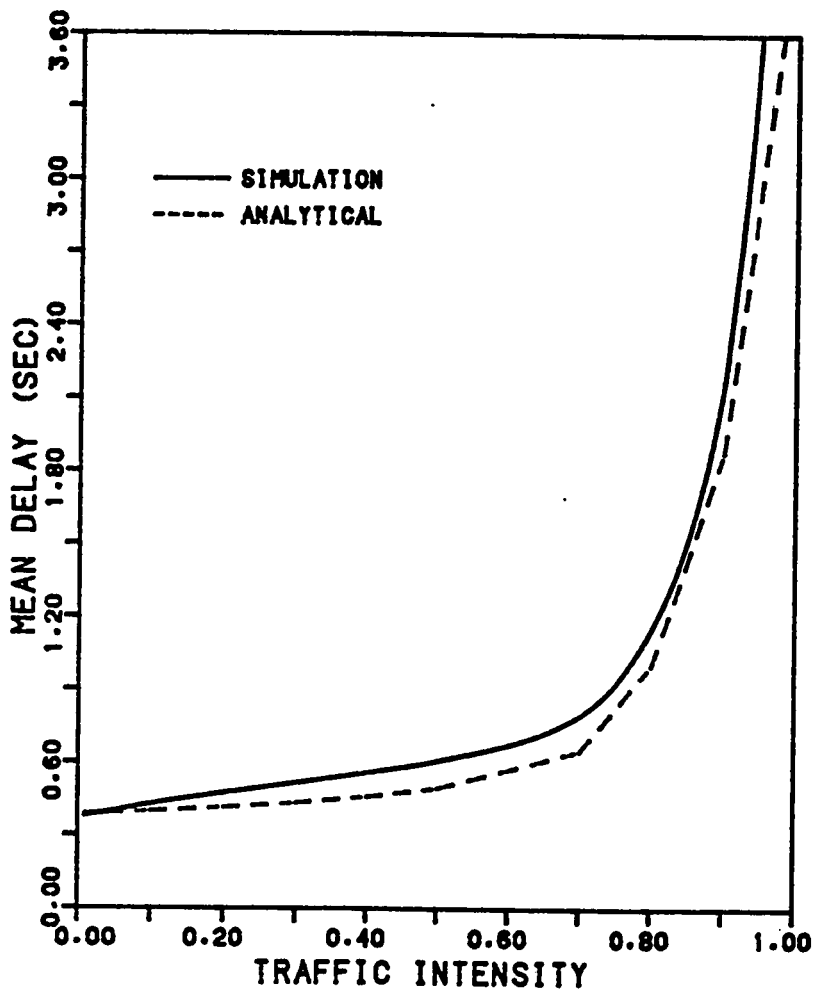


Figure 4.1(b). Comparisons between analytical and simulation results for Scheme I for $N = 10$, $\alpha = 1$, $\beta = 2$ and $R\tau = 0.27$ sec.

$$p_c = \sum_{k=2}^{N} \binom{N}{k} p_t^{\,k} (1 - p_t)^{N-k} \tag{4.7}$$

$$= 1 - [\,P(0 \text{ arrival}) + P(1 \text{ arrival})]$$

$$= 1 - [(1 - p_t)^N + \binom{N}{1} p_t (1 - p_t)^{N-1}]$$

$$\therefore\ p_c = 1 - [(1 - \frac{\lambda\tau}{p_s})^N + \frac{N\lambda\tau}{p_s} \cdot (1 - \frac{\lambda\tau}{p_s})^{N-1}] \tag{4.8}$$

Thus

$$P(\text{ system in TDMA mode }) = Np_s p_c$$

But

$$P(\text{S-ALOHA mode}) + P(\text{TDMA mode}) = 1$$

$$\therefore\ p_s + Np_s \cdot [1 - (1 - \frac{\lambda\tau}{p_s})^N - \frac{N\lambda\tau}{p_s}(1 - \frac{\lambda\tau}{p_s})^{N-1}] = 1 \tag{4.9}$$

The above equation is a transcendental equation in p_s, thus only numerical methods can be used to solve for p_s.

Newton-Raphson iterative method is used to calculate p_s. Table 4.2 gives a comparison between simulated and calculated p_s. Comparison of analytical and simulated results show that there is excellent agreement

TABLE 4.2. Comparison Between Simulated and Calculated (Newton Raphson Solution) p_s for Scheme II for N = 10.

Total Traffic Intensity ρ_t	p_s	
	Calculated	Simulated
0.01	0.9996	0.9998
0.04	0.9930	0.9936
0.1	0.9550	0.9538
0.2	0.8040	0.803
0.3	0.120	0.5242
0.4	0.094	0.2604
0.5	0.0913	0.1318
0.7	0.091	0.092
0.9	0.091	0.0912

between the results for low and high values of total traffic intensity. However for intermediate values of ρ_t, the analytical results for p_s are smaller. This was expected because the mathematical model deviates from the physical model; in particular, the deviation is more significant for the intermediate values of ρ_t. In the mathematical model, there is an implied assumption that all newly generated packets are first transmitted in a random access slot, which upon collision will be retransmitted during a reserved TDMA frame. However in the physical model, some packets generated in a TDMA frame can indeed be transmitted in the same frame if the user in question was not involved in a collision just prior to the beginning of the TDMA frame. Thus the probability of collision is higher for the mathematical model and consequently p_s will be smaller. For low values of ρ_t, there is very little collision; for high values of ρ_t, the probability that a large number of users collide simultaneously is high. Thus for these low and high values of ρ_t, analytical results for p_s, although smaller than simulation results are nearly the same.

We shall first determine E(D) for the channel with R = 0 and then we shall extend these results for channels with R > 0.

The basic assumption in our model for delay analysis is that a newly generated packet attempts its first transmission on a S-ALOHA slot, i.e. the service for newly generated packets is closed in TDMA mode. Due to this assumption, we expect slightly higher delay as compared to the simulated one.

The average delay of a newly generated packet is

$$E(T) = E(W) + \bar{x} \tag{4.10}$$

where E(W) is the average waiting time in the transmission queue and $\bar{x}$ is the average service time for a newly generated packet. The service time is τ sec in S-ALOHA mode while it is (N+1) τ sec while the system is in TDMA mode (In actual practice, the service time, for the packets generated in TDMA frame when the retx. buffer is empty, will be in general less than (N+1) τ. But due to our basic assumption, we are neglecting such a situation). Now

$$E(x) = \bar{x} = (1 - p_c^{'})\,\tau + p_c^{'}\,(N + 1)\,\tau \tag{4.11}$$

where $p_c^{'}$ is the probability of collision at the time of servicing a packet from the transmission queue. Therefore, $p_c^{'}$ is simply the probability of one or more transmissions from the remaining (N-1) users. Thus

$$p_c^{'} = 1 - (1 - p_t)^{N-1} \tag{4.12}$$

where $p_t = \lambda\tau/p_s$.

Also

$$E(x^2) = (1 - p_c^{'})\,\tau^2 + p_c^{'}\,(N + 1)^2\,\tau^2 \tag{4.13}$$

We can model the buffer behavior at a user as M/G/1 queue. Thus from [30], [36]

$$E(W) = \frac{\lambda}{2} \cdot \frac{E(x^2)}{1-\rho} \tag{4.14}$$

where

$$\rho \triangleq \lambda \bar{x}$$

and thus the average delay of a newly generated packet is

$$E(T) = \frac{\lambda}{2} \cdot \frac{E(x^2)}{1-\rho} + \bar{x} \tag{4.15}$$

Each collided packet has to wait for $\frac{N\tau}{2}$ sec on the average before it is retransmitted. Hence the total packet delay is

$$E(D) = E(T) + p_c' \frac{N\tau}{2} + \frac{\tau}{2} \text{sec} \tag{4.16}$$

where the term $\frac{\tau}{2}$ on RHS is added to account for the time slotting of channel.

This analytical model is expected to give higher values of delay because the assumption that all newly generated packets are first transmitted in a random access slot is too pessimistic. The model can be improved by calculating λ', the effective message arrival rate into the transmission queue in the following way:

$$\lambda' = \lambda - (1 - p_s)\, p_o\, \lambda \tag{4.17}$$

where p_o is the probability that the transmission queue buffer is empty at the beginning of a reservation frame. We can use simulated value of p_o. In this analysis, λ' is calculated by eliminating a newly arrived packet during a reservation frame, if at the same time the queue is empty. At higher values of traffic intensity, this may again become too optimistic since the number of newly arrived packets in such a mode may be more than one. Only one of them can be serviced in this mode, the remaining must go to the transmission queue.

Effect of Nonzero Propagation Delay

For $R > 0$, a packet needs at least $R\tau$ sec to get transmitted through the broadcast channel. Moreover, the collided packets have to wait for R slots before a TDMA frame is reserved. Thus, for $R > 0$, E(D) becomes

$$E(D)|_{R>0} = E(D)|_{R=0} + R\tau + p_c'(R\tau) \tag{4.18}$$

Analytical and simulated results for $N = 10$ are compared in Table 4.3 and are plotted in Fig. 4.2. The analytical and simulated results show a close agreement. The main reason for slight discrepancy between analytical and simulated results for $R = 0$ is due to the assumptions in the mathematical model which have been discussed earlier. For $R\tau > 0$, we have assumed the same service time distributions as in the case of $R\tau = 0$. However, this is

TABLE 4.3. Comparison Between Analytical and Simulated Average Delays for Scheme II (N = 10).

Total Traffic Intensity ρ_t	Simulated p_o	$R\tau = 0$ sec		$R\tau = 0.27$ sec	
		Analytical Delay (sec)	Simulated Delay (sec)	Analytical Delay (sec)	Simulated Delay (sec)
0.01	0.80	0.0327	0.0304	0.3051	0.3014
0.04	0.7844	0.0409	0.0338	0.3205	0.3335
0.1	0.7494	0.0583	0.044	0.3527	0.3792
0.2	0.6955	0.0955	0.0701	0.4203	0.4142
0.3	0.6301	0.1653	0.1201	0.5464	0.4713
0.4	0.5453	0.2916	0.1836	0.7713	0.5287
0.5	0.4522	0.380	0.2452	0.9163	0.5924
0.7	0.2370	0.498	0.4859	1.038	0.8378
0.9	0.0238	3.7207	3.9583	4.261	4.3126

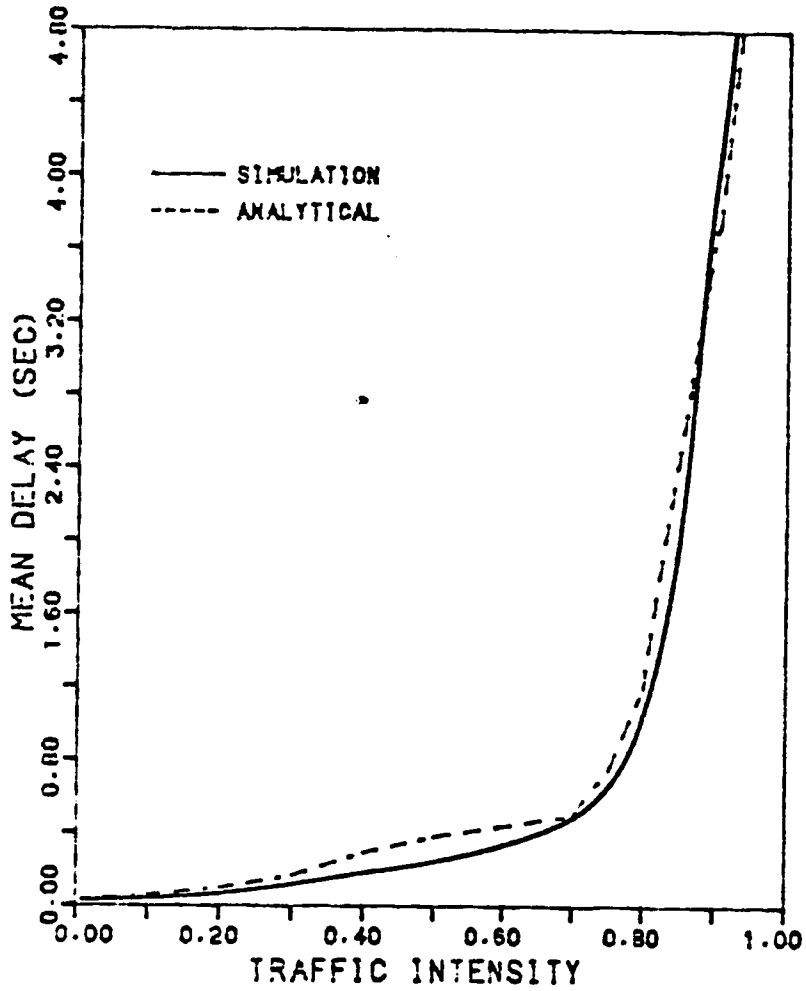


Figure 4.2(a). Comparison between analytical and simulated delay for Scheme II for N = 10 and $R\tau$ = 0.0 sec.

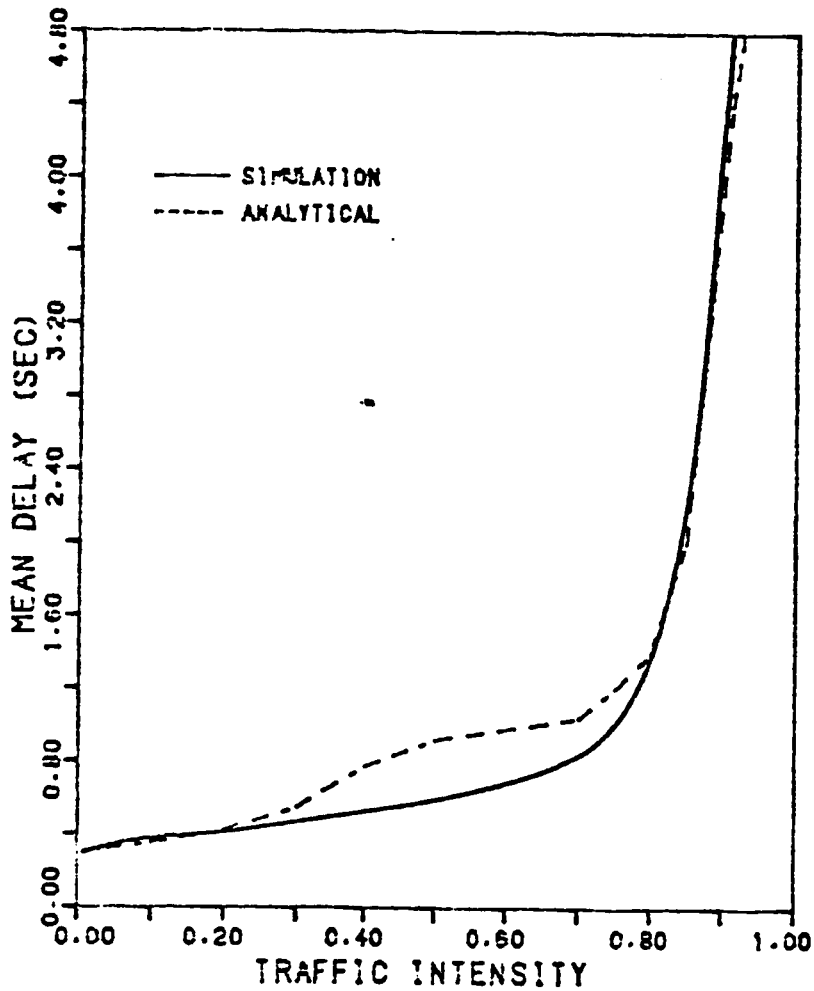


Figure 4.2(b). Comparison between analytical and simulated delay for Scheme II ($N = 10$, $R\tau = 0.27$ sec).

not quite correct. In the first case the service time is a random variable x with two possible values - τ and $(N+1)\tau$ with probabilities $(1-p_c')$ and p_c'. When $R > 0$, x varies between τ and $(RN+1)\tau$ with a certain probability density function. Evaluation of this probability density function would be very difficult and therefore as an approximation, we use the pdf of the previous case i.e. $R = 0$. At low values of traffic intensity, the probability of consecutive collisions are very low and thus the approximation does not cause too much error.

4.4 SCHEME III - DELAY ANALYSIS

We shall first explain a procedure to find p_s in this scheme for $R = 0$.

A packet which had a collision and is waiting for retransmission is said to be backlogged and the user which has such a collided packet in its retransmission buffer is also called backlogged (or in retransmission mode). For $R = 0$, no newly generated packet is transmitted until the collision is resolved, so each user can have at most one backlogged packet in this scheme.

The channel may be viewed as a discrete time system with N+1 possible states, corresponding to the number X_n of users in the retransmission mode at the beginning of the nth slot (n = 1,2,3,...). The sequence of system states (which are random variables X_1, X_2, ...) forms a discrete time Markov chain $X = \{X_n; n > 0\}$ with state-transition matrix $\underline{P} = \{p_{ij}\}$ where

$$p_{ij} = P\,[X_{n+1} = j \mid X_n = i] \tag{4.19}$$

and where

$$i, j \in \{0, 1, 2, \ldots, N\}$$

The probabilities p_{ij}s are called the transition probabilities for the Markov Chain (MC) X, and a MC X satisfying Eqn. (4.19) is called time-homogeneous (i.e. p_{ij} are independent of n) [30], [32].

Figure 4.3 shows the allowed transitions for Scheme III when N = 4. Once the system is at state k (k > 0), the state cannot increase during any subsequent slots until the system returns to state 0. Decreases in state are always in units of one, since the number of users in retransmission mode can be reduced by one during a single slot. The transition from 0 to 1 is impossible, because if there is no user in retranmission mode (i.e. we are in S-ALOHA mode) and exactly one user decides to send a packet, the transmission will always be successful. Based upon the arguments at the beginning of section (4.3), the probability (p_t) with which a user transmits a newly generated packet in a slot is

$$p_t = \frac{\lambda\tau}{p_s} .$$

we have the following comments about the transition probabilities.

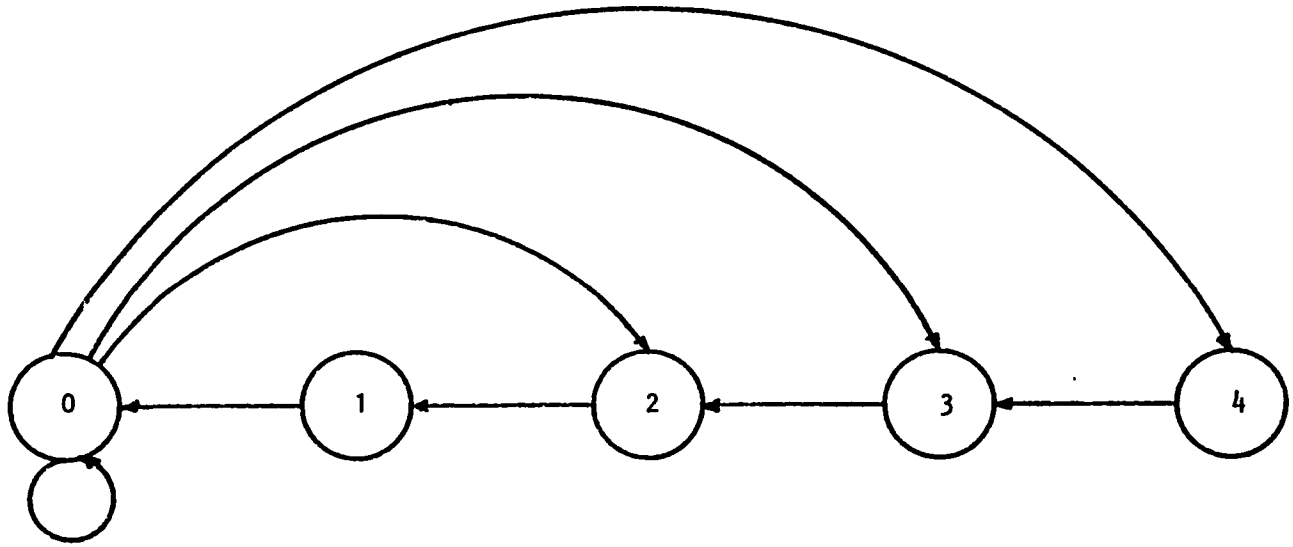


Figure 4.3. Allowed transitions for Markov model of Scheme III when N = 4.

a) $p_{ij} = 0 \,, \quad j \leq i - 2$

b) $p_{i,i-1} = 1 \,, \quad i \neq 0$

c) $p_{ij} = 0 \,, \quad i \neq 0$

$$p_{oo} = (1-p_t)^N + Np_t\,(1-p_t)^{N-1}$$

d) $p_{i,i+1} = 0 \,, \quad \forall\, i$

and

e) $p_{ij} = 0 \,, \quad i \neq 0,\, j > i$

$$p_{oj} = \binom{N}{j} p_t^j\,(1 - p_t)^{N-j}, \quad j \geq 2$$

Thus we can construct $\underline{P} = \{p_{ij}\}$ which is a (N+1) x (N+1) matrix.

Now the Markov Chain $X = \{X_n;\, n > 0\}$ is irreducible, aperiodic and positive recurrent (see [30], [32] for definitions), thus

$$\underline{\pi} = \underline{\pi} \cdot \underline{P} \tag{4.20}$$

where

$$\underline{\pi} = [\pi_0, \pi_1, \pi_2, \ldots, \pi_N] \tag{4.21}$$

is a vector of equalibrium state probabilities and where

$$\pi_j = \lim_{n \to \infty} P[X_n = j] \tag{4.22}$$

We are interested in π_o which is the probability that there is no user in retransmission mode and which is also the probability of finding the system in slotted ALOHA mode, so

$$p_s = \pi_o \tag{4.23}$$

But (N+1) Eqns. in (4.20) are transcendental in π_o. Numerical techniques can be applied to solve Eqns. (4.20) for $\underline{\pi}$ along with the condition

$$\sum_{k=0}^{N} \pi_k = 1 \tag{4.24}$$

To check the validity of Markov model, Gauss Seidle iterative method was used to solve Eqns. (4.20) & (4.24) for $\underline{\pi}$ when N = 10. These results show an excellent agreement with the simulated value of p_s as depicted in Table 4.4.

To illustrate the above concept an example is illustrated for N = 3 and $\lambda\tau = 0.1$. Now

$$\underline{\pi} = \underline{\pi} \cdot \underline{P}$$

TABLE 4.4. Comparison Between Analytical and Simulated Values of p_s for Scheme III for N = 10.

Total Traffic Intensity	p_s Analytical	p_s Simulated
0.01	0.9999	1
0.04	0.9986	0.9992
0.1	0.99128	0.9927
0.2	0.9657	0.968
0.3	0.9228	0.9138
0.4	0.8606	0.8392
0.5	0.7742	0.7463
0.7	0.41216	0.4274
0.9	0.1160	0.1132

where $\underline{\pi} = [\pi_0 \quad \pi_1 \quad \pi_2 \quad \pi_3]$ and

$$\underline{P} = \begin{bmatrix} p_{00} & 0 & p_{02} & p_{03} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

where

$$p_{00} = (1 - \frac{0.10}{\pi_0}) + 3\,(\frac{0.10}{\pi_0})\,(1 - \frac{0.10}{\pi_0})^2$$

$$p_{02} = \binom{3}{2}(\frac{0.10}{\pi_0})^2 \,.\, (1 - \frac{0.10}{\pi_0})$$

$$= 3\,(\frac{0.10}{\pi_0})^2\,(1 - \frac{0.10}{\pi_0})$$

and

$$p_{03} = (\frac{0.10}{\pi_0})^3$$

Now we have the following set of equations.

$$\pi_0 = (1 - \frac{0.1}{\pi_0})^3 \,.\, \pi_0 + 0.3\,(1 - \frac{0.1}{\pi_0})^2 + \pi_1$$

$$\pi_1 = \pi_2$$

$$\pi_2 = 0.3\left(\frac{0.1}{\pi_0}\right)^2 \left(1 - \frac{0.1}{\pi_0}\right) \pi_0 + \pi_3$$

$$\pi_3 = p_{03}\, \pi_0 = \frac{(0.1)^3}{\pi_0^2}$$

and $$\pi_0 + \pi_1 + \pi_2 + \pi_3 = 1$$

Gauss Seidle iterative method is used to solve the above equations, and we have the following results:

$$\pi_0 = 0.9114$$

$$\pi_1 = 0.0305$$

$$\pi_2 = 0.0305$$

and $$\pi_3 = 0.0276$$

We shall first find an expression for E(D) for the broadcast channel with R = 0 and then we shall extend these results for channels with R > 0.

The average delay of a newly generated packet is

$$E(T) = E(W) + \bar{x} \tag{4.25}$$

where E(W) is the average waiting time and $\bar{x}$ is the average service time for a newly generated packet. The service time is τ sec in S-ALOHA mode. To find average service time in reserved mode, let us first find the average number of collided packets resulting from a collision in a S-ALOHA slot. Let this number be $\bar{j}$. Now

$$P(j \text{ arrivals in a S-ALOHA slot}) = p_s \binom{N}{j} p_t^j (1 - p_t)^{N-j}$$

and

$$P(\text{collision}) = P(j \geq 2) = p_s[1 - (1-p_t^N) - Np_t(1-p_t)^{N-1}]$$

The probability of j arrivals, given that a collision has taken place is

$$\rho(j|j \geq 2) = \frac{\binom{N}{j} p_t^j (1-p_t)^{N-j}}{1-(1-p_t)^N - Np_t(1-p_t)^{N-1}} \quad , \quad j \geq 2$$

$$= p_j \text{ (say)}$$

$$\therefore \bar{j} = \sum_{j=2}^{N} j p_j \tag{4.26}$$

Thus the service time is $(\tau + \bar{j}\tau)$ when the system is in reserved mode. Thus the average service time is

$$E(x) = \bar{x} = (1-p_c^{'})\,\tau + p_c^{'}\,(\tau + \bar{j}\,\tau) \tag{4.27}$$

where $p_c^{'}$ is given by Eqn. (4.12).

Also

$$E(x^2) = (1-p_c^{'})\,\tau^2 + p_c^{'}\,(\tau + \bar{j}\,\tau)^2 \tag{4.28}$$

Now we can model the buffer behavior at a user as an M/G/1 queue, thus

$$E(T) = \frac{\lambda}{2} \cdot \frac{E(x^2)}{1-\rho} + \bar{x} + \frac{\tau}{2} \text{ sec} \tag{4.29}$$

where $\rho = \lambda\bar{x}$ and E(T) is the average delay of a newly generated packet. The term $\tau/2$ on RHS of Eqn. (4.29) is added to account for the time slotting of channel. In addition to E(T), each collided packet has a delay of $(\frac{\bar{j}}{2}\,\tau + \frac{\tau}{2})$ sec. Hence the average packet delay is

$$E(D) = E(T) + p_c^{'}(\frac{j}{2}\,\tau + \frac{\tau}{2}) \tag{4.30}$$

<u>Effect of Nonzero Propagation Delay</u>

For $R > 0$, a packet needs at least $R\tau$ sec to get transmitted through the channel. Each collided packet has to wait for R slots before reservation mode starts. Thus for $R > 0$,

$$E(D)|_{R>0} = E(D)|_{R=0} + R\tau + p_c'(R\tau) \tag{4.31}$$

Simulation and analytical results are compared for N = 10 in Table 4.5 and are plotted in Fig. 4.4. These results show a close agreement. The difference between the analytical model and the physical model which was encountered in Scheme II is significantly reduced here. In this scheme (R=0) when the system goes into a reservation mode only the collided users have reserved slots. Thus all new packets generated during the reserved mode must be routed through the basic transmission queue.

However for R > 0, the assumptions about the pdf of the service time random variable x is again somewhat inaccurate, particularly for higher values of traffic intensity. Discussions relating to the pdf of x in section 4.3 are relevant here also.

4.5 SCHEME IV - DELAY ANALYSIS

The exact delay analysis for Scheme IV becomes very complicated due to correlated total input traffic and a decision process at a slot while the system is in states # 2 and # 3. We present here an approximate analysis for $R \approx 0$ channels only. One major difficulty arises when one tries to find an analytical expression for p_s. An important result which we deduce from our simulation study of multiple access Scheme IV is that p_s is almost independent of the number of users (N) and it depends only on ρ_t. These results are

TABLE 4.5. Comparison Between Analytical and Simulated Delays for Scheme III (N=10).

Total Traffic Intensity ρ_t	$R\tau = 0$ sec		$R\tau = 0.27$ sec	
	Analytical Delay (sec)	Simulated Delay (sec)	Analytical Delay (sec)	Simulated Delay (sec)
0.01	0.0306	0.03	0.303	0.3011
0.04	0.0325	0.0309	0.3121	0.3086
0.1	0.0363	0.0327	0.3299	0.3248
0.2	0.0428	0.0366	0.3592	0.3509
0.3	0.0497	0.0423	0.3892	0.3806
0.4	0.0576	0.0501	0.4217	0.4191
0.5	0.0671	0.0614	0.4591	0.4742
0.7	0.1118	0.1185	0.6012	0.7487
0.9	0.5989	1.0361	1.139	2.9872

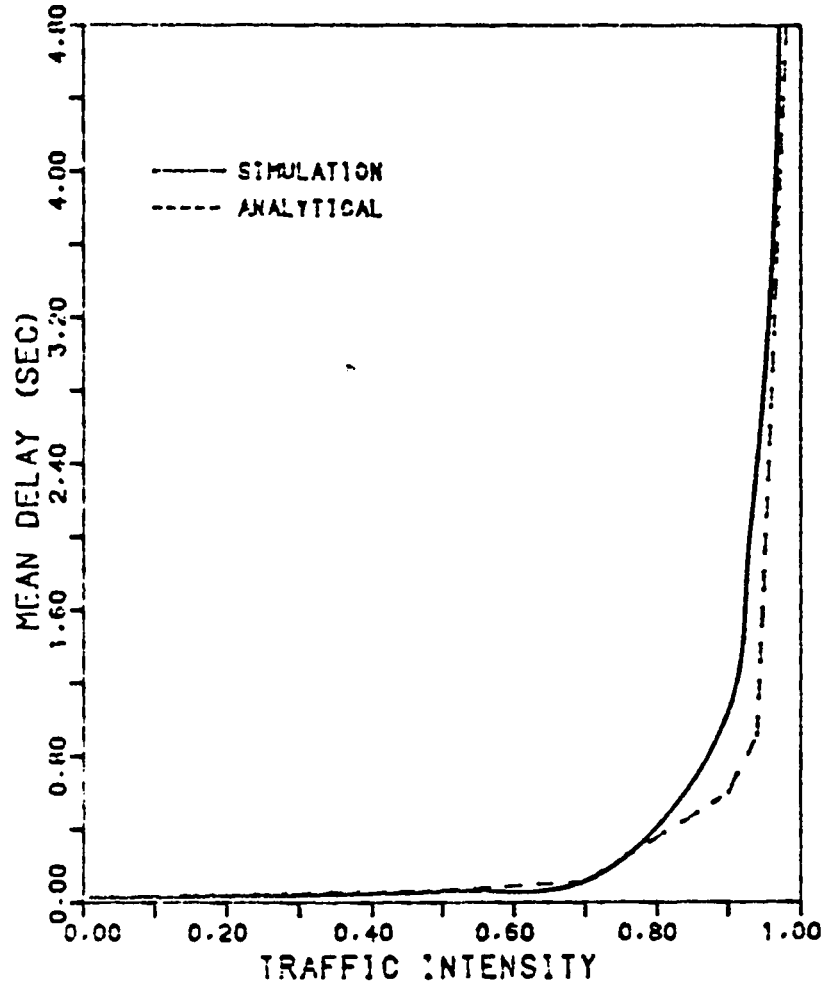


Figure 4.4(a). Comparison between simulated and analytical delay for Scheme III ($N = 10$, $R\tau = 0$ sec).

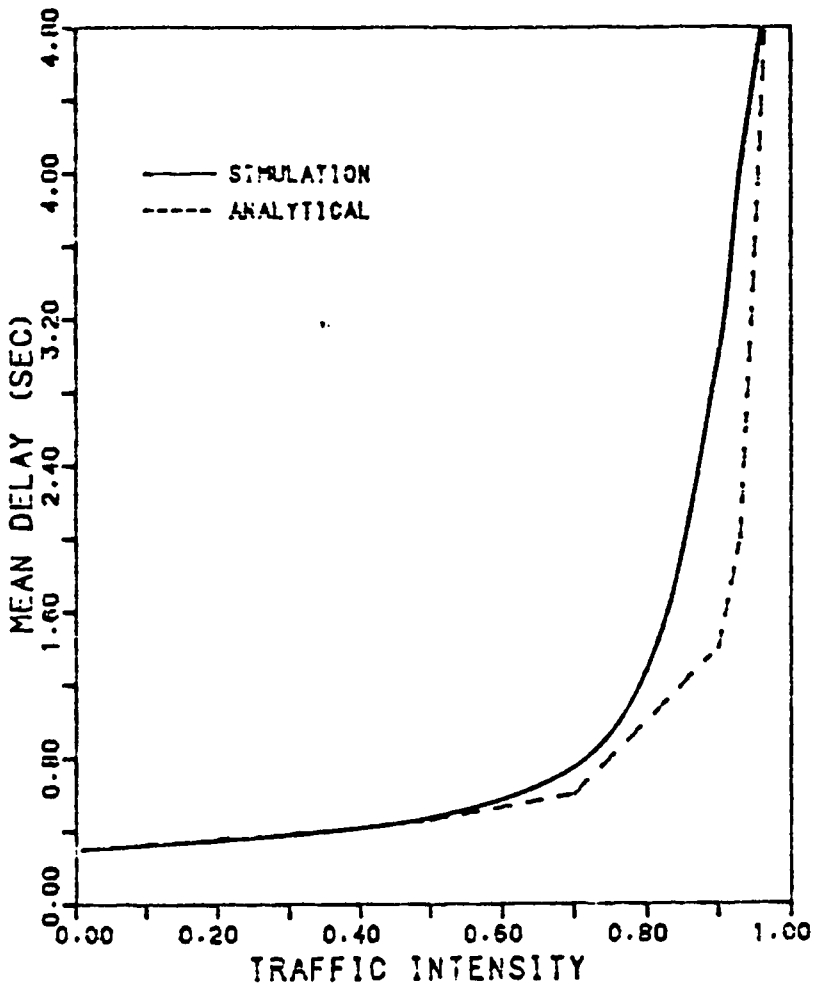


Figure 4.4(b). Comparison between simulated and analytical delay for Scheme III ($N = 10$, $R\tau = 0.27$ sec).

tabulated in Table 4.6 and the simulation run was 50,000 slots for a particular ρ_t.

As p_s is a function of ρ_t only, we can approximate data in Table 4.6 by least square curve fitting method using an nth degree polynomial in ρ_t. If n=4, we have

$$p_s = 1.005 - 0.1937\rho_t + 0.5632\rho_t^2 - 3.569\rho_t^3 + 2.203\rho_t^4 \qquad (4.32)$$

The mean square error is 8.8×10^{-6}. Equation (4.32) gives an empirical relation for p_s.

Let the total traffic (newly generated plus collided packets) forms an independent Poisson process with mean $N\lambda'$ and further let ρ' be the corresponding traffic intensity ($\rho' = N\lambda'\tau$), thus

$$N\lambda' = N\lambda + p_s \cdot P[\text{collision}|\text{S-ALOHA mode}]\, N\lambda$$

$$= N\lambda + p_s \cdot p_c \cdot N\lambda$$

$$\therefore \quad \rho' = \rho_t[1 + p_s\, p_c] \qquad (4.33)$$

where p_c is given by Eqn. (4.8).

Now we can model our queueing system as an M/D/1 queue where

TABLE 4.6. Simulation Results for p_s in Scheme IV for R = 0.

Total Traffic Intensity ρ_t	N = 10 p_s	N = 20 p_s	N = 100 p_s
0.01	0.99996	0.99996	0.99999
0.04	0.99876	0.99848	0.998799
0.1	0.99154	0.99114	0.99047
0.2	0.96466	0.96268	0.96093
0.3	0.9154	0.91438	0.906
0.4	0.84178	0.8384	0.8318
0.5	0.7439	0.73732	0.7279
0.7	0.45264	0.43946	0.4363
0.9	0.1267	0.12554	0.12856
1.0	0.01072	0.01358	0.01787

where the input traffic intensity is ρ', and we use the standard delay result [30],

$$E(D) = \frac{\rho' + \frac{(\rho')^2}{2(1-\rho')}}{N\lambda} + \frac{\tau}{2} \text{ sec.} \tag{4.34}$$

The comparisons between simulated and analytical results are made in Table 4.7 and plotted in Fig. 4.5 for R = 0. The close agreement of results (especially for $\rho_t \leq 0.8$) suggests that Scheme IV behaves like a perfect scheduling algorithm (M/D/1 queueing system) with the modified value of traffic intensity ρ' given by Eqn. (4.33).

TABLE 4.7. Simulation and Analytical Results for Scheme IV when R = 0.

Total Traffic Intensity ρ_t	N = 10		N = 100	
	Analytical E(D) sec	Simulated E(D) sec	Analytical E(D) sec	Simulated E(D) sec
0.01	0.0300	0.03	0.0300	0.03
0.04	0.0304	0.0309	0.03040	0.0307
0.1	0.0312	0.0326	0.0312	0.0329
0.2	0.0330	0.0364	0.033	0.0371
0.3	0.0355	0.0417	0.0355	0.0432
0.4	0.0394	0.0487	0.0394	0.0502
0.5	0.0458	0.058	0.0458	0.0606
0.7	0.1031	0.0975	0.10310	0.1029
0.9	1.11	0.2717	1.110	0.2611

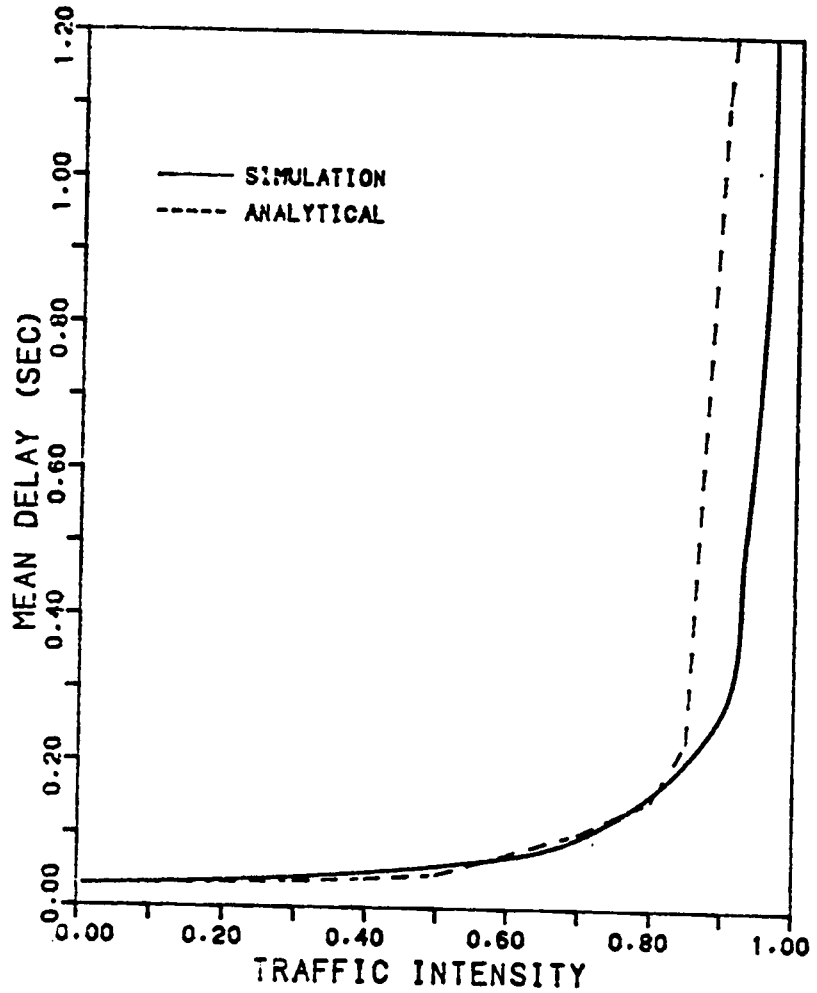


Figure 4.5. Comparison between analytical & simulated results for Scheme IV for R = 0, & N = 10.

Chapter 5

BUFFER ANALYSES

5.1 INTRODUCTION

We have assumed an infinite buffer in the delay analyses and simulation of our multiple access scheme in the previous sections. That assumption made both analysis and simulation simple. However, in practice, each user is equipped with finite buffers.

We make the following assumptions regarding the buffer behaviors of MA schemes due to follow in the next sections:

1) Each user maintains two finite length buffers. The first buffer (henceforth called main buffer) of length L packets is used to accommodate newly arriving packets. The second buffer (henceforth called retransmission buffer) is used to store collided packets, and

2) the probability of overflow (P_{of}) is the probability a newly arriving packet finds the buffer full and is therefore lost. We have to make arrangements to reschedule the transmissions of lost packets. For simulation purposes, P_{of} is also equivalent to

the average fractions of the total number of arriving packets rejected by the buffer [33]. We are mainly concerned with the design of main buffer for various traffic intensities for a specified P_{of}.

We shall be referring to the results of Kekre and Saxena approach for finite buffer behavior with Poisson arrivals with random server interruptions [34] for the analyses of multiple access Schemes II & III. We briefly describe this approach in Appendix 'C' as applied to single packet messages containing fixed number of bits.

5.2 SCHEME I - BUFFER ANALYSIS

We shall present buffer analysis for $R \approx 0$. We are interested in the design of a buffer which is used to store both newly generated and collided packets. (If $\beta \geq \alpha$, then we can have two buffers instead, one for newly generated packets and the other for collided packets. In this case, the length of retransmission buffer will be fixed and will be 'α' packets). We can decompose our buffer analysis into two parts:

a) analysis in TDMA slots and

b) analysis in S-ALOHA slots.

Then the overflow probability for a newly arriving packet at buffer is

$$(P_{of})_{Total} = P(S\text{-}ALOHA) \cdot (P_{of})_{S\text{-}ALOHA} + P(TDMA) \cdot (P_{of})_{TDMA}$$

or

$$(P_{of})_{Total} = \left(\frac{\alpha}{\alpha+\beta N}\right)(P_{of})_{S\text{-}ALOHA} + \left(\frac{\beta N}{\alpha+\beta N}\right)(P_{of})_{TDMA} \qquad (5.1)$$

<u>a) Analysis in TDMA Slots</u>

The analysis by Yan [35] is applied here to determine $(P_{of})_{TDMA}$.

Let t_n be the instants just after a packet service terminates and q_n be the number of packets in the system at time t_n. It can be shown that the sequence $\{q_n, n \geq 0\}$ forms a homogeneous finite state Markov chain over the integers $\{0, 1, 2, \ldots, L-1\}$, where L is the length of buffer. This chain is aperiodic, and irreducible.

Let

$\underline{\pi}^t = [\pi_o, \pi_1, \ldots, \pi_{L-1}]$ be the steady state probability of the queue size, where

$$\pi_i = \lim_{n\to\infty} P[q_n = i]$$

then

$$\underline{\pi} = \underline{P} \cdot \underline{\pi} \qquad (5.2)$$

where

$$\underline{P} = \begin{bmatrix} P_{e,0} & P_{b,0} & 0 & \text{-----} & 0 \\ P_{e,1} & P_{b,1} & P_{b,0} & & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ P_{e,L-2} & P_{b,L-2} & P_{b,L-3} & & P_{b,0} \\ (1 - \sum_{i=0}^{L-2} P_{e,i}) & (1 - \sum_{i=0}^{L-2} P_{b,i}) & (1 - \sum_{i=0}^{L-3} P_{b,i}) & & (1 - P_{b,0}) \end{bmatrix} \tag{5.3}$$

is a (L x L) matrix of transition probabilities and where

$$P_{b,k} = e^{-\lambda' N\tau} \cdot \frac{(\lambda' N\tau)^k}{k!}, \; k \geq 0 \tag{5.4}$$

where λ' is given by Eqn. (4.3) and

$$P_{e,k} = \frac{e^{-\lambda' N\tau}}{(k+1)!} \{(\lambda' N\tau)^{k+1} + \frac{1}{1-e^{-N\lambda'\tau}} (e^{-N\lambda'\tau} . [\lambda'(N+1)\tau]^{k+1} - [\lambda'\tau]^{k+1})\}, \quad k \geq 0 \tag{5.5}$$

Thus $\underline{\pi}$ can be found.

Now according to [35]

$$(P_{of})_{TDMA} = 1 - \frac{1}{\lambda' N\tau[1 + \pi_0 \frac{e^{-\lambda'(N\tau-\tau)}}{1 - e^{-\lambda' N\tau}}]} \tag{5.6}$$

<u>b. Analysis in S-ALOHA Slots</u>

Same analysis in the preceding paragraphs can be applied for single user to get $(P_{of})_{S\text{-}ALOHA}$. Here N = 1 (i.e. every slot can be accessed by every user) and $\lambda' = \lambda$. Working on the same lines,

$$(P_{of})_{S\text{-}ALOHA} = 1 - \frac{1}{\lambda\tau[1 + \frac{\pi_0}{1 - e^{-\lambda\tau}}]} \tag{5.7}$$

Thus $(P_{of})_{Total}$ is determined.

P_{of}'s for various traffic intensities are plotted as a function of buffer length (L) in Fig. 5.1 for N = 10 and $\alpha = \beta = 1$. Computer simulations show a close agreement with analytical results (see Table 5.1).

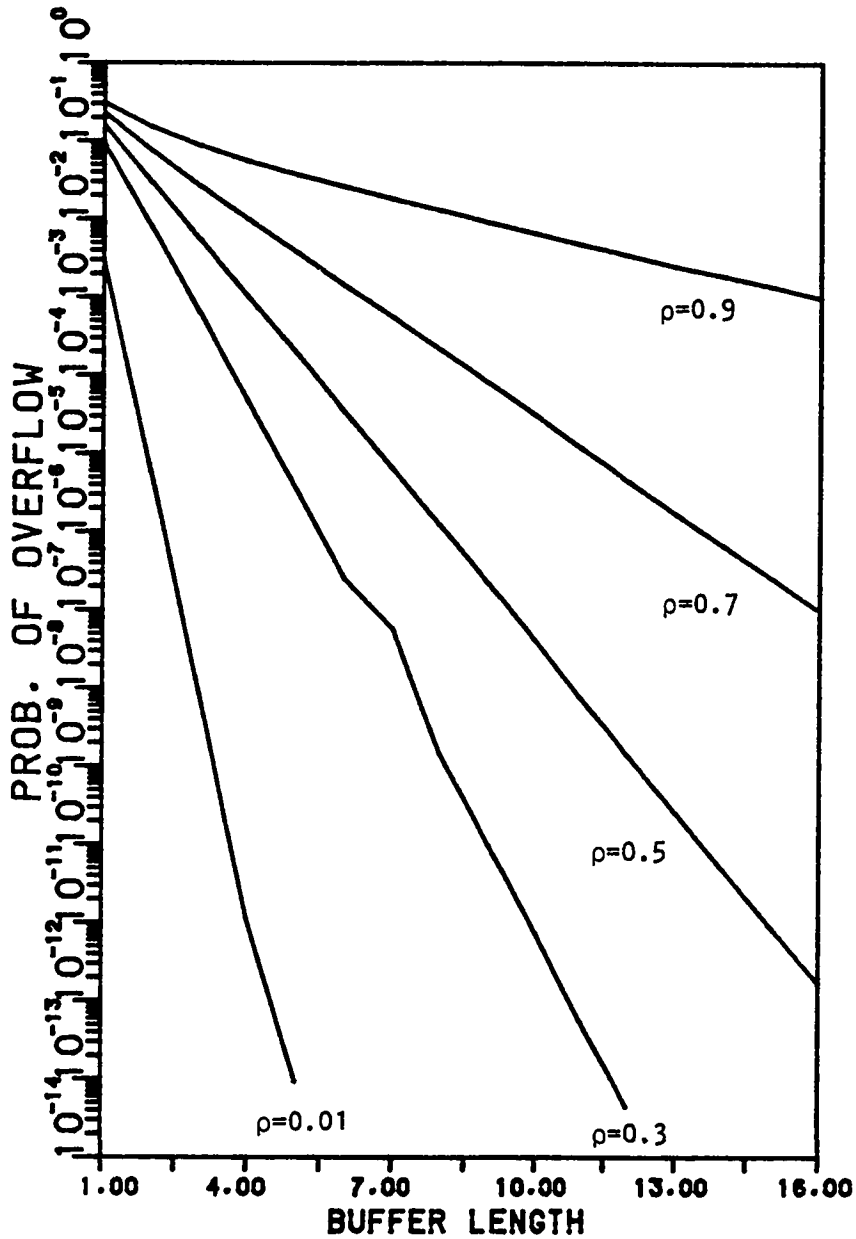


Figure 5.1. Prob. of overflow as a function of main buffer length for Scheme I for various traffic intensities for $N = 10$, & $\alpha = \beta = 1$.

TABLE 5.1. Comparison Between Analytical and Simulated P_{of} for $N = 10$, $\alpha = \beta = 1$, and $L = 3$ for Scheme I.

Total Traffic Intensity	P_{of} (Simulated)	P_{of} Analytical)
0.01	0	5.9×10^{-8}
0.04	0	4.0×10^{-6}
0.1	0	7.2×10^{-5}
0.2	3×10^{-4}	7.2×10^{-4}
0.3	1.27×10^{-3}	3.0×10^{-3}
0.4	4.7×10^{-3}	8.3×10^{-3}
0.5	1.3×10^{-2}	1.8×10^{-2}
0.7	5.2×10^{-2}	6.0×10^{-2}
0.9	1.34×10^{-1}	1.33×10^{-1}

5.3 BUFFER BEHAVIOR - SCHEME II

As all the users are identical, we need to consider buffering situation at only one user. The length of retransmission buffer is fixed and is equal to $[R]^{\dagger}$ packets, where $[R]^{\dagger}$ is the largest integer which is not larger than (R+1). The reason for this fixed length is that a user can have at most $[R]^{\dagger}$ collided packets in this multiple access scheme. The retransmission buffer will have zero overflow probability. We are only interested in the design of main buffer. The buffering situation at a user is illustrated in Fig. 5.2. Normally, the switch 'S' is at position '1' and we have normal S-ALOHA mode (State # 1), until a collision is detected. Upon detecting a collision, 'S' moves to position '0' (reserved mode) and it will remain in that position until TDMA frame is over. Only at one situation in the reserved mode the switch 'S' will be at '1' for only one slot duration when the retransmission buffer at that user is empty. The buffer behavior is analyzed using Kekre and Saxena approach [34]. Here

$$p_{s1} = P[\text{S-ALOHA mode}] + \\ + P[\text{TDMA mode and a user's retransmission buffer is empty}] \tag{5.8}$$

or

$$p_{s1} = p_s+(1-p_s)(\frac{1}{N}).P[\text{Retransmission buffer at a user is empty}] \tag{5.9}$$

Now

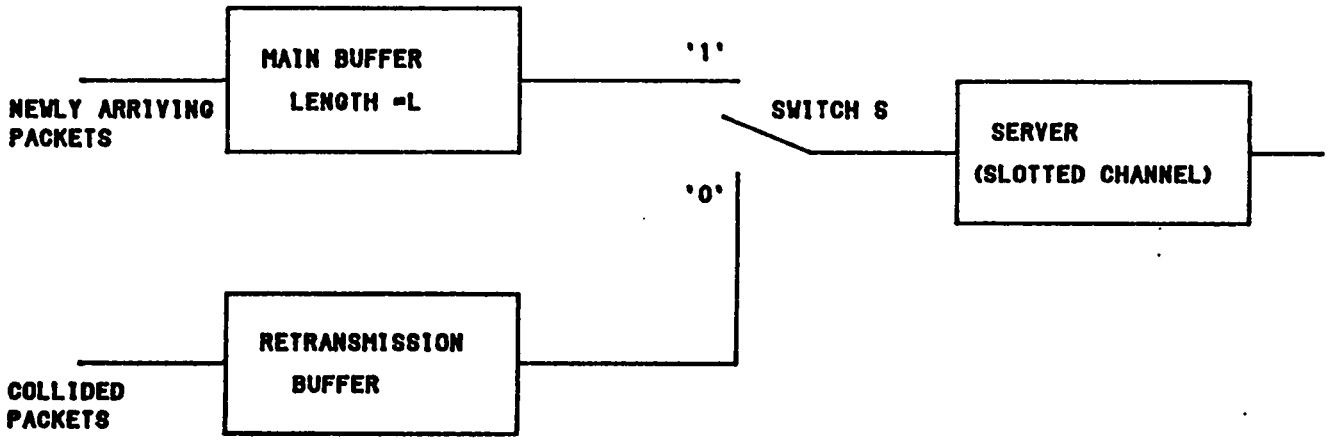


Figure 5.2. Buffering situation at a source for Scheme II.

Now

P[Retx. buffer at a user is empty] =

= P[S-ALOHA] . P[of collision due to other N-1 users only|S-ALOHA]

$$= p_s \cdot (1-p_t).[1-(1-p_t)^{N-1} - (N-1)\, p_t(1-p_t)^{N-2}] \qquad (5.10)$$

where

$$p_t = \lambda\tau/p_s$$

Now from Eqns. (5. 9) & (5.10)

$$p_{s1}=p_s+ \frac{(1-p_s)p_s(1-p_t)}{N}[1-(1-p_t)^{N-1}-(N-1)\, p_t(1-p_t)^{N-2}] \qquad (5.11)$$

Kekre and Saxena [34] approach is applied and P_{of}s for various traffic intensities as a function buffer length are plotted in Fig. 5.3 for N = 10. These results are also verified by long simulation runs (100,000 slots). The analytical calculations for P_{of} were made on computer. Due to finite word length (15 digit accuracy on double precision), the coefficient $< 10^{-15}$ was set equal to zero. Table 5.2 shows a comparison between analytical and simulated results for L = 2 and N = 10.

It is obvious from Fig. 5.3 that a small buffer length is required to achieve a very low overflow probability. For example, to get $P_{of} \approx 10^{-10}$,

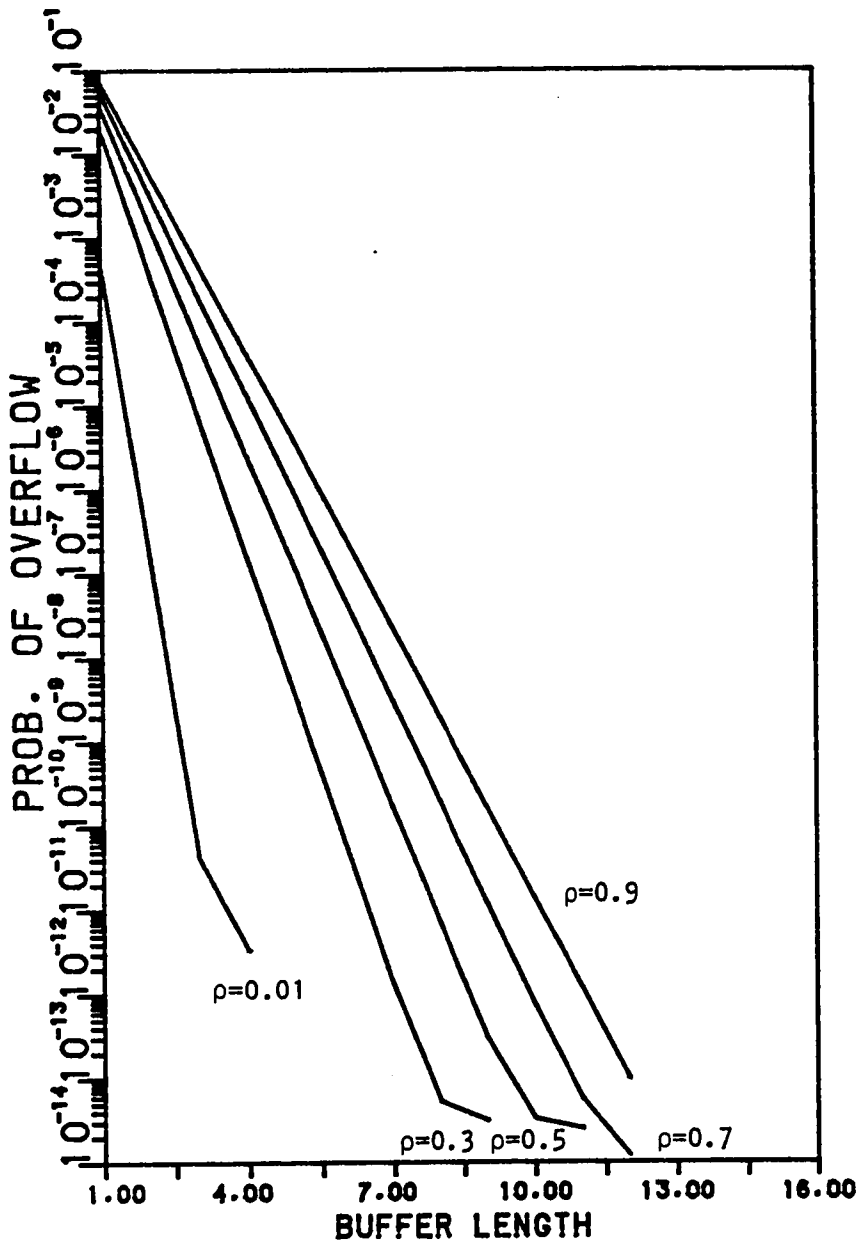


Figure 5.3. P_{of} as a function of main buffer length for multiaccess Scheme II for various traffic intensities for N = 10.

TABLE 5.2. Comparison Between Analytical and Simulated P_{of} for N = 10 and L = 2 for Scheme II.

Total Traffic Intensity ρ_t	P_{of} (Simulated)	P_{of} (Analytical)
0.01	0	1.7×10^{-7}
0.04	0	2.7×10^{-6}
0.1	0	2×10^{-5}
0.2	1×10^{-4}	1.2×10^{-4}
0.3	5.9×10^{-4}	4.6×10^{-4}
0.4	1.9×10^{-3}	1.2×10^{-3}
0.5	3×10^{-3}	2.1×10^{-3}
0.7	4.8×10^{-3}	4.2×10^{-3}
0.9	5.7×10^{-3}	6.8×10^{-3}

buffer length of three is sufficient for $\rho_t = 0.01$ and the buffer length of nine is required for $\rho_t = 0.9$.

5.4 BUFFER BEHAVIOR - SCHEME III

In this multiple access scheme, the length of retransmission buffer at each user is assumed to be $[R]^\dagger$ packets, as there may be at most $[R]^\dagger$ collided packets requeued to this buffer. The retransmission buffer will have zero overflow probability. We are only interested in the design of main buffer. The buffers at one of the identical users can be modelled as illustrated in Fig. 5.2. In normal operation, the switch 'S' is at position '1' and we have normal S-ALOHA mode (State # 1) until a collision is detected. Upon detecting a collision, 'S' moves to position '0' and it will remain at this position until all the collided packets resulting from the previous slots are retransmitted. Kekre & Saxena approach [34] for finite buffer with random server interruptions may be applied for this scheme also. Clearly

$$p_{s1} = P[\text{switch is at '1'}]$$

$$= P[\text{S-ALOHA mode}]$$

or

$$p_{s1} = p_s \tag{5.12}$$

where p_s is given by Eqn. (4.11) and $p_{s0} = 1 - p_s$.

The probabilities of overflow (P_{of}) for various traffic intensities

as a function of main buffer length (L) are plotted in Fig. 5.4 for N = 10. These results are also verified by long simulation runs (100,000 slots). The analytical calculations for P_{of} were made on computer. Due to finite word length, the coefficient $< 10^{-15}$ was set equal to zero. Table 5.3 shows a comparison between simulated and analytical result for N = 10, & L = 2. A small buffer length is required at each user to get a very low overflow probability. For example, to achieve $P_{of} \approx 10^{-10}$, buffer lengths of three and nine are sufficient for $\rho_t = 0.01$ & $\rho_t = 0.9$ respectively. Scheme III gives slightly lower P_{of} than Scheme II for same L and ρ_t.

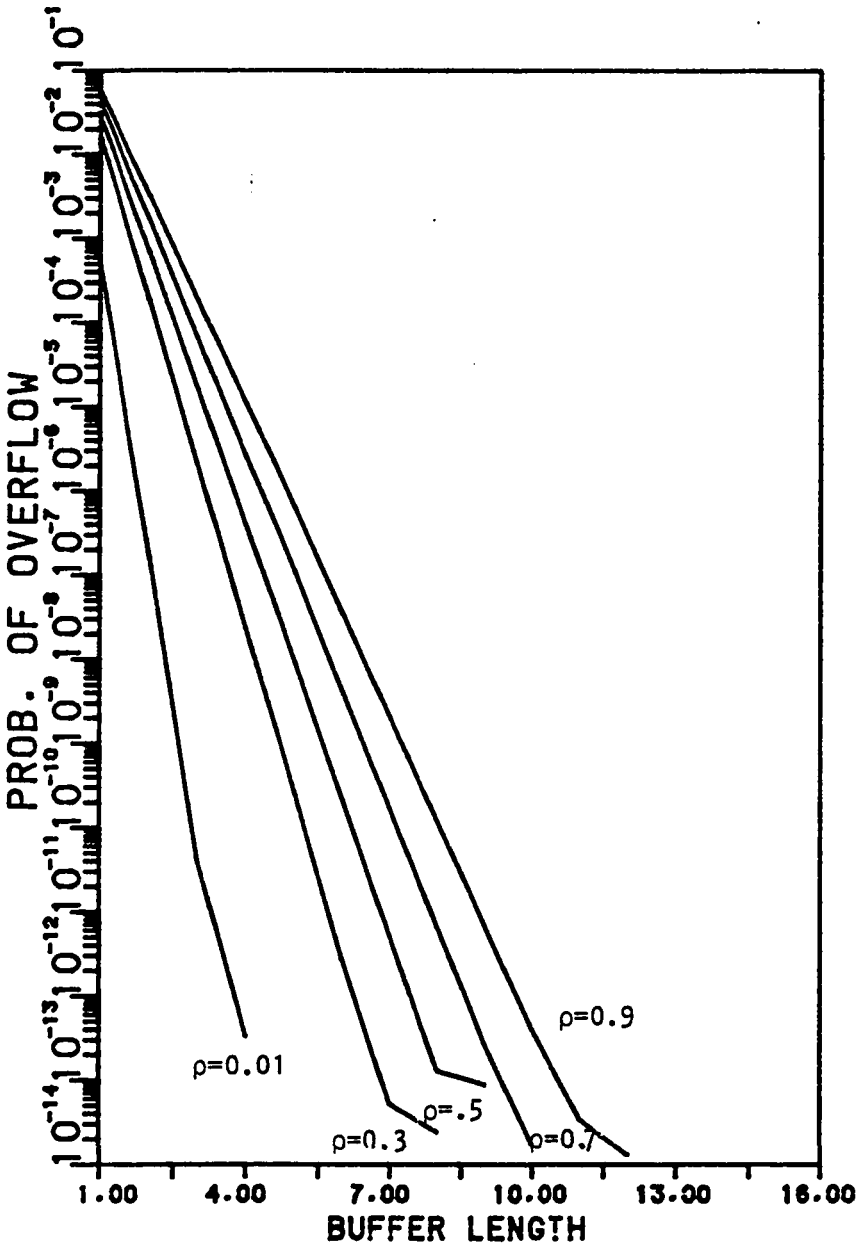


Figure 5.4. P_{of} as a function of main buffer length for Scheme III for various traffic intensities for N = 10.

TABLE 5.3. Comparison Between Analytical and Simulated P_{of} for N = 10 and L = 2 for Scheme III.

Total Traffic Intensity ρ_t	P_{of} (Simulated)	P_{of} (Analytical)
0.01	0	1.7×10^{-7}
0.04	0	2.7×10^{-6}
0.1	0	1.7×10^{-5}
0.2	0	7.6×10^{-5}
0.3	0	1.9×10^{-4}
0.4	2.5×10^{-5}	3.9×10^{-4}
0.5	2.7×10^{-4}	6.7×10^{-4}
0.7	7.3×10^{-4}	1.7×10^{-3}
0.9	9.7×10^{-4}	3.3×10^{-3}

Chapter 6

DISCUSSION OF RESULTS & CONCLUSIONS

6.1 DISCUSSION ON PROPOSED SCHEMES

General

We make the following general observations regarding the four proposed multiple access (MA) schemes:

1) Scheme I has the simplest management because the channel has static slot assignment to the users.
2) Scheme II is simpler than MA Schemes III and IV because a user has to maintain only a reservation table, and
3) Scheme IV is the most complex one to implement as a user has to maintain two tables (Reservation Table (RT) and Queue Length Table (QLT) and it has to sense the state of the channel at each slot so as to send the queue length information using all minislots.

Stability

All proposed MA schemes are stable. This is due to the fact that a packet collides at most once before it is received successfully.

Delay - Throughput Tradeoffs

In all proposed MA schemes, the maximum throughput can approach unity. In Scheme I, this is guaranteed iff $\beta >> \alpha$. Schemes II, III & IV adapt dynamically and smoothly to traffic variations. At low traffic intensities, these schemes behave like slotted ALOHA while at high traffic intensities these schemes tend to dynamic assignment techniques.

Scheme I has better delay characteristics than TDMA at low values of throughput only. At higher values of traffic intensity, delay performance deteriorates because the random access slots provide little service due to high probability of collision while the reservation mode does not have the dynamic adaptability of the later schemes. However unlike the slotted ALOHA scheme, this is a stable scheme.

Scheme III offers better delay-throughput tradeoffs than Scheme II, because in the later case we reserve a slot for each user on detecting a collision and some of these slots may be unused hence decreasing throughput and increasing the average delay. But Scheme II is simpler to implement than Scheme III. In the former case, we have to sense only a collision and then we update the Reservation Table (R.T.).

Scheme IV offers best delay-throughput tradeoffs due to the efficient utilization of slots. But the major drawback is the complexity of implementation.

The main disadvantage common in Schemes III & IV is that the overhead increase with the number of users (N) and thus limiting the maximum achievable throughput. At low values of ρ ($\rho \leq 0.5$), Schemes III and IV behave almost the same but Scheme IV has better performance at high ρ. Performance comparisons among all four proposed schemes and classical schemes (S-ALOHA and TDMA) are made in Figs. 6.1, 6.2 for $R \approx 0$ case and in Figs. 6.3, 6.4 for satellite channel. $R \approx 0$ case refers to ground radio and local area network (LAN) environments. For N large (e.g. N = 100), both Schemes III & IV offer better delay-throughput characteristics over slotted ALOHA and TDMA. For $R \approx 0$ and N = 100, Scheme IV nearly tends to perfect scheduling algorithm (M/D/1).

Buffer Requirements

The buffer requirements for Scheme I largely depend upon the choice of α and β. Scheme II has larger buffer requirements over Scheme III in order to get same probability of overflow (P_{of}). This is due to the fact that a user with a newly generated packet has to wait on the average $\frac{N\tau}{2}$ sec when the system is in TDMA mode.

6.2 COMPARISONS

We shall make comparisons considering two different channel environments:

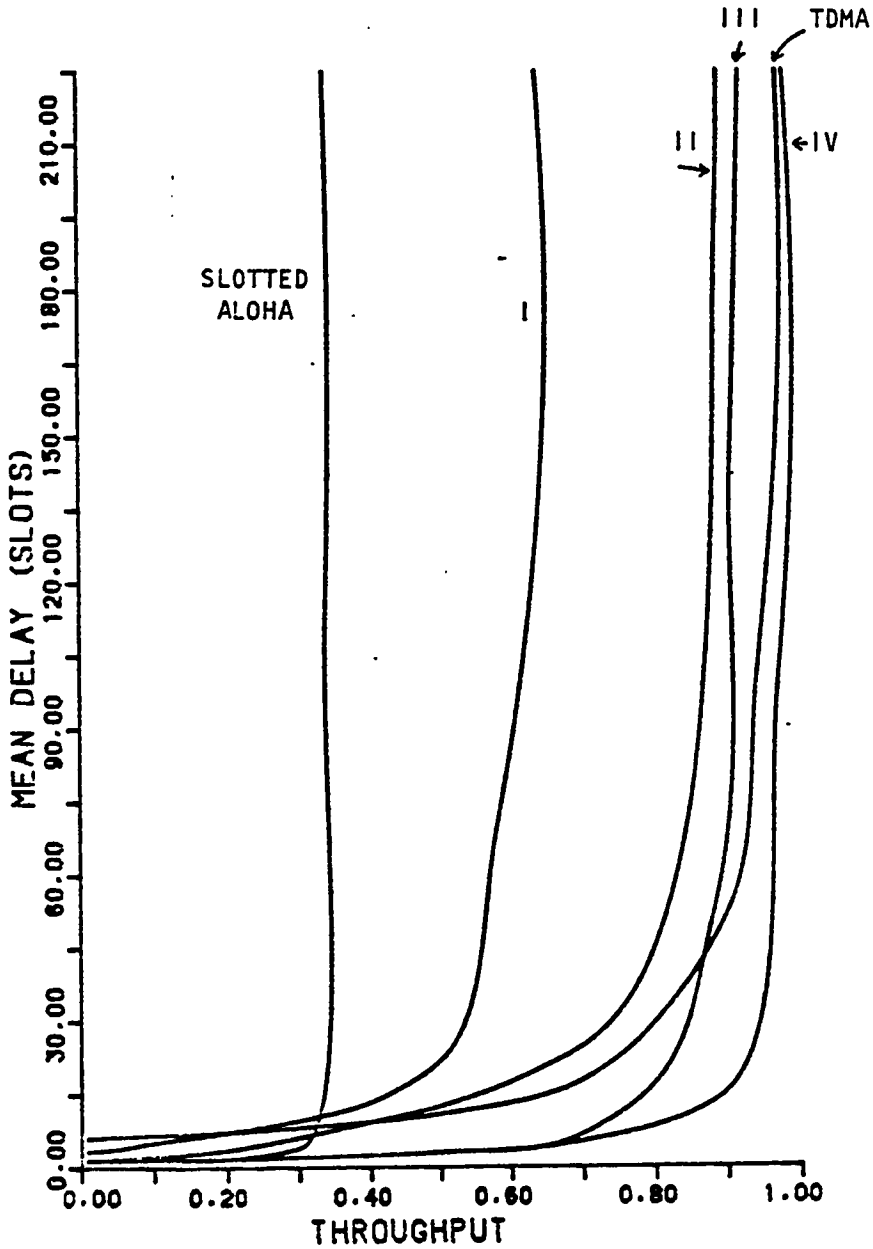


Figure 6.1. Comparison between four proposed schemes, classical slotted ALOHA and TDMA for N = 10 and R $\simeq$ 0. (Scheme I is with α = 10, β = 1).

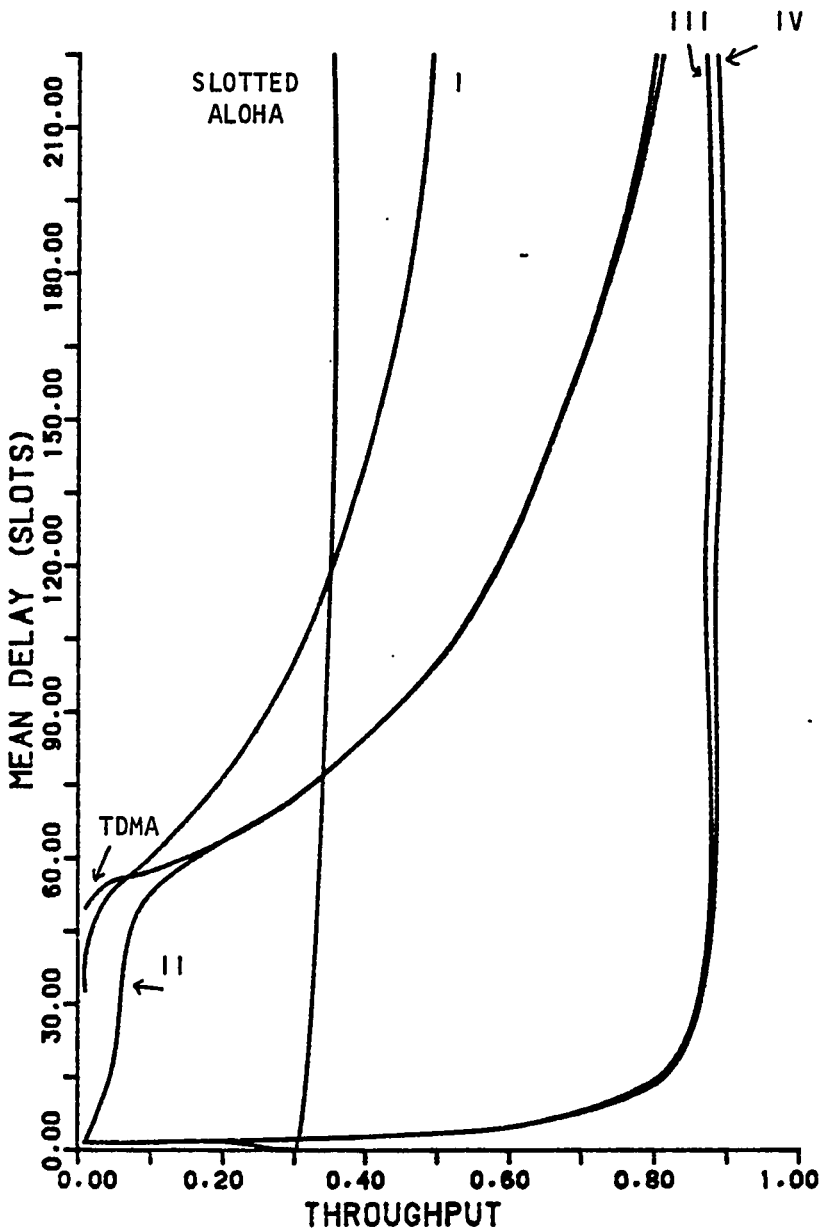


Figure 6.2. Comparison between four proposed schemes (Scheme I with $\alpha = 100$, $\beta = 1$), slotted ALOHA and TDMA for $N = 100$ and $R \simeq 0$.

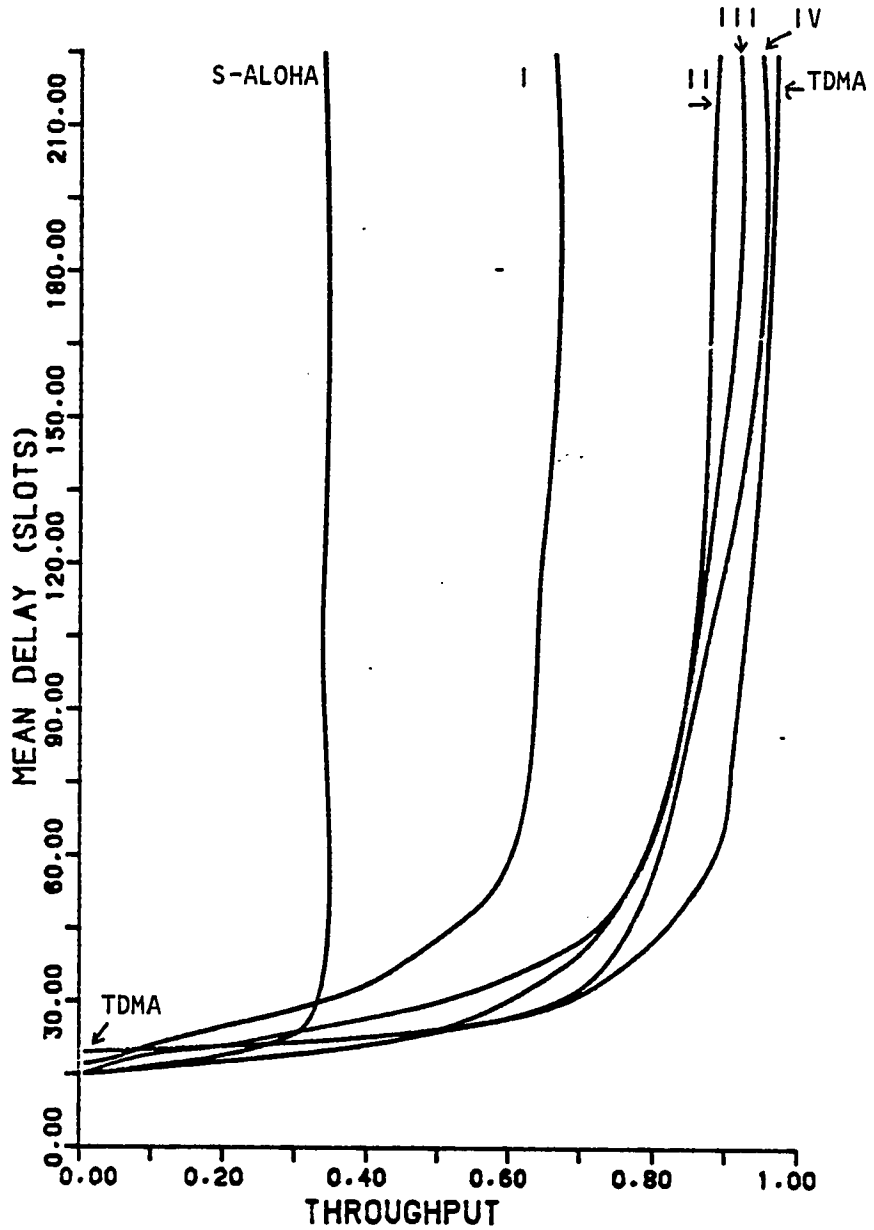


Figure 6.3. Comparison curves for four proposed schemes (Scheme I with $\alpha = 10$, $\beta = 1$), slotted ALOHA and TDMA for $N = 10$ and $R\tau = 0.27$.

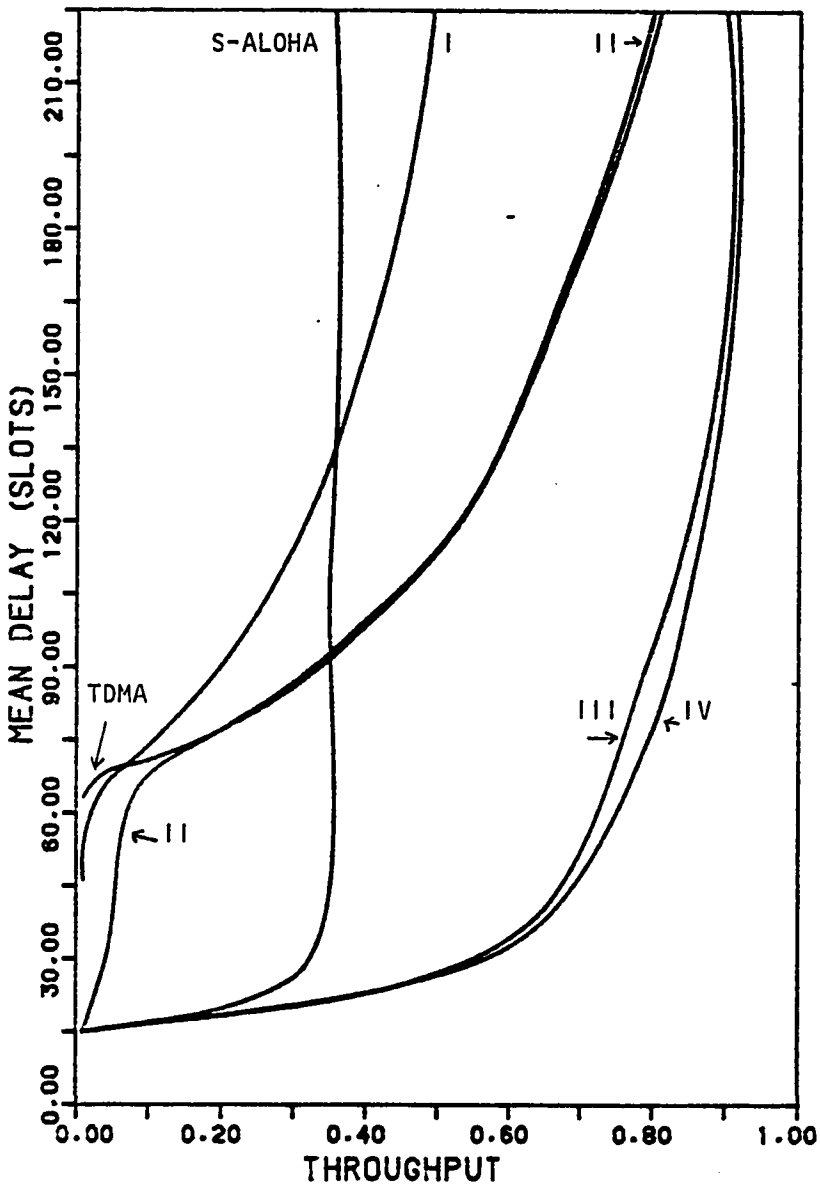


Figure 6.4. Comparison curves for four proposed schemes (Scheme I with $\alpha = 100$, $\beta = 1$), S-ALOHA and TDMA for $N = 100$ and $R\tau = 0.27$.

a) ground radio and local area network (LAN), i.e. $R \approx 0$. Here the propagation delay is much less than the packet transmission time (τ) ($R << 1$).

b) satellite channel, i.e. $R\tau = 0.27$ sec.

Ground Radio and LAN Environments

We shall briefly describe, and then compare with our proposed MA schemes, the following schemes/algorithms:

(i) tree algorithm [12]

(ii) slotted 1-persistent CSMA [15]

(iii) slotted nonpersistent CSMA [15]

(iv) URN protocol [18].

(i) **Tree Algorithms [12]**

Under this algorithm, sources are assigned to the leaves of a tree graph. Packet collisions are resolved by systematically moving from node to node through the tree, trying to determine the branches containing the conflicting users. Lower and upper bounds for E(D) are considered. The main drawback for this algorithm is that the maximum throughput is only 0.43. The important advantage is that this scheme is stable and gives excellent delay-

throughput tradeoffs if throughput < 0.43. Only Scheme I (considered with N = 10, α = 10 and β = 1) gives poor performance at low values of throughput when compared with tree algorithm, while all other proposed schemes give better performance.

(ii) Slotted 1-Persistent CSMA [15]

CSMA schemes are feasible only when the channel propagation delay is very small as compared to the packet transmission time. In such an environment, one may attempt to avoid collisions by listening to the carrier due to another user's transmission before transmitting, and inhibiting transmission if the channel is sensed busy. In slotted 1-persistent CSMA, a ready user senses the channel and operates as follows:

1) If the channel is sensed idel, it transmits the packet with probability one,

2) If the channel is sensed busy, it waits until the channel goes idle and then immediately transmits the packet with probability one.

The main disadvantage in this scheme is that the maximum throughput is only 0.531. Only Schemes I & II give poor performance at low values of throughput when compared with 1-persistent CSMA. Proposed MA schemes are compared with this algorithm (with propagation delay = (0.01) τ).

(iii) Slotted Nonpersistent CSMA [15]

Under this scheme, a ready user senses the channel and operates as follows:

1) If the channel is sensed idle, it transmits the packet

2) If the channel is sensed busy, then the terminal (or user) schedules the retransmission of the packet to some later time according to retransmission delay distribution. At this new point in time, it senses the channel and repeats the algorithm described.

The main advantage is high maximum throughput (0.857). Again propagation delay of 0.01τ is used in this scheme. Only Schemes III & IV give better performance than nonpersistent CSMA.

(iv) URN Protocol

Under this protocol, each user knows the number of ready users at each slot and then based on this information, transmission rights in each slot are assigned among the sources. The maximum channel throughput is unity. Urn scheme gives better delay throughput performance when compared with Schemes I & II. Scheme III gives better performance than Urn for values of

throughput ≤ 0.7, while Scheme IV performs better than Urn for all values of throughputs. The major drawback of Urn scheme is that each user should have information about the number of ready users and their assigned slots at each slot.

The proposed MA schemes are compared with these existing schemes for $N = 10$ and $R \approx 0$ in Figs. 6.5, 6.6, 6.7 and 6.8.

Satellite Channel

We shall consider:

i) tree algorithm

ii) R-ALOHA

iii) Roberts Reservation Scheme.

(i) **Tree Algorithm**

The details are given at the beginning of this section. Scheme I performs better than tree algorithm at high values of throughput only, while Schemes II, III & IV always perform better than tree algorithm for all values of traffic intensities.

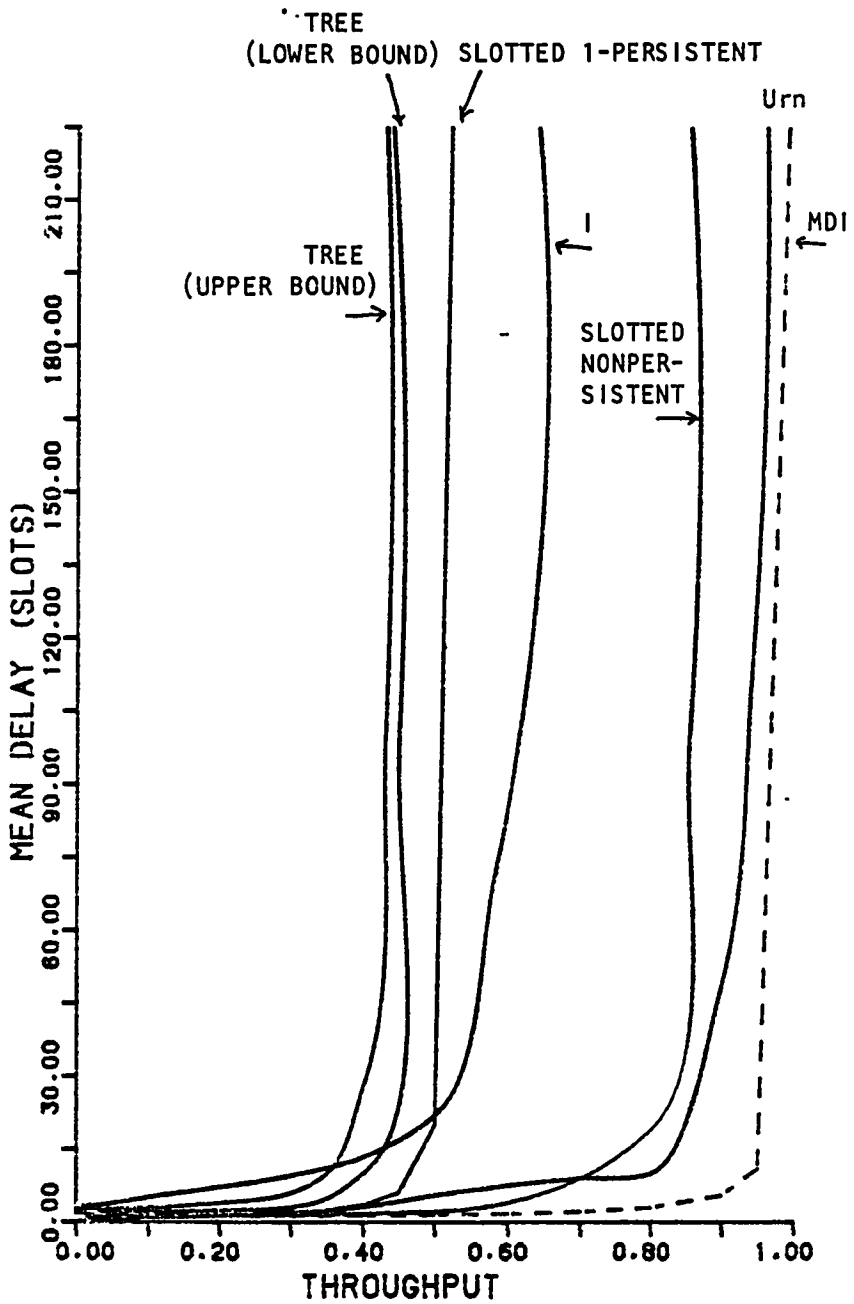


Figure 6.5. Comparison curves for tree algorithm, slotted 1-persistent, slotted Non-persistent, Urn, MDI and Scheme I (with $\alpha = 10$, $\beta = 1$) for $N = 10$ and $R \simeq 0$.

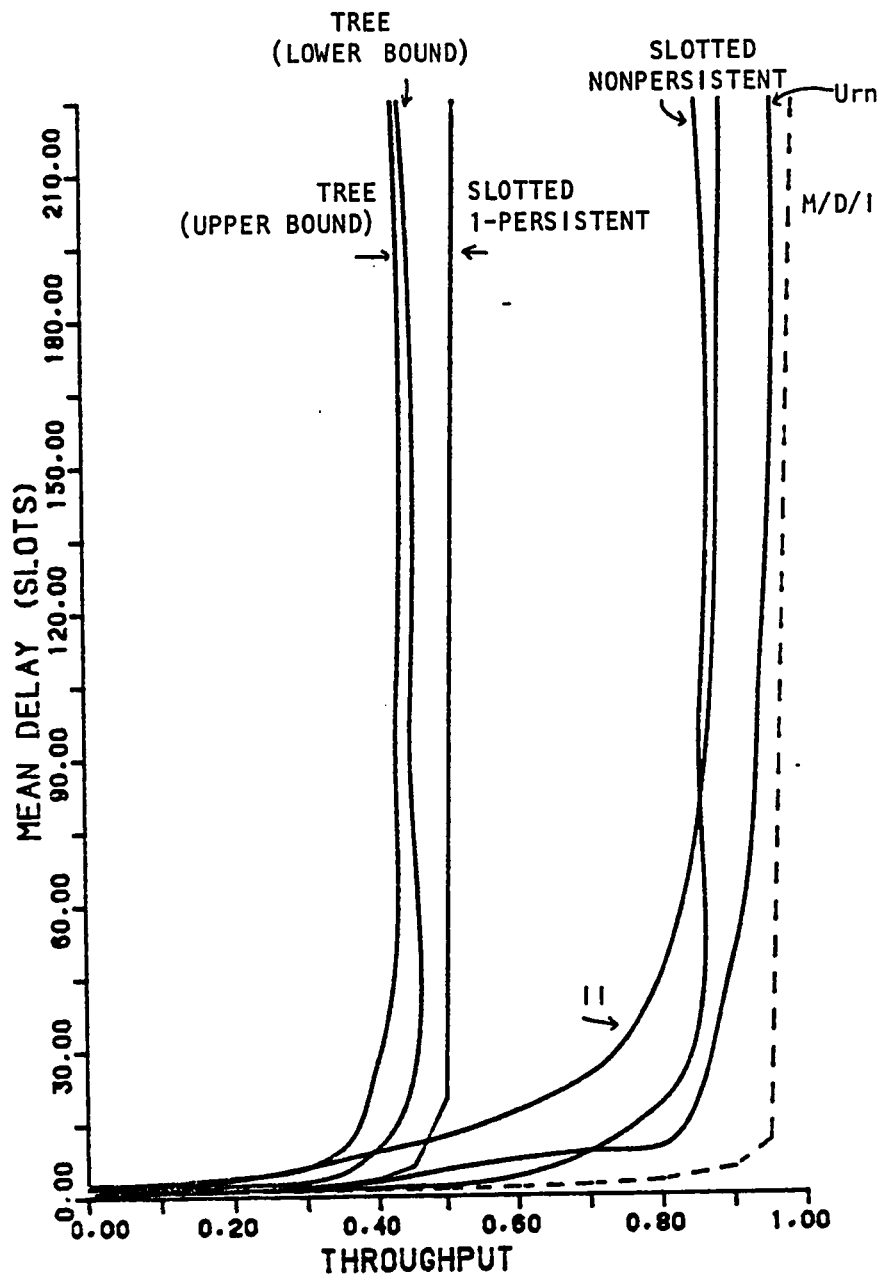


Figure 6.6. Comparison curves for tree algorithm, slotted 1-persistent, slotted Nonpersistent, Urn, MDI and Scheme II for N = 10 and R ≃ 0.

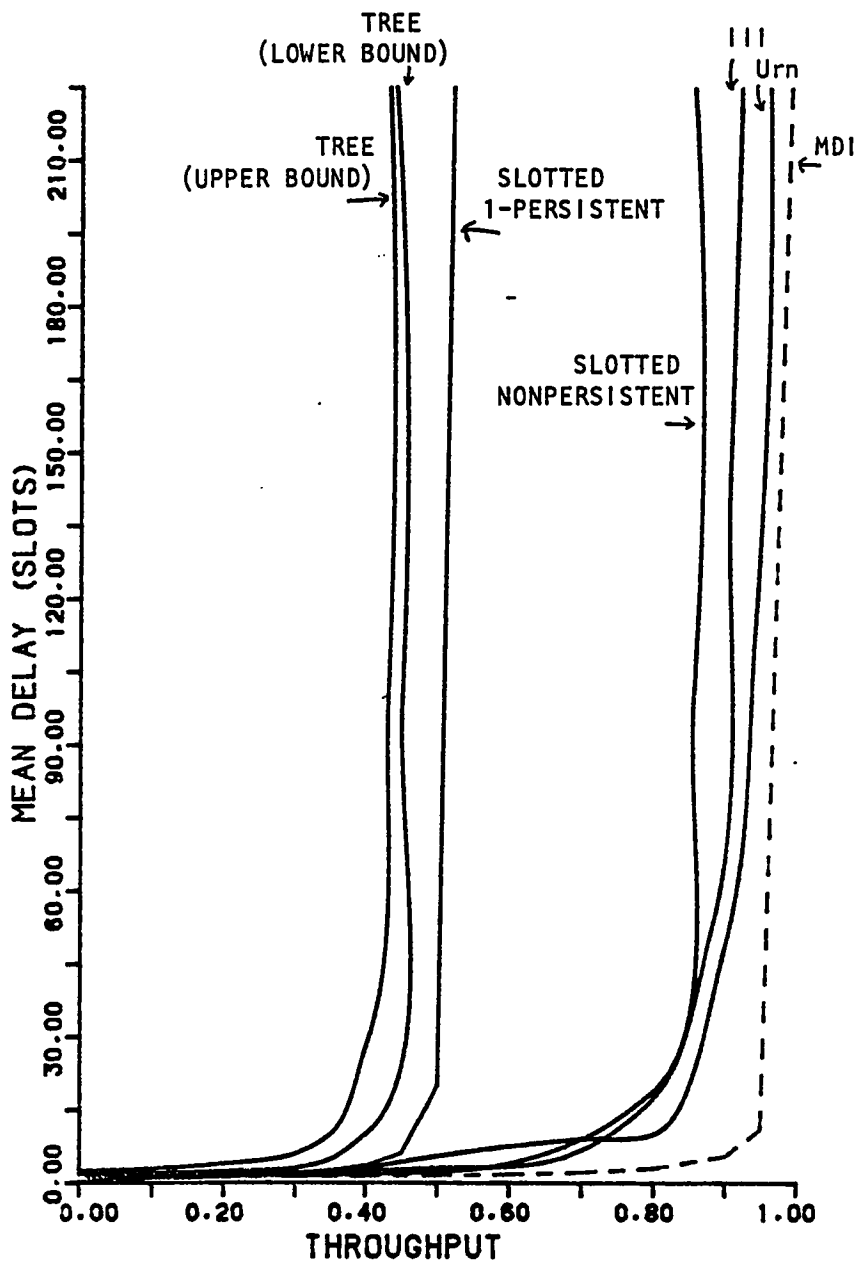


Figure 6.7. Comparison curves for tree algorithm, slotted 1-persistent, slotted Nonpersistent, Urn, MDI and Scheme III for N = 10 and R $\simeq$ 0.

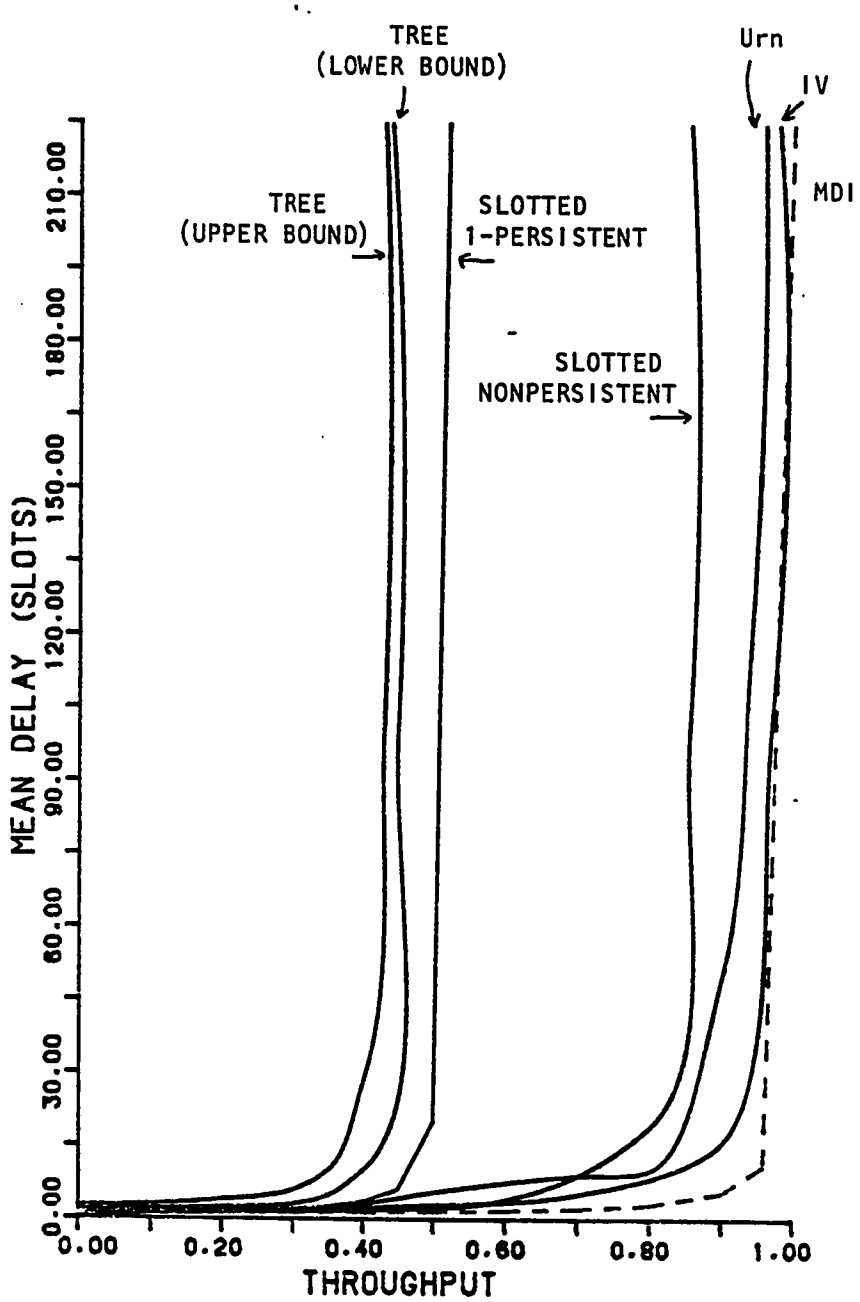


Figure 6.8. Comparison curves for tree algorithm, slotted 1-persistent, slotted Nonpersistent Urn, MDI and Scheme IV for N = 10 and R $\simeq$ 0.

(ii) R-ALOHA [2]

Under R-ALOHA, the slots are organized into frames of equal size. The duration of a frame must be greater than satellite propagation delay. A user who has successfully accessed slot in a frame is guaranteed access to the same slot in the succeeding frames and this continues until the user stops using it. "Unused" slots are free to be accessed by all users in a slotted ALOHA contention mode. An unused slot in the current frame is a slot which, in the preceding frame, either was idle or contained a collision. R-ALOHA is effective only if the users generate stream type traffic or long multipacket messages. The major disadvantage is that for single packet messages (as is our case), R-ALOHA just becomes S-ALOHA.

(iii) Robert's Reservation Scheme [19], [36]

Under this protocol, time slots are organized into frames. Each frame consists of a data subframe (consisting of M slots) and a reservation frame; each slot in the reservation subframe is further subdivided into V smaller slots. The smaller slots are for reservation packets to be used on a contention basis with slotted ALOHA. All other slots are data slots and are used on a reservation basis, free of conflict. Details of operation are given in [19], [36]. We have compared our proposed m.a. schemes with Robert's scheme (with $V = 6$, $K = 6$ and $M = 2$). The main disadvantages of Robert's scheme over the proposed ones are:

(1) higher delay (at least twice propagation delay) at low traffic intensities

(2) Complexity in the implementation of Robert's scheme, because when no packet is waiting in the system, all the data slots are converted into reservation slots (small slots).

All of our proposed MA schemes perform better than Robert's scheme, except Scheme I, which is inferior over a certain range of the throughput.

The proposed schemes are compared with these existing schemes for $N = 10$ and $R\tau = 0.27$ sec in Figs. 6.9, 6.10, 6.11 & 6.12.

6.3 CONCLUSIONS

Four multiple access schemes in packet communications for broadcast channels have been proposed. These schemes are studied under two different channel environments; ground radio (or LAN) and satellite. Random schemes (e.g., Slotted ALOHA and Tree algorithm) are efficient at low values of throughput while the performance of fixed assignment TDMA is better when throughput is high. Mixing of random access with TDMA may be done in a search to achieve better delay-throughput characteristics for the whole range of traffic intensity. Scheme I has static assignment for slotted ALOHA and

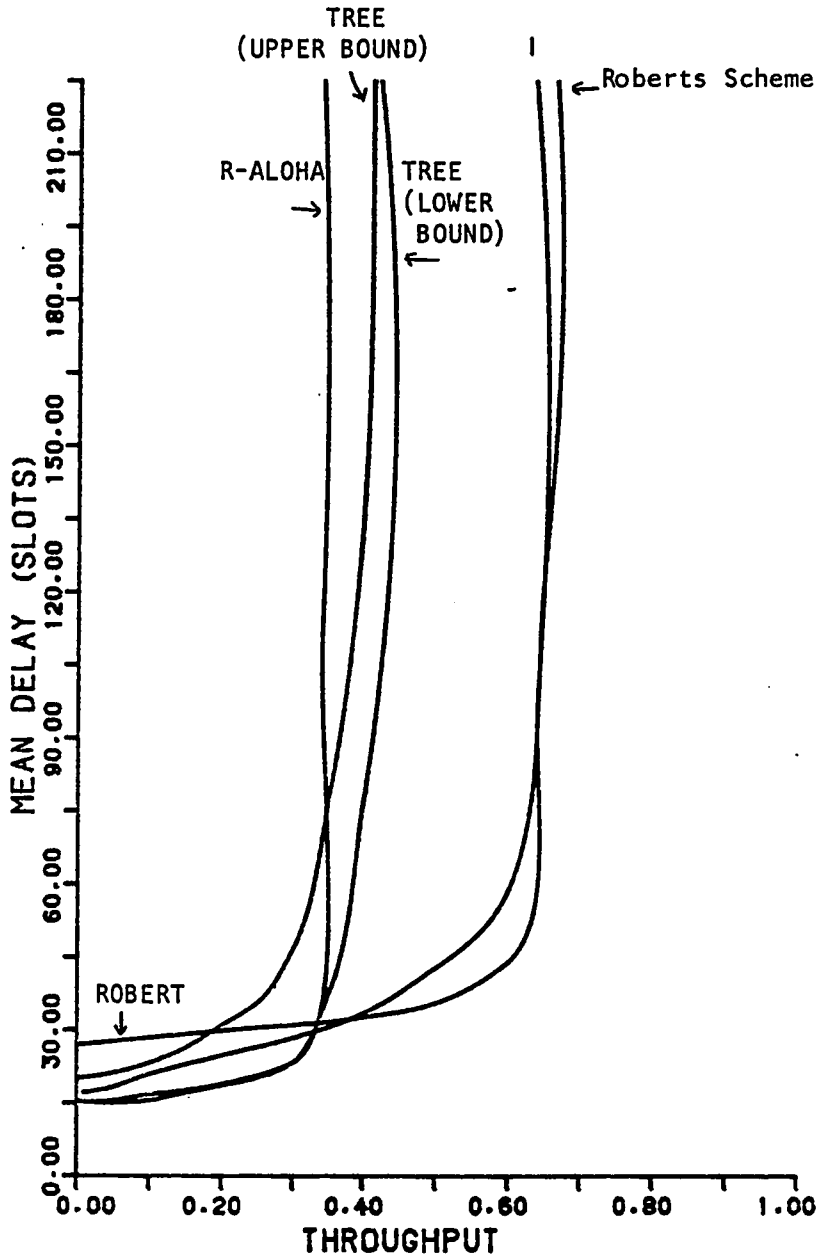


Figure 6.9. Comparison curves for R-ALOHA, tree algorithm, Scheme I (α = 10, β = 1), and Robert's scheme (K = V = 6, M = 2) for N = 10 and $R\tau$ = 0.27.

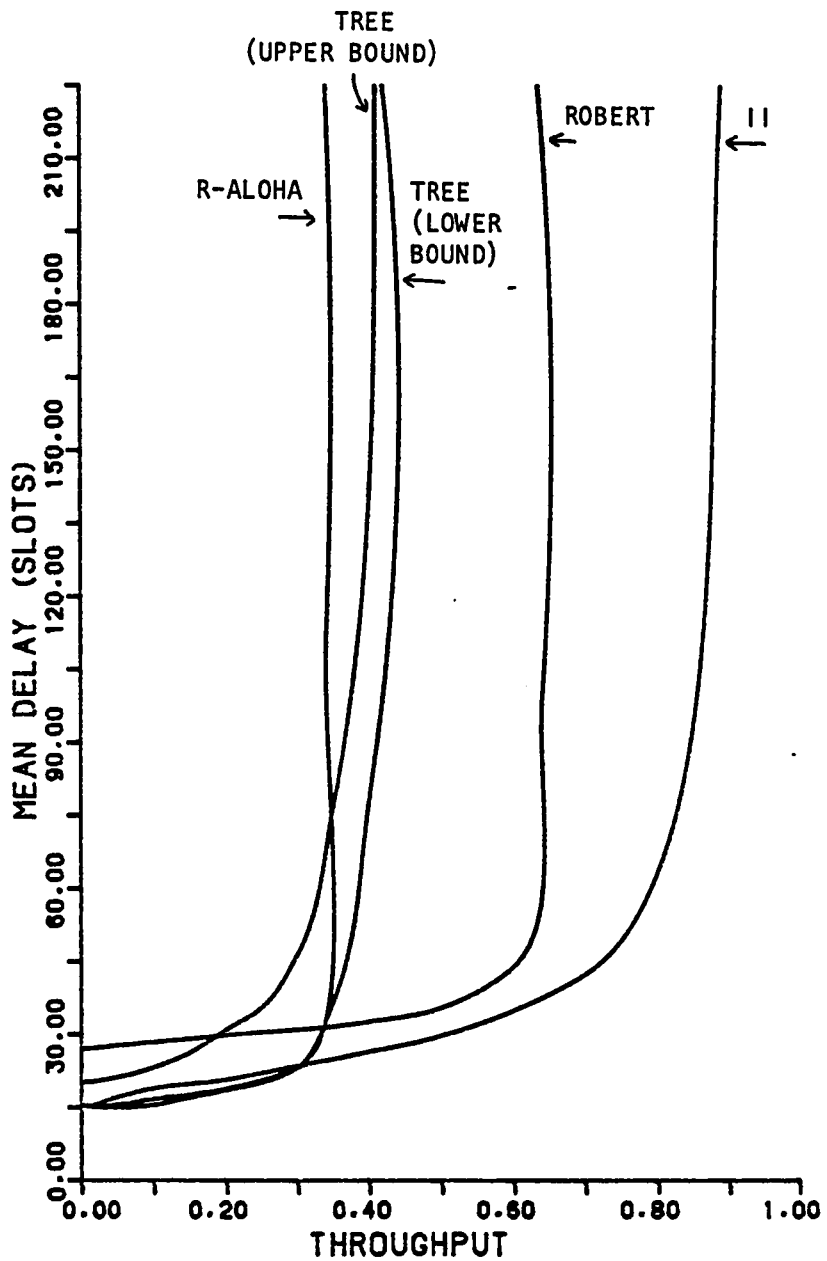


Figure 6.10. Comparison curves for R-ALOHA, tree algorithm, Scheme II and Robert's scheme ($K = V = 6$, $M = 2$) for $N = 10$ and $R\tau = 0.27$.

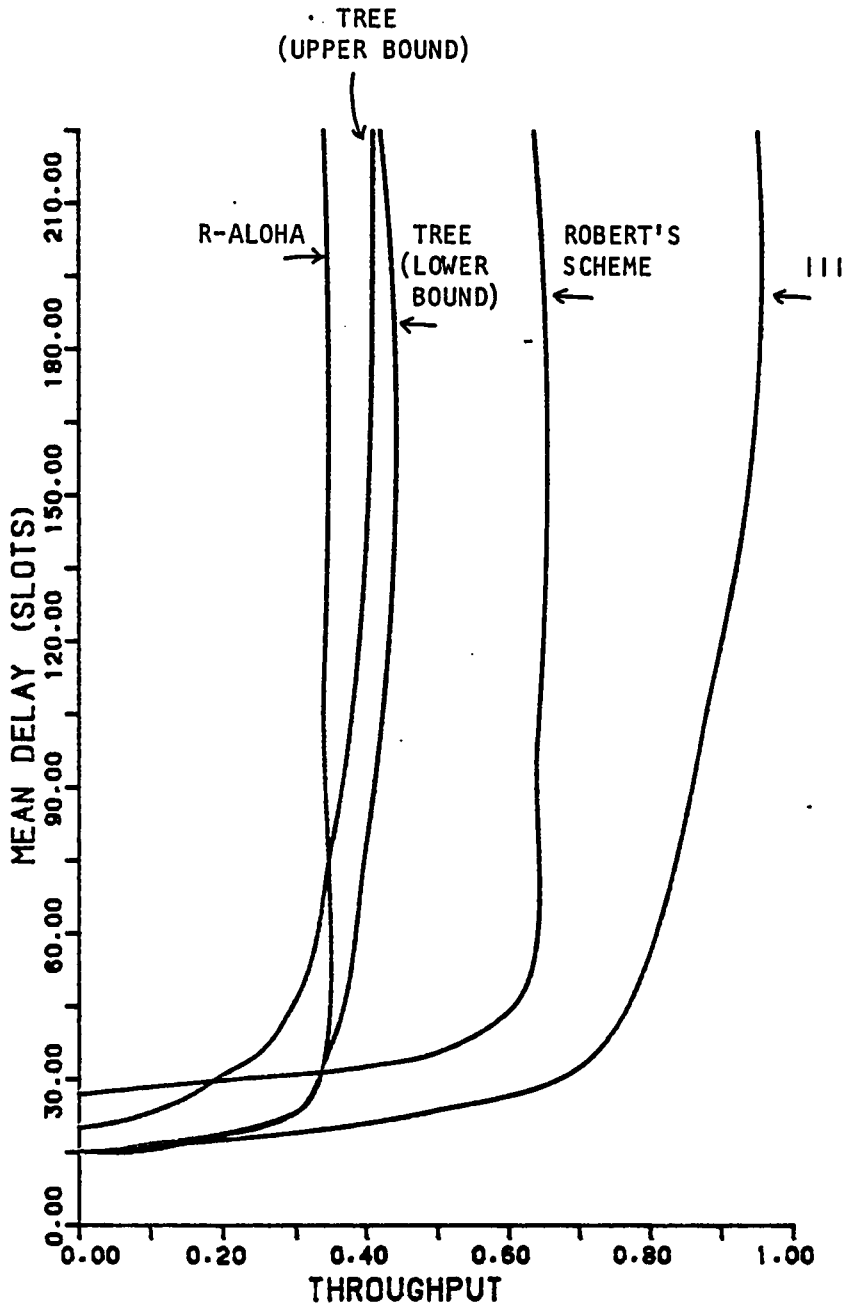


Figure 6.11. Comparison among R-ALOHA, Tree, Scheme III and Robert's scheme ($K = V = 6$, $M = 2$), for $N = 10$ and $R\tau = 0.27$.

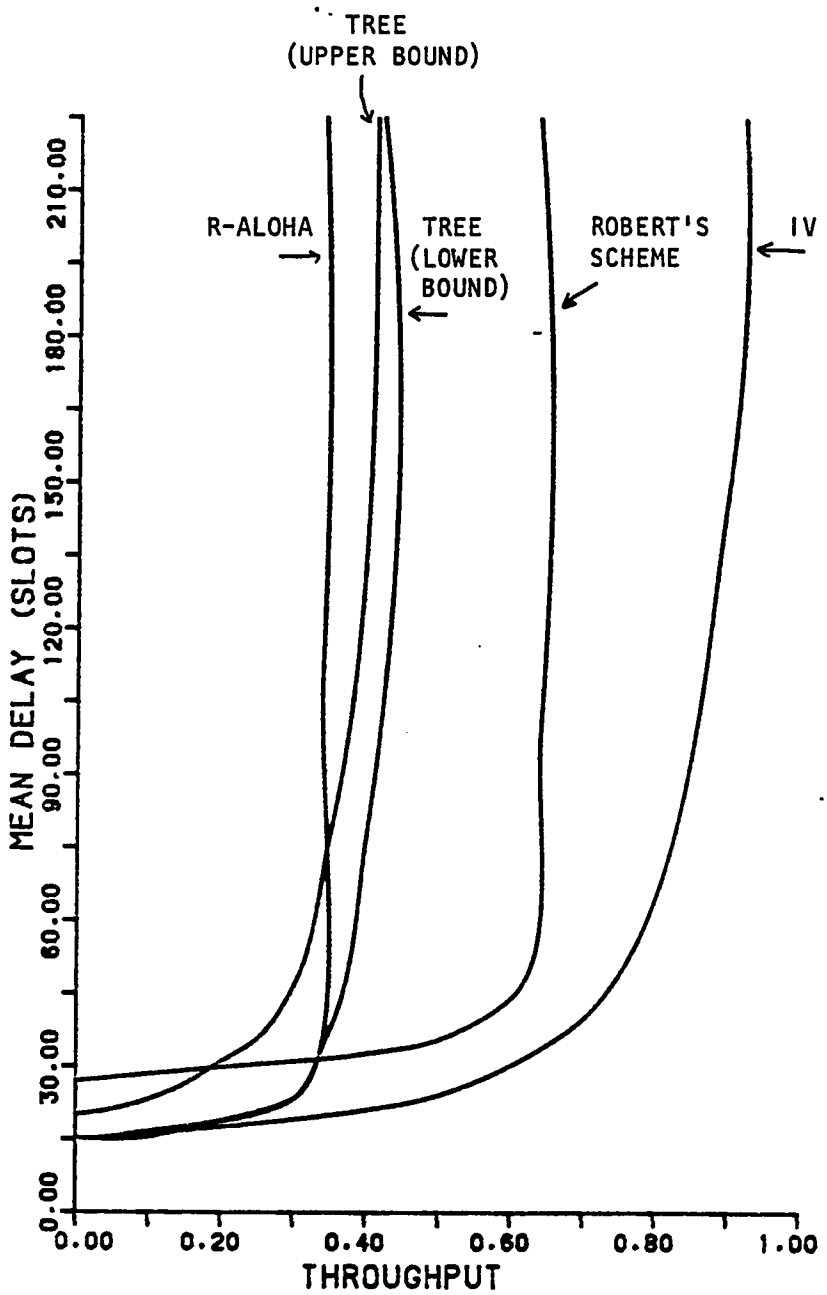


Figure 6.12. Comparison among R-ALOHA, Tree, Scheme IV and Robert's scheme ($K = V = 6$, $M = 2$), for $N = 10$ and $R\tau = 0.27$.

TDMA mode and it offers better performance than TDMA at low traffic intensities only. Under Scheme II, the reservation decisions are made only on collision detection; otherwise system remains in S-ALOHA mode. This scheme adapts from S-ALOHA at low traffic intensities to TDMA at high traffic intensities. Scheme III is a more complex one and requires a small overhead in each packet for the purpose of user identification, thus reserving slots for collided users on each collision. Scheme IV is just the extension of Scheme III with the additional capability of sending queue length information of each collided user, hence reserving more slots for that user in order to avoid further collisions. Schemes III & IV are just S-ALOHA at low traffic and behave nearly perfect scheduling algorithm (M/D/1) at high traffic intensities.

The most interesting feature of all proposed schemes is the stability. This is due to the fact that a packet suffers at most one collision before it is received successfully. The maximum throughput in each scheme can approach unity (if overhead is neglected). Delay analyses for all schemes are performed and are verified by simulation. Buffer analyses show that a user needs a buffer of small lengths ($L \sim 10$) in order to achieve very small probability of overflow.

6.4 SUGGESTIONS FOR FUTURE WORK

The following suggestions are made for future research work on this topic:

(1) We have only considered single packet messages in all schemes. The performances of these schemes should be simulated and analyzed for multipacket messages.

(2) In practice, messages belong to a number of priority classes. The priority level of a message may depend, for example, on its length, source, destination or its type. Non-preemptive priority discipline may be applied to these MA schemes, and

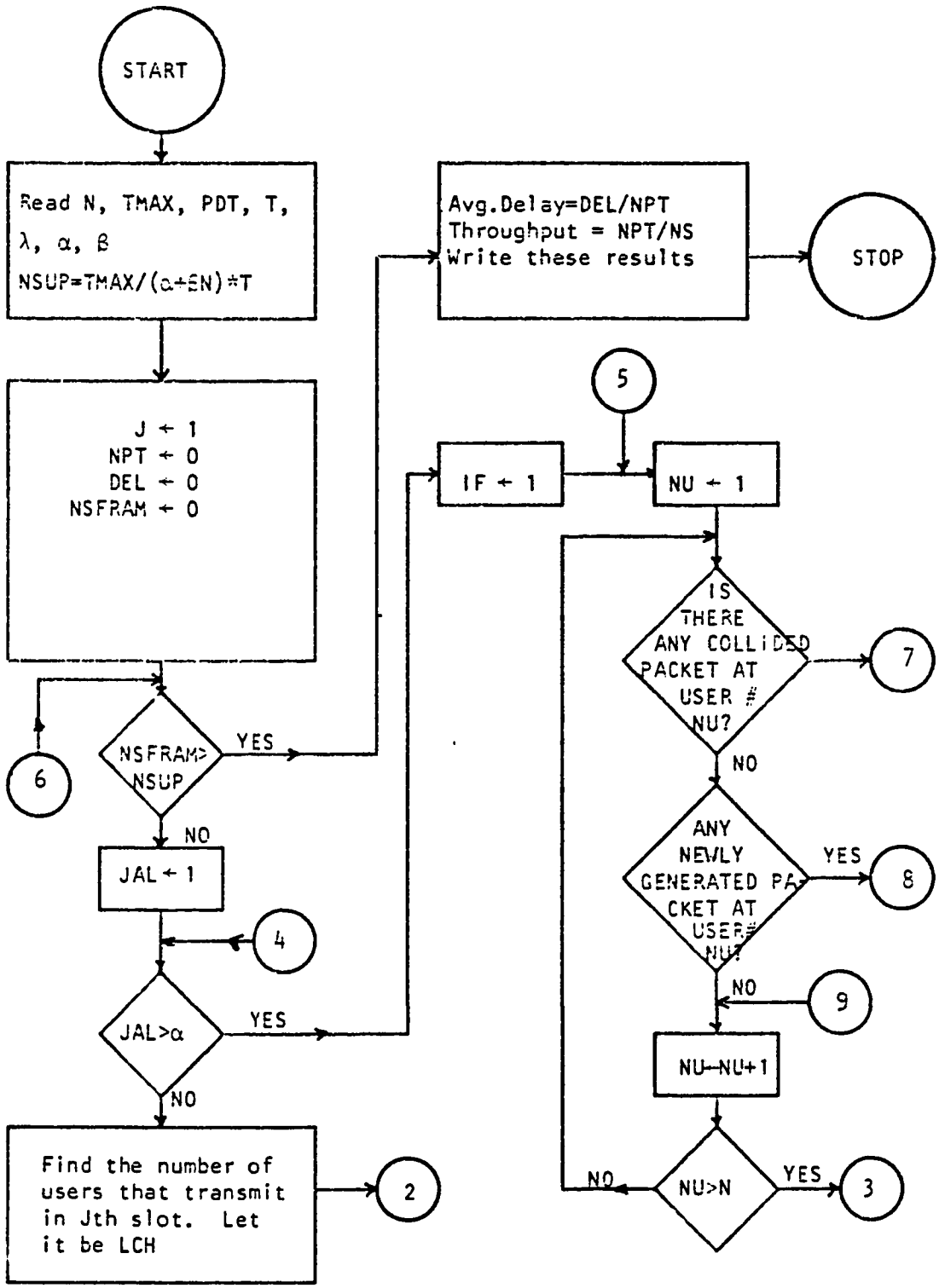
(3) In Scheme IV, we transmit queue length information of a user when that user has undergone a collision. Transmitting queue length information could be one possibility. Other possibilities like message length and priority etc. may be investigated.

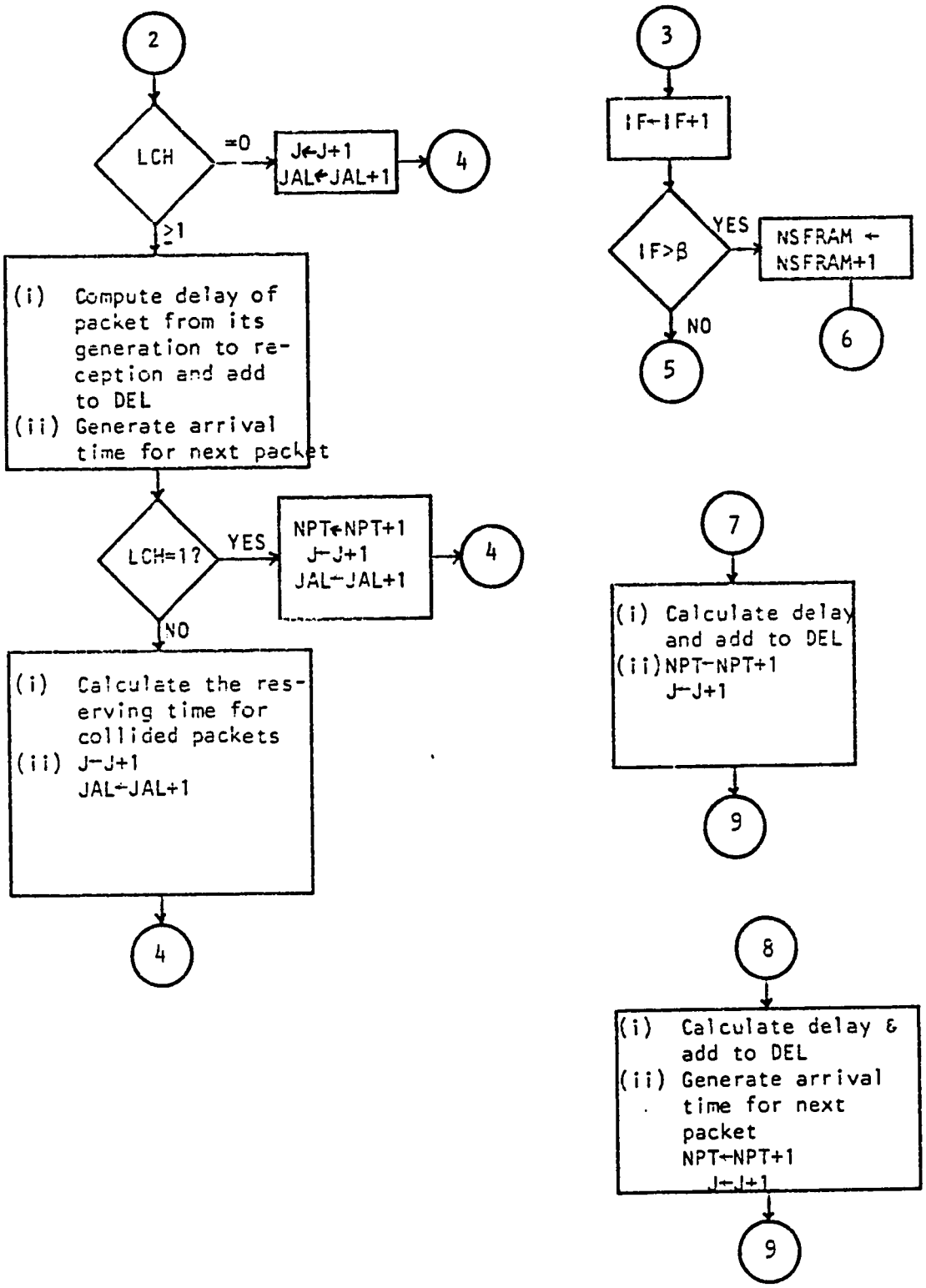
APPENDIX 'A'

The following notations will be used:

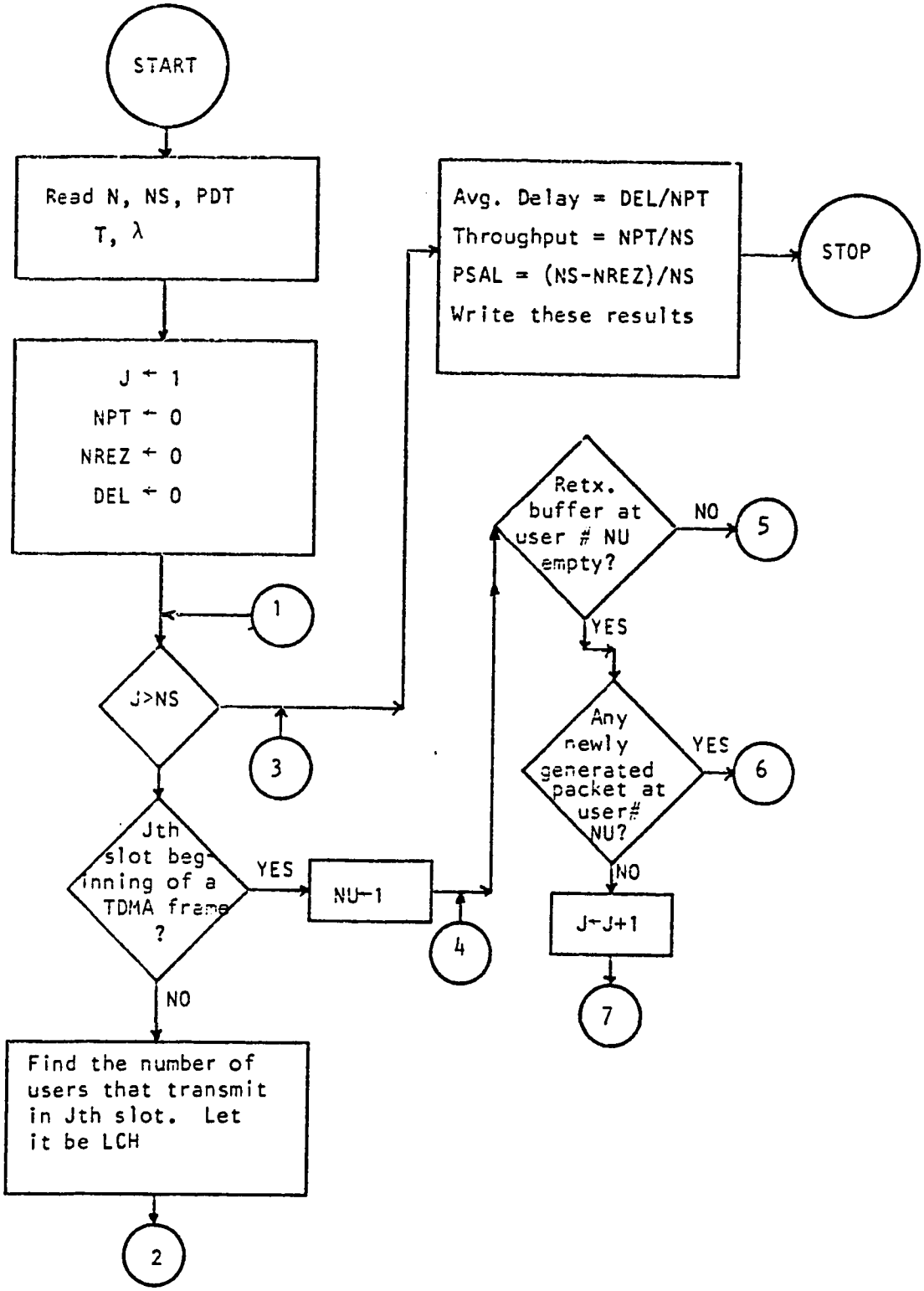
N	= no. of users
TMAX	= Time for simulation run (sec)
NS	= Time for simulation run (slots)
PDT	= Round trip propagation delay (sec)
T	= slot width (sec)
λ	= Avg. no. of packets arriving at each user (Poisson distributed)
J	= A variable used to count the number of slots
NPT	= A variable used to count the no. of successful packets received
DEL	= A variable used to calculate avg. delay.

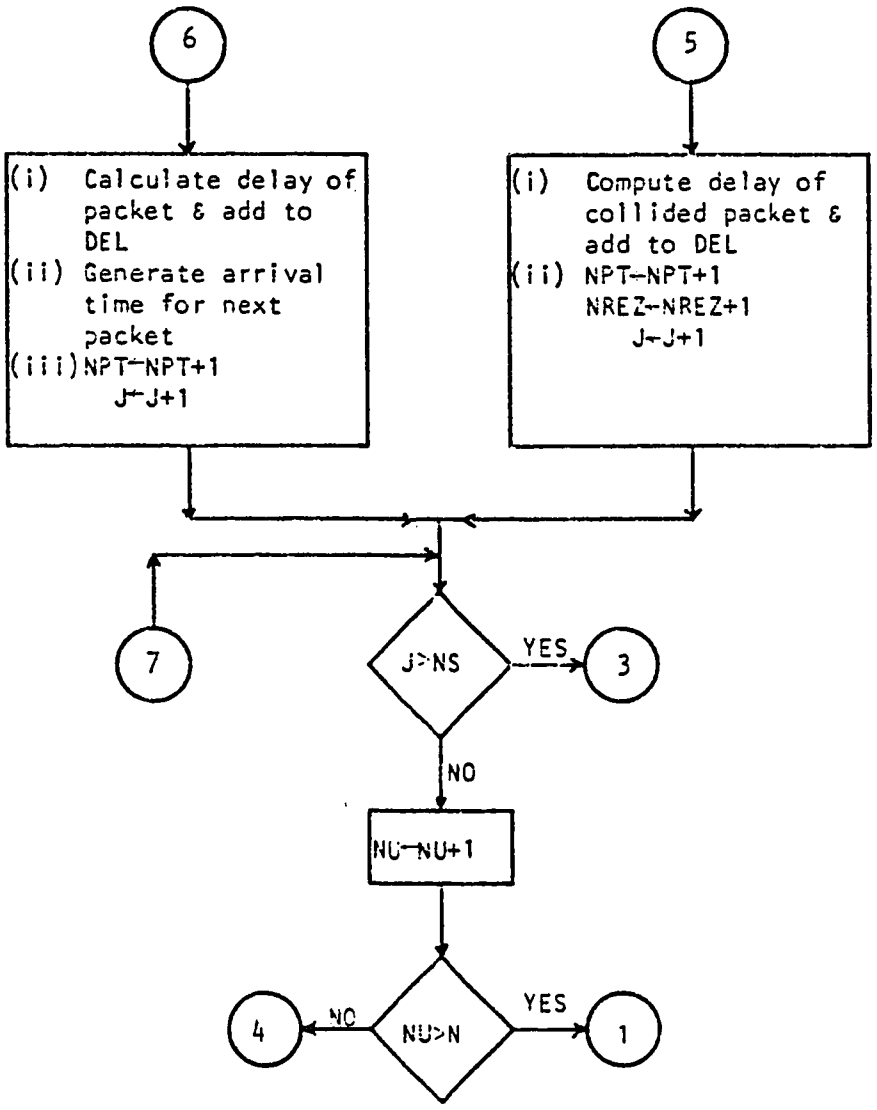
A.1

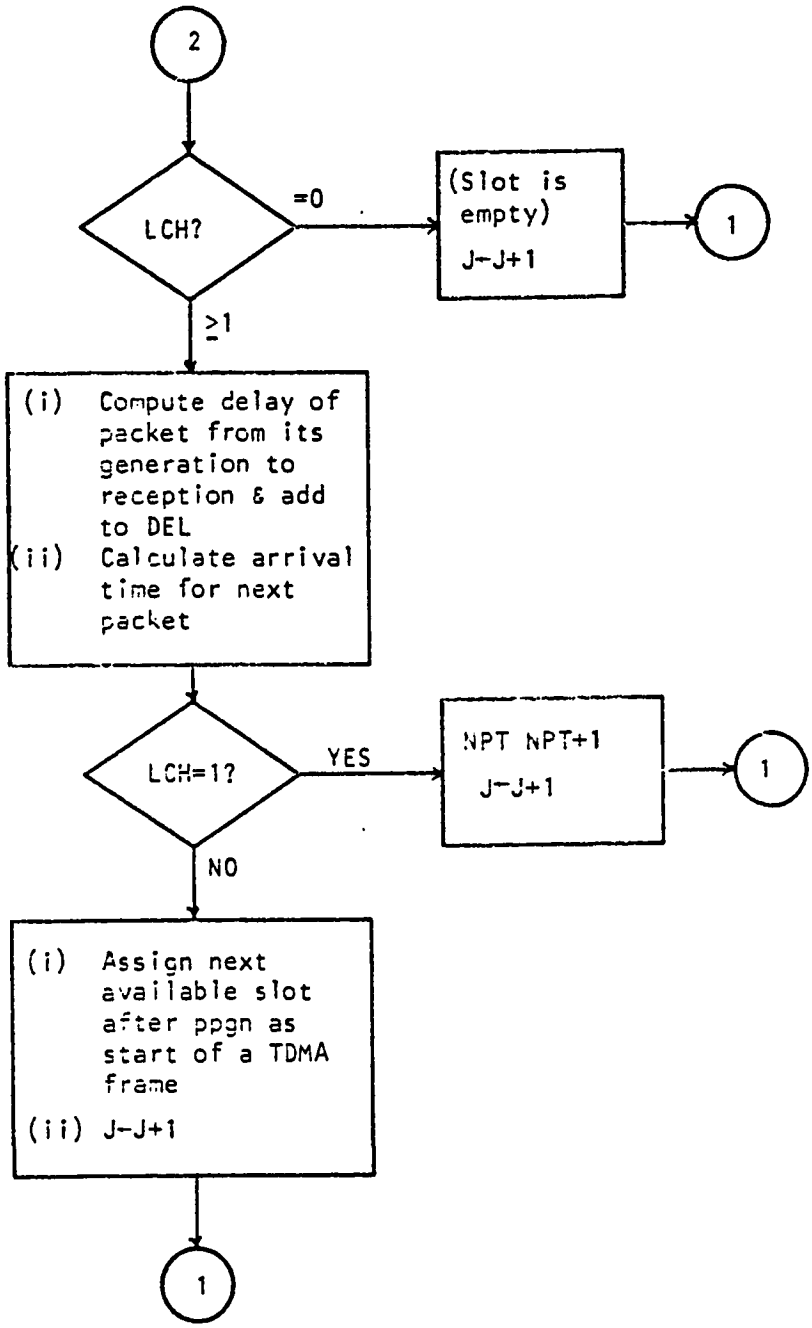

START
Read N, TMAX, PDT, T, λ, α, β
NSUP=TMAX/(α+EN)*T
J ← 1
NPT ← 0
DEL ← 0
NSFRAM ← 0
NSFRAM> NSUP
YES
NO
6
JAL ← 1
4
JAL>α
YES
NO
Find the number of users that transmit in Jth slot. Let it be LCH
2
IF ← 1
5
NU ← 1
IS THERE ANY COLLIDED PACKET AT USER # NU?
7
NO
ANY NEWLY GENERATED PACKET AT USER# NU?
YES
8
NO
9
NU←NU+1
NU>N
NO
YES
3
Avg.Delay=DEL/NPT
Throughput = NPT/NS
Write these results
STOP


2
LCH
=0
J←J+1
JAL←JAL+1
4
≥1
(i) Compute delay of packet from its generation to reception and add to DEL
(ii) Generate arrival time for next packet
LCH=1?
YES
NPT←NPT+1
J←J+1
JAL←JAL+1
4
NO
(i) Calculate the reserving time for collided packets
(ii) J←J+1
JAL←JAL+1
4
3
IF←IF+1
IF>β
YES
NSFRAM ←
NSFRAM+1
6
NO
5
7
(i) Calculate delay and add to DEL
(ii) NPT←NPT+1
J←J+1
9
8
(i) Calculate delay & add to DEL
(ii) Generate arrival time for next packet
NPT←NPT+1
J←J+1
9

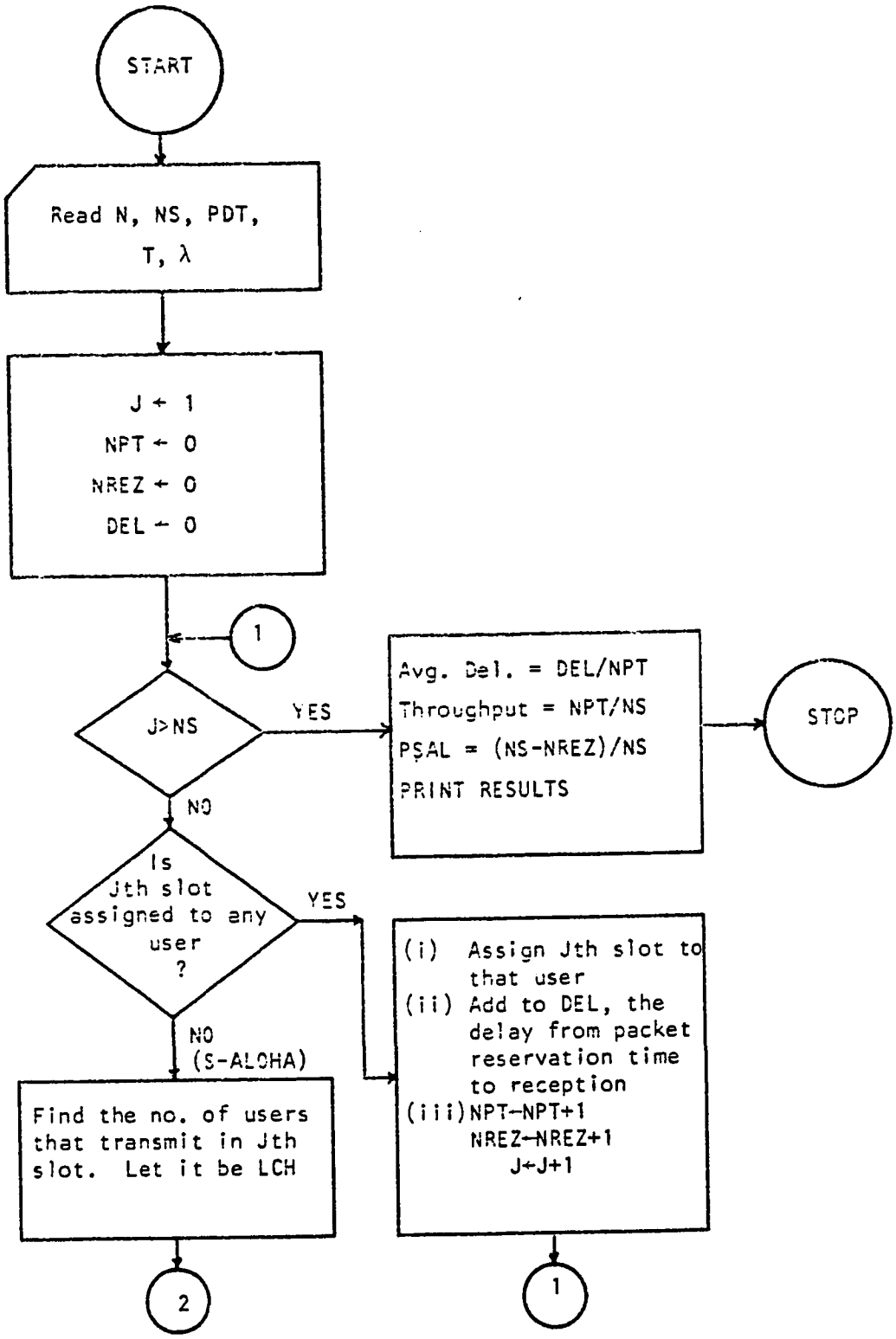
A.2

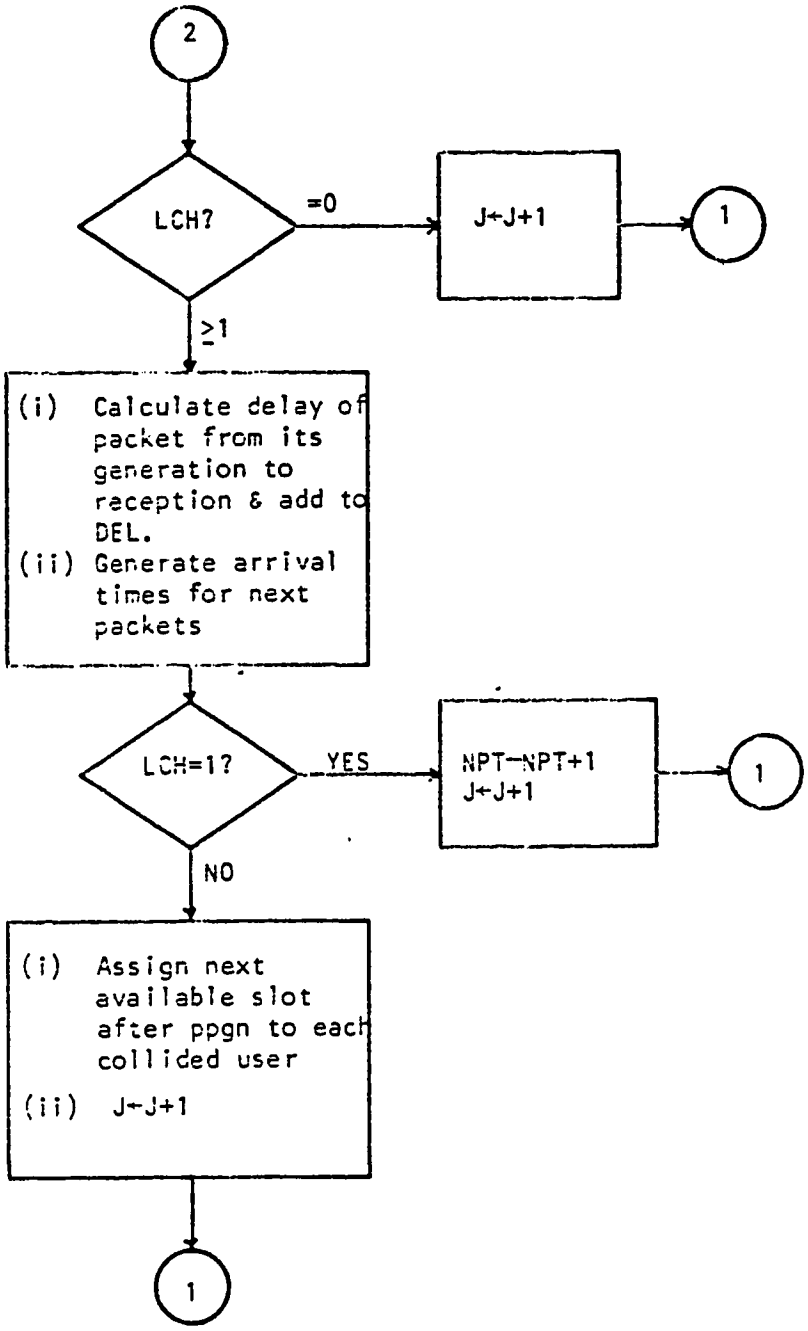

START
Read N, NS, PDT
T, λ
J ← 1
NPT ← 0
NREZ ← 0
DEL ← 0
1
J>NS
3
Jth slot beginning of a TDMA frame ?
YES
NO
NU←1
4
Find the number of users that transmit in Jth slot. Let it be LCH
2
Avg. Delay = DEL/NPT
Throughput = NPT/NS
PSAL = (NS-NREZ)/NS
Write these results
STOP
Retx. buffer at user # NU empty?
NO
5
YES
Any newly generated packet at user# NU?
YES
6
NO
J←J+1
7


6
5
(i) Calculate delay of packet & add to DEL
(ii) Generate arrival time for next packet
(iii) NPT←NPT+1
J←J+1
(i) Compute delay of collided packet & add to DEL
(ii) NPT←NPT+1
NREZ←NREZ+1
J←J+1
7
J>NS
YES
3
NO
NU←NU+1
4
NO
NU>N
YES
1

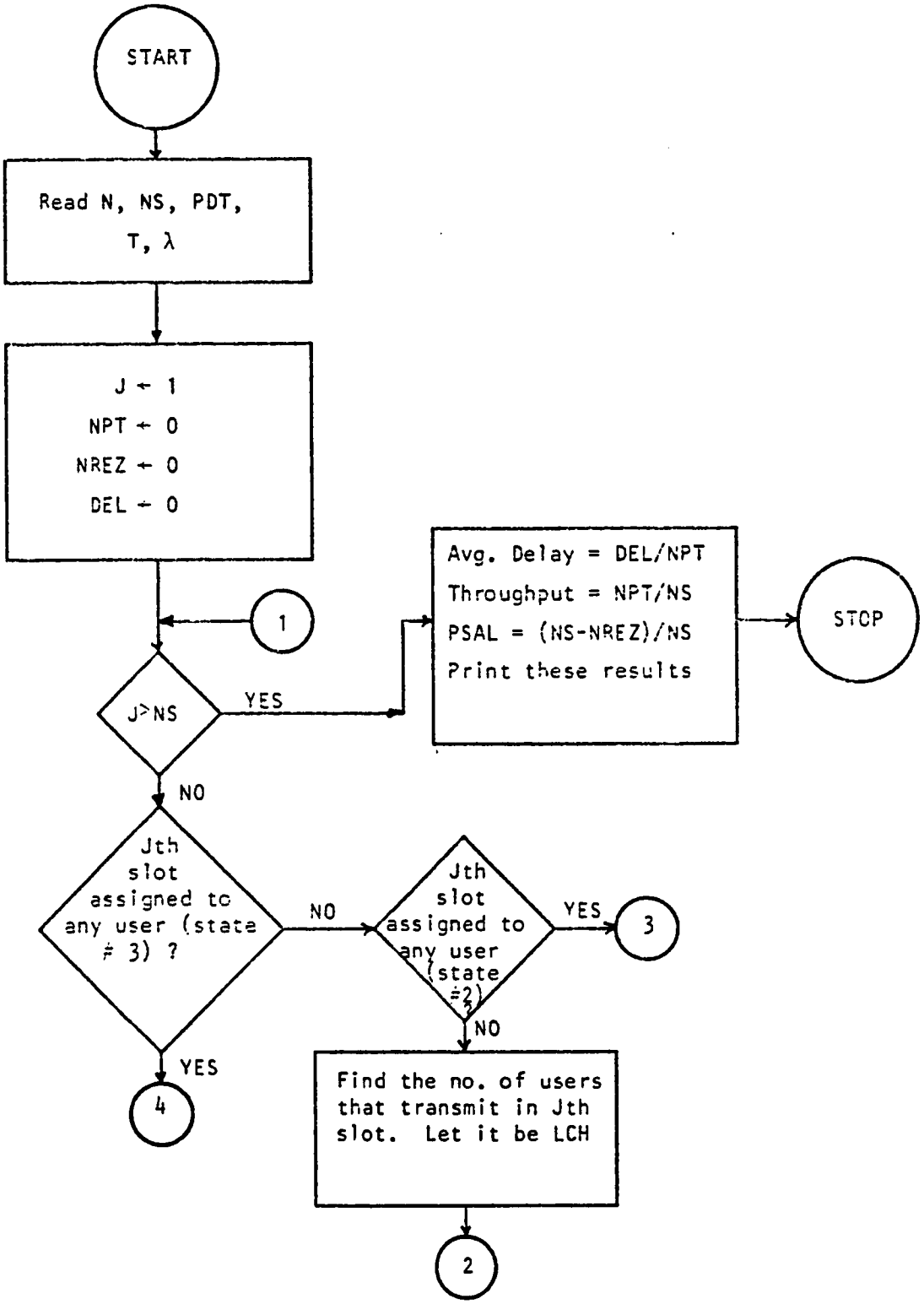

2
LCH?
=0
(Slot is empty)
J←J+1
1
≥1
(i) Compute delay of packet from its generation to reception & add to DEL
(ii) Calculate arrival time for next packet
LCH=1?
YES
NPT NPT+1
J←J+1
1
NO
(i) Assign next available slot after ppgn as start of a TDMA frame
(ii) J←J+1
1

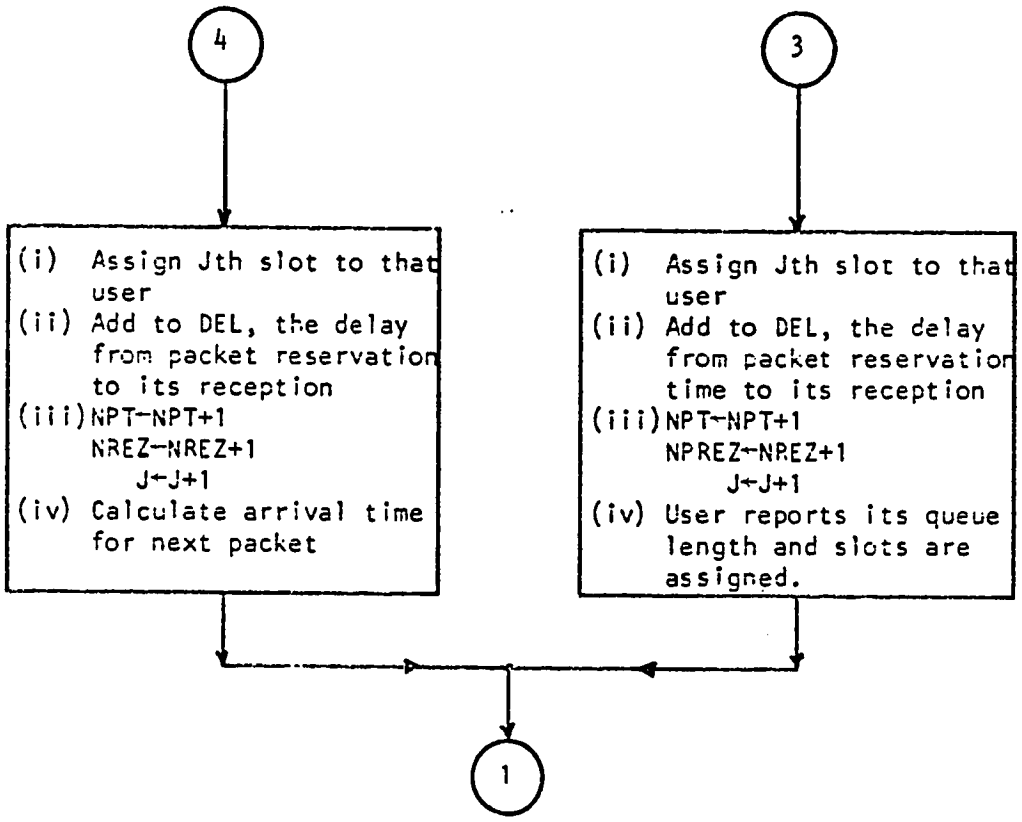
A.3

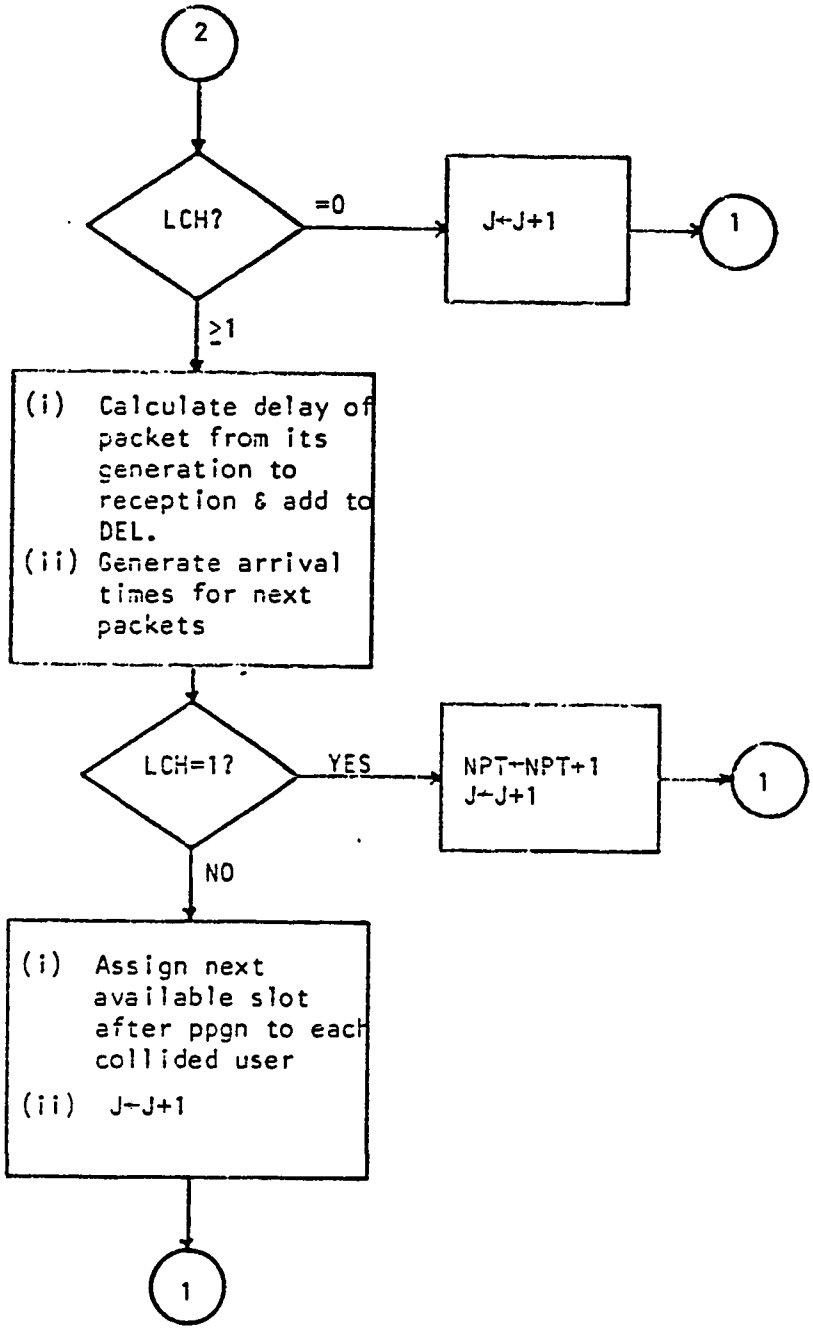

START
Read N, NS, PDT, T, λ
J ← 1
NPT ← 0
NREZ ← 0
DEL ← 0
1
J>NS
YES
NO
Avg. Del. = DEL/NPT
Throughput = NPT/NS
PSAL = (NS-NREZ)/NS
PRINT RESULTS
STOP
Is Jth slot assigned to any user ?
YES
NO (S-ALOHA)
(i) Assign Jth slot to that user
(ii) Add to DEL, the delay from packet reservation time to reception
(iii) NPT←NPT+1
NREZ←NREZ+1
J←J+1
Find the no. of users that transmit in Jth slot. Let it be LCH
2
1


2
LCH?
=0
J←J+1
1
≥1
(i) Calculate delay of packet from its generation to reception & add to DEL.
(ii) Generate arrival times for next packets
LCH=1?
YES
NPT←NPT+1
J←J+1
1
NO
(i) Assign next available slot after ppgn to each collided user
(ii) J←J+1
1

A.4


START
Read N, NS, PDT, T, λ
J ← 1
NPT ← 0
NREZ ← 0
DEL ← 0
1
J>NS
YES
Avg. Delay = DEL/NPT
Throughput = NPT/NS
PSAL = (NS-NREZ)/NS
Print these results
STOP
NO
Jth slot assigned to any user (state ≠ 3) ?
NO
Jth slot assigned to any user (state ≠2)
YES
3
NO
YES
4
Find the no. of users that transmit in Jth slot. Let it be LCH
2


4
3
(i) Assign Jth slot to that user
(ii) Add to DEL, the delay from packet reservation to its reception
(iii) NPT←NPT+1
NREZ←NREZ+1
J←J+1
(iv) Calculate arrival time for next packet
(i) Assign Jth slot to that user
(ii) Add to DEL, the delay from packet reservation time to its reception
(iii) NPT←NPT+1
NPREZ←NREZ+1
J←J+1
(iv) User reports its queue length and slots are assigned.
1


2
LCH?
=0
J←J+1
1
≥1
(i) Calculate delay of packet from its generation to reception & add to DEL.
(ii) Generate arrival times for next packets
LCH=1?
YES
NPT←NPT+1
J←J+1
1
NO
(i) Assign next available slot after ppgn to each collided user
(ii) J←J+1
1

APPENDIX 'B'

```
C*****************************************************
C
C
C                        SCHEME I
C       (INFINITE BUFFERS ARE ASSUMED AT EACH USER)
C
C  N=NUMBER OF USERS
C  T=SLOT LENGTH(SEC.)
C  PDT=PROPAGATION DELAY TIME OF BROADCAST CHANNEL
C  TMAX=RUN LENGTH OF SIMULATION (SEC.)
C  NS=TMAX/T = NO. OF SLOTS CONSIDERED
C  ALAM=AVERAGE NO. OF PACKETS/SEC GENERATED BY EACH
C        IDENTICAL USER  (POISSON DISTRIBUTED)
C  RHO=TOTAL TRAFFIC INTENSITY=N*ALAM*T
C  ALSLT: NO. OF RANDOM ACCESS SLOTS IN A SUPERFRAME
C  BETA : NO. OF TDMA FRAMES IN A SUPERFRAM
C  NPT:  A VAIABLE USED TO COUNT THE NO. OF SUCCESSFUL
C        PACKETS TRANSMITTED
C  NRT:  A VAIABLE USED TO COUNT THE NO. OF COLLIDED
C        PACKETS
C  DEL:  A VARIBLE USED TO CALCULATE AVERAGE DELAY OF A
C        PACKET
C  NSFRAM: A VARIABLE USED TO COUNT SUPERFRAMES
C  TNEXT(K): ARRIVAL TIME OF NEXT NEWLY GENERATED PACKET
C            AT KTH USER
C  LQL(K):  QUEUE LENGTH OF COLLIDED PACKETS AT KTH USER
C  TDMA(K,J): RESERVING TIME FOR JTH COLLIDED PACKET AT
C             KTH USER (TO BE RETRANSMITTED IN TDMA MODE)
C  LCH: A VARIABLE USED TO FIND THE STATUS OF PRESNT
C       SLOT IN S-ALOHA
C       IF LCH=0 -->  EMPTY SLOT
C          LCH=1 -->  ONLY ONE TRANSMISSION
C          LCH>1 -->  MORE THAN ONE TRANSMISSIONS
C                     (COLLISION)
C  NSAVE(K): A VARIABLE USED TO IDENTIFY COLLIDED USER
C            IN S-ALOHA MODE
C            IF NSAVE(K)=K --> KTH USER IS INVOLVED IN
C                              COLLISION
C               NSAVE(I)=0 --> KTH USER IS NOT INVOLVED
C                              IN COLLISION
C  S :   THROUGHPUT OF THE CHANNEL
C
C*****************************************************
C
      DIMENSION TNEXT(10),TDMA(10,100),LQL(10),NSAVE(10),
     1IX(10)
      INTEGER BETA,ALSLT
```

```
C
C  READING SYSTEM PARAMETERS
C
      READ(5,*)N,T,PDT
      READ(5,*)TMAX
      READ(5,*)ALSLT,BETA
      WRITE(6,20)
20    FORMAT('1',//,20X,'SCH I INFINITE BUFFER CASE'/)
      NS=IFIX(TMAX/T+T/2)
      WRITE(6,17)N,TMAX,T,PDT,NS
17    FORMAT(5X,'NO. OF USERS=',I3,5X,'TMAX(SEC)=',F6.1,
     15X,'TIME FOR EACH STATION=',F6.3,/,7X,'PDT=',F7.4,
     25X,'NS=',I6/)
     WRITE(6,118)ALSLT,BETA
118  FORMAT(5X,'NO. OF S-ALOHA SLOTS IN EACH SUPERFRAME='
    1,I3,/,7X,'NO. OF TDMA FRAMES IN EACH SUPERFRAME=',
    2I4/)
      T1030=10**30.
      NPDT=IFIX(PDT/T)+1
      WRITE(6,11)
11    FORMAT(7X,'LAMBDA',08X,'RHO',15X,'S',9X,
     1'AVG. DELAY'//)
      PDTT=PDT+T
      TSFRAM=(BETA)*N*T+(ALSLT*T)
      DO 101 NO=1,10
C
C  READING MEAN PACKET ARRIVAL RATE AT EACH USER
C
      READ(5,*)ALAM
      TMEAN=1./ALAM
C
C INITIALIZING COUNTERS &
C SEED ASSIGNMENT TO EACH USER (FOR RANDOM NUMBER
C GENERATION)
C
      NSFRAM=-1
      NPT=0
      NRT=0
      DEL=0.
      DO 100 I=1,N
      IX(I)=888*I+1
      IUU=IX(I)
      CALL RANDU(IUU,IY,YFL)
      IX(I)=IY
      TNEXT(I)=-(TMEAN)*ALOG(YFL)
      TDMA(I,1)=T1030
      LQL(I)=0
  100 CONTINUE
  144 NSFRAM=NSFRAM+1
  46  TEMP=NSFRAM*TSFRAM
```

```
C
C  START OF A SUPERFRAME
C
      DO 47 J=1,ALSLT
C
C  NORMAL SLOTTED ALOHA MODE
C
      TS=TEMP+(J-1)*T
      IF(TS.GE.TMAX) GO TO 59
      LCH=0
      DO 58 K=1,N
 58   NSAVE(K)=0
      DO 48 JS=1,N
      IF(TNEXT(JS).LE.TS)THEN
        LCH=LCH+1
        DEL=DEL+TS-TNEXT(JS)+PDTT
        IUU=IX(JS)
        CALL RANDU(IUU,IY,YFL)
        IX(JS)=IY
        TNEXT(JS)=TNEXT(JS)-TMEAN*ALOG(YFL)
        NSAVE(JS)=JS
      ENDIF
 48   CONTINUE
      IF(LCH.EQ.0) GO TO 47
C
C LCH=1 -->  SINGLE SUCCESSFUL TRANSMISSION
C
      IF(LCH.EQ.1) THEN
        NPT=NPT+1
        GO TO 47
      ENDIF
C
C LCH>1 --> A COLLISION HAS TAKEN PLACE
C
      DO 50 I2=1,N
      LSAVE=NSAVE(I2)
      IF(LSAVE.NE.0) THEN
        NRT=NRT+1
        DEL=DEL+TS-TNEXT(LSAVE)+PDTT
        IUU=IX(LSAVE)
        CALL RANDU(IUU,IY,YFL)
        IX(LSAVE)=IY
        TNEXT(LSAVE)=TNEXT(LSAVE)-TMEAN*ALOG(YFL)
        LQL(LSAVE)=LQL(LSAVE)+1
        L=LQL(LSAVE)
        TDMA(LSAVE,L)=TS+PDTT
      ENDIF
 50   CONTINUE
 47   CONTINUE
```

```
C
C  START OF TDMA MODE (PRIORITY IS GIVEN TO COLLIDED
C PACKETS )
C
 466  DO 51 KKK=1,BETA
      DUM=TS+T
      DO 51 J=1,N
      TS=DUM+(J-1)*T
      IF(TS.GE.TMAX) GO TO 59
C
      IF(TDMA(J,1).LE.TS) THEN
        NPT=NPT+1
        DEL=DEL+TS-TDMA(J,1)+PDTT
        LQL(J)=LQL(J)-1
        L=LQL(J)
        IF(L.EQ.0) THEN
          TDMA(J,1)=T1030
          GO TO 52
        ENDIF
        DO 53 KK=1,L
 53     TDMA(J,KK)=TDMA(J,KK+1)
 52     CONTINUE
        GO TO 51
      ENDIF
C
      IF(TNEXT(J).LE.TS) THEN
        NPT=NPT+1
        DEL=DEL+TS-TNEXT(J)+PDTT
        IUU=IX(J)
        CALL RANDU(IUU,IY,YFL)
        IX(J)=IY
        TNEXT(J)=TNEXT(J)-TMEAN*ALOG(YFL)
      ENDIF
 51   CONTINUE
C
 49   GO TO 144
C
 59   DEL=DEL/NPT
      KSLOT=IFIX(TS/T)
      RK=FLOAT(KSLOT)
      S=FLOAT(NPT)/RK
      RHO=N*ALAM*T
      WRITE(6,2)ALAM,RHO,S,DEL
 2    FORMAT(7X,F7.3,5X,F8.5,8X,F8.4,5X,F12.4//)
 101  CONTINUE
      STOP
      END
```

```
$ENTRY
10,0.02,0.27
1000.
10,1
0.05
0.2
0.5
1.
1.5
2.
2.5
3.5
4.5
5.
```

B.2

```
C*****************************************************
C
C
C                        SCHEME II
C       (INFINITE BUFFERS ARE ASSUMED AT EACH USER)
C
C  N=NUMBER OF USERS
C  T=SLOT LENGTH(SEC.)
C  PDT=PROPAGATION DELAY TIME OF BROADCAST CHANNEL
C  TMAX=RUN LENGTH OF SIMULATION (SEC.)
C  NS=TMAX/T = NO. OF SLOTS CONSIDERED
C  ALAM=AVERAGE NO. OF PACKETS/SEC GENERATED BY EACH
C        IDENTICAL USER  (POISSON DISTRIBUTED)
C  RHO=TOTAL TRAFFIC INTENSITY=N*ALAM*T
C  NPT:  A VAIABLE USED TO COUNT THE NO. OF SUCCESSFUL
C        PACKETS TRANSMITTED
C  NRT:  A VAIABLE USED TO COUNT THE NO. OF COLLIDED
C        PACKETS
C  DEL:  A VARIBLE USED TO CALCULATE AVERAGE DELAY OF A
C        PACKET
C  TNEXT(K): ARRIVAL TIME OF NEXT NEWLY GENERATED PACKET
C            AT KTH USER
C  NSRES(K,J):  AN ARRAY TO STORE RESERVED SLOTS NUMBER
C               FOR KTH USER
C  LQL(K):  QUEUE LENGTH OF COLLIDED PACKETS AT KTH USER
C  TSRES(K,J): RESERVING TIME FOR JTH COLLIDED PACKET AT
C              KTH USER
C  LCH: A VARIABLE USED TO FIND THE STATUS OF PRESNT
C       SLOT IN S-ALOHA
C       IF LCH=0 -->  EMPTY SLOT
C          LCH=1 -->  ONLY ONE TRANSMISSION
C          LCH>1 -->  MORE THAN ONE TRANSMISSIONS
C                     (COLLISION)
C  NSAVE(K): A VARIABLE USED TO IDENTIFY COLLIDED USER
C            IN S-ALOHA MODE
C            IF NSAVE(K)=K --> KTH USER IS INVOLVED IN
C                              COLLISION
C               NSAVE(I)=0 --> KTH USER IS NOT INVOLVED
C                              IN COLLISION
C  MAX : A VARIABLE USED TO GIVE THE MAXIMUM SLOT NUMBER
C        AT WHICH RESERVATION HAS BEEN ASSIGNED
C  NTDM : A VARIABLE USED TO COUNT THE NUMBER OF
C         RESERVED FRAMES
C  KOL : A VARIABLE USED TO CALCULATE THE NO. OF
C        COLLISIONS WHICH THE SYSTEM HAS TO RESOLVE AT
C        PRESENT
C  PSAL: PROBABILITY THAT THE SYSTEM IS IN S-ALOHA MODE
C  S :   THROUGHPUT OF THE CHANNEL
```

```
C
C*****************************************************
C
      DIMENSION TNEXT(10 ),IX(10 ),NSAVE(10 ),
     1TSRES(10 ,70 ),LQL(10 ),NSRES(10 ,70 )
C
C  READING SYSTEM PARAMETERS
C
      READ(5,*)N,T,PDT
      READ(5,*)TMAX
      WRITE(6,20)
20    FORMAT('1',//,20X,'SCH II INFINITE BUFFER CASE'/)
      NS=IFIX(TMAX/T+T/2)
      WRITE(6,17)N,TMAX,T,PDT,NS
17    FORMAT(5X,'NO. OF USERS=',I3,5X,'TMAX(SEC)=',F6.1,
     15X,'TIME FOR EACH STATION=',F6.3,/,7X,'PDT=',F7.4,
     25X,'NS=',I6/)
      T1030=10**30.
      INFIN=9999999
      NPDT=IFIX(PDT/T)+1
      WRITE(6,11)
11    FORMAT(7X,'LAMBDA',08X,'RHO',15X,'S',9X,
     1'AVG. DELAY'//)
      PDTT=PDT+T
      DO 101 NO=1,10
C
C  READING MEAN PACKET ARRIVAL RATE AT EACH USER
C
      READ(5,*)ALAM
      TMEAN=1./ALAM
C
C INITIALIZING COUNTERS &
C SEED ASSIGNMENT TO EACH USER (FOR RANDOM NUMBER
C GENERATION)
C
      NPT=0
      NRT=0
      DEL=0.
      MAX=0
      KOL=0
      NTDM=0
      DO 100 I=1,N
      IX(I)=888*I+1
      IUU=IX(I)
      CALL RANDU(IUU,IY,YFL)
      IX(I)=IY
      TNEXT(I)=-TMEAN*ALOG(YFL)
      NSRES(I,1)=INFIN
      TSRES(I,1)=T1030
      LQL(I)=0
```

```
100     CONTINUE
        TS=0.0
        J=1
 160    IF(J.GT.NS)GO TO 592
        IF(KOL.EQ.0)GO TO 62
C
C  WHETHER THE PRESENT SLOT BELONGS TO A RESERVED FRAME?
C
        IF(J.NE.NSRES(1,1))GO TO 62
 32     NTDM=NTDM+1
        DO 230 JR=1,N
        IF(J.EQ.NSRES(JR,1))THEN
          IF(TSRES(JR,1).GT.TS)GO TO 63
          NPT=NPT+1
          DEL=DEL+PDTT+TS-TSRES(JR,1)
          LQL(JR)=LQL(JR)-1
          IF(LQL(JR).EQ.0)THEN
            TSRES(JR,1)=T1030
            GO TO 90
          ENDIF
          L=LQL(JR)
          DO 233 JZ=1,L
          TSRES(JR,JZ)=TSRES(JR,JZ+1)
 233      CONTINUE
          GO TO 90
 63       CONTINUE
C
C USER #JR HAS NO COLLIDED PACKET TO TRANSMIT IN ITS
C ASSIGNED SLOT; CHECKING FOR ANY NEWLY ARRIVED PACKET
C
          IF(TNEXT(JR).LE.TS)THEN
            NPT=NPT+1
            DEL=DEL+PDTT+TS-TNEXT(JR)
            IUU=IX(JR)
            CALL RANDU(IUU,IY,YFL)
            IX(JR)=IY
            TNEXT(JR)=TNEXT(JR)-TMEAN*ALOG(YFL)
            TS=TS+T
            J=J+1
            GO TO 231
          ENDIF
 90       TS=TS+T
          J=J+1
 231      IF(JR.EQ.N)THEN
            KOL=KOL-1
            DO 95 I=1,N
            IF(KOL.EQ.0)THEN
              NSRES(I,1)=INFIN
              GO TO 95
            ENDIF
```

```
          DO 96 II=1,KOL
          NSRES(I,II)=NSRES(I,II+1)
 96       CONTINUE
 95       CONTINUE
          GO TO 160
        ENDIF
      ENDIF
 230  CONTINUE
C
C NORMAL S-ALOHA OPERATION
C
 62   LCH=0
      DO 58 K=1,N
 58   NSAVE(K)=0
 401  DO 48 JS=1,N
      IF(TNEXT(JS).LE.TS)THEN
        LCH=LCH+1
        NSAVE(JS)=JS
        DEL=DEL+TS-TNEXT(JS)+PDTT
        IUU=IX(JS)
        CALL RANDU(IUU,IY,YFL)
        IX(JS)=IY
        TNEXT(JS)=TNEXT(JS)-TMEAN*ALOG(YFL)
      ENDIF
 48   CONTINUE
C
      IF(LCH.EQ.0) GO TO 47
C
C LCH=1 -->  SINGLE SUCCESSFUL TRANSMISSION
C
      IF(LCH.EQ.1) THEN
        NPT=NPT+1
        GO TO 47
      ENDIF
C
C LCH>1 --> COLLISION HAS TAKEN PLACE
C
 59   INC=0
      KOL=KOL+1
      DO 581I=1,N
      LSAVE=NSAVE(I)
      IF(LSAVE.EQ.0) GO TO 114
      NRT=NRT+1
 65   LQL(I)=LQL(I)+1
      LQ1=LQL(I)
      TSRES(I,LQ1)=TS+PDTT
 114  NSRES(I,KOL)=NPDT+J+INC
      IF(NSRES(I,KOL).LE.MAX)NSRES(I,KOL)=MAX+1
      INC=INC+1
      MAX=NSRES(I,KOL)
```

```
 581  CONTINUE
 47   TS=TS+T
      J=J+1
      GO TO 160
 592  DEL=DEL/NPT
      S=FLOAT(NPT)/FLOAT(NS)
      NTEMP=NS-(NTDM*N)
      PSAL=FLOAT(NTEMP)/FLOAT(NS)
      RHO=N*ALAM*T
      WRITE(6,2)ALAM,RHO,S,DEL
      WRITE(6,555)NRT ,PSAL
 555  FORMAT(5X,'NRT=',I6,5X,'PSAL=',F10.6/)
 2    FORMAT(7X,F7.3,5X,F8.5,8X,F8.4,5X,F12.4//)
 101  CONTINUE
      STOP
      END
$ENTRY
10,0.02,0.27
1000.
0.05
0.2
0.5
1.
1.5
2.
2.5
3.5
4.5
5.
```

B.3

```
C
C*****************************************************
C
C
C                        SCHEME III
C       (INFINITE BUFFERS ARE ASSUMED AT EACH USER)
C
C  N=NUMBER OF USERS
C  T=SLOT LENGTH(SEC.)
C  PDT=PROPAGATION DELAY TIME OF BROADCAST CHANNEL
C  TMAX=RUN LENGTH OF SIMULATION (SEC.)
C  NS=TMAX/T = NO. OF SLOTS CONSIDERED
C  ALAM=AVERAGE NO. OF PACKETS/SEC GENERATED BY EACH
C        IDENTICAL USER  (POISSON DISTRIBUTED)
C  RHO=TOTAL TRAFFIC INTENSITY=N*ALAM*T
C  NPT:  A VAIABLE USED TO COUNT THE NO. OF SUCCESSFUL
C        PACKETS TRANSMITTED
C  NRT:  A VAIABLE USED TO COUNT THE NO. OF COLLIDED
C        PACKETS
C  DEL:  A VARIBLE USED TO CALCULATE AVERAGE DELAY OF A
C        PACKET
C  TNEXT(K): ARRIVAL TIME OF NEXT NEWLY GENERATED PACKET
C            AT KTH USER
C  NSRES(K,J):  AN ARRAY TO STORE RESERVED SLOTS NUMBER
C               FOR KTH USER
C  LQL(K):  QUEUE LENGTH OF COLLIDED PACKETS AT KTH USER
C  TSRES(K,J): RESERVING TIME FOR JTH COLLIDED PACKET AT
C              KTH USER
C  NREZ : A VARIABLE USED TO COUNT THE NO. OF SLOTS FOR
C         WHICH THE SYSTEM REMAINED IN RESERVED MODE
C  LCH: A VARIABLE USED TO FIND THE STATUS OF PRESNT
C       SLOT IN S-ALOHA
C       IF LCH=0 -->  EMPTY SLOT
C          LCH=1 -->  ONLY ONE TRANSMISSION
C          LCH>1 -->  MORE THAN ONE TRANSMISSIONS
C                     (COLLISION)
C  NSAVE(K): A VARIABLE USED TO IDENTIFY COLLIDED USER
C            IN S-ALOHA MODE
C            IF NSAVE(K)=K --> KTH USER IS INVOLVED IN
C                              COLLISION
```

```
C                NSAVE(I)=0 --> KTH USER IS NOT INVOLVED
C                                IN COLLISION
C  MAX : A VARIABLE USED TO GIVE THE MAXIMUM SLOT NUMBER
C        AT WHICH RESERVATION HAS BEEN ASSIGNED
C  PSAL: PROBABILITY THAT THE SYSTEM IS IN S-ALOHA MODE
C  S :   THROUGHPUT OF THE CHANNEL
C
C*****************************************************
C
      DIMENSION TNEXT(10 ),IX(10 ),NSAVE(10 ),
     1TSRES(10 ,70 ),LQL(10 ),NSRES(10 ,70 )
C
C  READING SYSTEM PARAMETERS
C
      READ(5,*)N,T,PDT
      READ(5,*)TMAX
      WRITE(6,20)
20    FORMAT('1',//,20X,'SCH III INFINITE BUFFER CASE'/)
      NS=IFIX(TMAX/T+T/2)
      WRITE(6,17)N,TMAX,T,PDT,NS
17    FORMAT(5X,'NO. OF USERS=',I3,5X,'TMAX(SEC)=',F6.1,
     15X,'TIME FOR EACH STATION=',F6.3,/,7X,'PDT=',F7.4,
     25X,'NS=',I6/)
      T1030=10**30.
      INFIN=9999999
      NPDT=IFIX(PDT/T)+1
      WRITE(6,11)
11    FORMAT(7X,'LAMBDA',08X,'RHO',15X,'S',9X,
     1'AVG. DELAY'//)
      PDTT=PDT+T
      DO 101 NO=1,10
C
C  READING MEAN PACKET ARRIVAL RATE AT EACH USER
C
      READ(5,*)ALAM
      TMEAN=1./ALAM
C
C INITIALIZING COUNTERS &
C SEED ASSIGNMENT TO EACH USER (FOR RANDOM NUMBER
C GENERATION)
C
      NPT=0
      NRT=0
      NREZ=0
      DEL=0.
      MAX=0
      DO 100 I=1,N
      IX(I)=888*I+1
      IUU=IX(I)
```

```
      CALL RANDU(IUU,IY,YFL)
      IX(I)=IY
      TNEXT(I)=-TMEAN*ALOG(YFL)
      NSRES(I,1)=INFIN
      TSRES(I,1)=T1030
      LQL(I)=0
100   CONTINUE
C
      TS=-T
      DO 47 J=1,NS
      TS=TS+T
C
C SEARCHING THAT IF THE PRESENT SLOT 'J' IS ASSIGNED TO
C ANY USER
C
      DO 230 JR=1,N
      IF(J.EQ.NSRES(JR,1))THEN
        NPT=NPT+1
        NREZ=NREZ+1
        DEL=DEL+PDTT+TS-TSRES(JR,1)
        LQL(JR)=LQL(JR)-1
        IF(LQL(JR).EQ.0)THEN
          NSRES(JR,1)=INFIN
          TSRES(JR,1)=T1030
          GO TO 47
        ENDIF
        L=LQL(JR)
        DO 233 JZ=1,L
        NSRES(JR,JZ)=NSRES(JR,JZ+1)
        TSRES(JR,JZ)=TSRES(JR,JZ+1)
233     CONTINUE
        GO TO 47
      ENDIF
 230  CONTINUE
C
C NORMAL S-ALOHA OPERATION
C
      LCH=0
      DO 58 K=1,N
 58   NSAVE(K)=0
C
C FIND THE STATUS OF PRESENT SLOT,FIND DELAY,GENERATE
C ARRIVAL TIME FOR NEXT PACKET (IF APPLICABLE)
C
 401  DO 48 JS=1,N
      IF(TNEXT(JS).LE.TS)THEN
        LCH=LCH+1
        NSAVE(JS)=JS
        DEL=DEL+TS-TNEXT(JS)+PDTT
```

```
        IUU=IX(JS)
        CALL RANDU(IUU,IY,YFL)
        IX(JS)=IY
        TNEXT(JS)=TNEXT(JS)-TMEAN*ALOG(YFL)
      ENDIF
 48   CONTINUE
C
      IF(LCH.EQ.0) GO TO 47
      IF(LCH.EQ.1) THEN
        NPT=NPT+1
        GO TO 47
      ENDIF
C LCH >1  A COLLISON HAS TAKEN PLACE
C
 59   INC=0
      DO 581I=1,N
      IF(NSAVE(I).EQ.0) GO TO 581
      NRT=NRT+1
 65   LQL(I)=LQL(I)+1
      LQ1=LQL(I)
      TSRES(I,LQ1)=TS+PDTT
      NSRES(I,LQ1)=NPDT+J+INC
      IF(NSRES(I,LQ1).LE.MAX)NSRES(I,LQ1)=MAX+1
      INC=INC+1
      MAX=NSRES(I,LQ1)
 581  CONTINUE
 47   CONTINUE
C
 592  DEL=DEL/NPT
      S=FLOAT(NPT)/FLOAT(NS)
      RHO=N*ALAM*T
      PSAL=FLOAT(NS-NREZ)/FLOAT(NS)
      WRITE(6,2)ALAM,RHO,S,DEL
 2    FORMAT(7X,F7.3,5X,F8.5,8X,F8.4,5X,F12.4//)
      WRITE(6,*)PSAL
      WRITE(6,1002)NRT
 1002 FORMAT(5X,'NO. OF RETXS.=',I5)
C
 101  CONTINUE
      STOP
      END

$ENTRY
10, 0.02 ,0.27
1000.
0.05
0.2
0.5
1.
```

1.5
2.
2.5
3.5
4.5
5.

B.4

```
C*****************************************************
C
C
C                          SCHEME IV
C        (INFINITE BUFFERS ARE ASSUMED AT EACH USER)
C
C  N=NUMBER OF USERS
C  T=SLOT LENGTH(SEC.)
C  PDT=PROPAGATION DELAY TIME OF BROADCAST CHANNEL
C  TMAX=RUN LENGTH OF SIMULATION (SEC.)
C  NS=TMAX/T = NO. OF SLOTS CONSIDERED
C  ALAM=AVERAGE NO. OF PACKETS/SEC GENERATED BY EACH
C        IDENTICAL USER  (POISSON DISTRIBUTED)
C  RHO=TOTAL TRAFFIC INTENSITY=N*ALAM*T
C  NPT:  A VAIABLE USED TO COUNT THE NO. OF SUCCESSFUL
C        PACKETS TRANSMITTED
C  NRT:  A VAIABLE USED TO COUNT THE NO. OF COLLIDED
C        PACKETS
C  DEL:  A VARIBLE USED TO CALCULATE AVERAGE DELAY OF A
C        PACKET
C  CAT(K,J): ARRIVAL TIME OF JTH  NEWLY GENERATED PACKET
C            AT KTH USER
C  NSRES1(K,J): AN ARRAY TO STORE RESERVED SLOTS NUMBER
C               FOR KTH USER FOR STATE #2
C  NSREQ2(K,J): AN ARRAY TO STORE RESERVED SLOTS NUMBER
C               FOR KTH USER FOR STATE #3
C  LQL(K):  QUEUE LENGTH OF COLLIDED PACKETS AT KTH USER
C  TSRES(K,J): RESERVING TIME FOR JTH COLLIDED PACKET AT
C              KTH USER
C  ISLRES: A VARIABLE USED TO COUNT THE NO. OF SLOTS FOR
C          WHICH THE SYSTEM REMAINED IN RESERVED MODE
C  LCH: A VARIABLE USED TO FIND THE STATUS OF PRESNT
C       SLOT IN S-ALOHA
C       IF LCH=0 -->  EMPTY SLOT
C          LCH=1 -->  ONLY ONE TRANSMISSION
C          LCH>1 -->  MORE THAN ONE TRANSMISSIONS
C                     (COLLISION)
C  NSAVE(K): A VARIABLE USED TO IDENTIFY COLLIDED USER
C            IN S-ALOHA MODE
C            IF NSAVE(K)=K --> KTH USER IS INVOLVED IN
C                              COLLISION
C               NSAVE(I)=0 --> KTH USER IS NOT INVOLVED
C                              IN COLLISION
C  NP(K) : A VARIABLE WHICH GIVES THE NEXT NEWLY
C          GENERATED PACKET NUMBER AT KTH USER
C  LMAX :  A VARIABLE USED TO CALCULATE MAXIMUM QUEUE
C          LENGTH REACHED
```

```
C  LX(K) : A VARIABLE USED TO ESTIMATE QUEUE LEGTH AT
C          KTH USER
C  LREP(K): REPORTED QUEUE LENGTH OF MAIN BUFFER BY KTH
C           USER WHILE EXECUTING STATE #2
C  LCODE(K): IF LCODE(K)=1 ,THEN KTH USER IS NOT ALLOWED
C            ATTEMPT ON RANDOM ACCESS UNTIL ITS ALL
C            RESERVED SLOTS (BASED UPON QUEUE LENGTH
C            INFORMATION) ARE OVER. OTHERWISE ,
C            LCODE(K)=0
C  MAX : A VARIABLE USED TO GIVE THE MAXIMUM SLOT NUMBER
C        AT WHICH RESERVATION HAS BEEN ASSIGNED
C  PSAL: PROBABILITY THAT THE SYSTEM IS IN S-ALOHA MODE
C  S :   THROUGHPUT OF THE CHANNEL
C
C*****************************************************
      DIMENSION IX(10),NSAVE(10),CAT(10, 1000),LQL(10),
     1NSRES1(10,100),TSRES(10, 100),LREP(10),LX(10),
     2NSREQ2(10,100),NP(10),LCODE(10)
C
C  READING SYSTEM PARAMETERS
C
      READ(5,*)N,T,PDT
      READ(5,*)TMAX
      WRITE(6,20)
20    FORMAT('1',//,20X,'SCH IV  INFINITE BUFFER CASE'/)
      NS=IFIX(TMAX/T+T/2)
      WRITE(6,17)N,TMAX,T,PDT,NS
17    FORMAT(5X,'NO. OF USERS=',I3,5X,'TMAX(SEC)=',F6.1,
     15X,'TIME FOR EACH STATION=',F6.3,/,7X,'PDT=',F7.4,
     25X,'NS=',I6/)
      T1030=10**30.
      INFIN=9999999
      NPDT=IFIX(PDT/T)+1
      WRITE(6,11)
11    FORMAT(7X,'LAMBDA',08X,'RHO',15X,'S',9X,
     1'AVG. DELAY'//)
      PDTT=PDT+T
      DO 101 NO=1,10
C
C  READING MEAN PACKET ARRIVAL RATE AT EACH USER
C
      READ(5,*)ALAM
      TMEAN=1./ALAM
C
C INITIALIZING COUNTERS &
C SEED ASSIGNMENT TO EACH USER (FOR RANDOM NUMBER
C GENERATION)
C
      NPT=0
      NRT=0
```

```
      DEL=0.
      MAX=0
      DO 100 I=1,N
      IX(I)=888*I+1
      IUU=IX(I)
      CALL RANDU(IUU,IY,YFL)
      IX(I)=IY
      CAT(I,1)=-TMEAN*ALOG(YFL)
      DO 39 II=1,NS
      IUU=IX(I)
      CALL RANDU(IUU,IY,YFL)
      IX(I)=IY
      CAT(I,II+1)=CAT(I,II)-TMEAN*(ALOG(YFL))
      IF(CAT(I,II+1).GE.TMAX) GO TO 53
 39   CONTINUE
 53   NSRES1(I,1)=INFIN
      TSRES(I,1)=T1030
      LQL(I)=0
      NP(I)=1
      NSREQ2(I,1)=INFIN
      LREP(I)=0
      LCODE(I)=0
 100  CONTINUE
      LMAX=0
      ISLRES=0
      TS=-T
      J=1
 777  IF(J.GT.NS)GO TO 592
      TS=TS+T
C
C TO CALCULATE MAIN BUFFER QUEUE LENGTH
C
      DO 73 NB=1,N
      LX(NB)=0
      NTEMP=NP(NB)
 75   IF(CAT(NB,NTEMP).LE.TS)THEN
          LX(NB)=LX(NB)+1
          NTEMP=NTEMP+1
          GO TO 75
      ENDIF
      IF(LX(NB).GT.LMAX)LMAX=LX(NB)
 73   CONTINUE
      DO 230 JR=1,N
C
C WHETHER THE SYSTEM IS IN STATE #3 ?
C
 1000 IF(J.EQ.NSREQ2(JR,1))THEN
        NTEMP=NP(JR)
        ISLRES=ISLRES+1
        IF(CAT(JR,NTEMP).LE.TS)THEN
```

```
          NPT=NPT+1
          DEL=DEL+PDTT+TS-CAT(JR,NTEMP)
          NP(JR)=NP(JR)+1
          LREP(JR)=LREP(JR)-1
          LTEMP=LREP(JR)
          IF(LTEMP.EQ.0)THEN
            LCODE(JR)=0
            NSREQ2(JR,1)=INFIN
            GO TO 47
          ENDIF
          DO 1001 IT=1,LTEMP
          NSREQ2(JR,IT)=NSREQ2(JR,IT+1)
 1001     CONTINUE
          J=J+1
          TS=TS+T
          IF(J.GT.NS)GO TO 592
          GO TO 1000
        ENDIF
      ENDIF
C
C WHETHER THE SYSTEM IS IN STATE #2 ?
C
      IF(J.EQ.NSRES1(JR,1))THEN
        NPT=NPT+1
        ISLRES=ISLRES+1
        DEL=DEL+PDTT+TS-TSRES(JR,1)
        LQL(JR)=LQL(JR)-1
C
C REPORTING QUEUE LENGTH FOR STATE #3 & RESERVING SLOTS
C
        IF(LCODE(JR).EQ.0)THEN
          LREP(JR)=LX(JR)
          LT=LREP(JR)
          IF(LT.EQ.0) THEN
            NSREQ2(JR,1)=INFIN
            GO TO 262
          ENDIF
          INC=0
          DO 261 IT=1,LT
          NSREQ2(JR,IT)=J+NPDT+INC
          IF(NSREQ2(JR,IT).LE.MAX)NSREQ2(JR,IT)=MAX+1
          INC=INC+1
          MAX=NSREQ2(JR,IT)
 261      CONTINUE
          LCODE(JR)=1
        ENDIF
 262    IF(LQL(JR).EQ.0)THEN
          NSRES1(JR,1)=INFIN
          TSRES(JR,1)=T1030
          GO TO 47
```

```
          ENDIF
          L=LQL(JR)
          DO 233 JZ=1,L
          NSRES1(JR,JZ)=NSRES1(JR,JZ+1)
          TSRES(JR,JZ)=TSRES(JR,JZ+1)
 233      CONTINUE
          GO TO 47
        ENDIF
 230    CONTINUE
C
C NORMAL S-ALOHA OPERATION
C
        LCH=0
        DO 58 K=1,N
 58     NSAVE(K)=0
 401    DO 48 JS=1,N
        IF(LCODE(JS).EQ.1)GO TO 48
        NTEMP=NP(JS)
        IF(CAT(JS,NTEMP).LE.TS)THEN
          LCH=LCH+1
          NSAVE(JS)=JS
          DEL=DEL+TS-CAT(JS,NTEMP)+PDTT
          NP(JS)=NP(JS)+1
        ENDIF
 48     CONTINUE
C
        IF(LCH.EQ.0) GO TO 47
C
C LCH=1 --> SINGLE SUCCESSFUL TRANSMISSION
C
        IF(LCH.EQ.1) THEN
          NPT=NPT+1
          GO TO 47
        ENDIF
C
C LCH >1 --> COLLISION HAS TAKEN PLACE
C
 59     INC=0
        DO 581I=1,N
        LSAVE=NSAVE(I)
        IF(LSAVE.EQ.0) GO TO 581
        NRT=NRT+1
 65     LQL(I)=LQL(I)+1
        LQ1=LQL(I)
        TSRES(I,LQ1)=TS+PDTT
        NSRES1(I,LQ1)=NPDT+J+INC
        IF(NSRES1(I,LQ1).LE.MAX)NSRES1(I,LQ1)=MAX+1
        INC=INC+1
        MAX=NSRES1(I,LQ1)
 581    CONTINUE
```

```
 47    J=J+1
       GO TO 777
C
 592   DEL=DEL/NPT
       S=FLOAT(NPT)/FLOAT(NS)
       RHO=N*ALAM*T
       WRITE(6,2)ALAM,RHO,S,DEL
 2     FORMAT(7X,F7.3,5X,F8.5,8X,F8.4,5X,F12.4/ )
       NSSAL=NS-ISLRES
       PSAL=FLOAT(NSSAL)/FLOAT(NS)
       WRITE(6,1004)PSAL
       WRITE(6 ,1003)LMAX
       WRITE(6,1002)NRT
 1002  FORMAT(5X,'NO. OF RETRANSMISSIONS=',I5)
 1003  FORMAT(15X,'MAX.QUEUE LENGTH REACHED=',I4)
 1004  FORMAT(15X,'PSAL=',E16.8)
 101   CONTINUE
       STOP
       END
$ENTRY
10,0.02,0.27
1000.
0.05
0.2
0.5
1.
1.5
2.
2.5
3.5
4.5
5.
```

```
C
C         SUBROUTINE RANDU
C
C PURPOSE
C  COMPUTES UNIFORMLY DISTRIBUTED RANDOM REAL NUMBERS
C  BETWEEN 0 AND 1.0 AND RANDOM INTEGERS BETWEEN ZERO
C  AND 2**31. EACH ENTRY USES AS INPUT AN INTEGER
C  RANDOM NUMBER AND PRODUCES A NEW INTEGER AND REAL
C  RANDOM NUMBER.
C
C DESCRIPTION OF PARAMETERS
C  IX - FOR THE FIRST ENTRY THIS MUST CONTAIN ANY ODD
C       INTEGER NUMBER WITH NINE OR LESS DIGITS. AFTER
C       THE FIRST ENTRY, IX SHOULD BE THE PREVIOUS VALUE
C       OF IY COMPUTED BY THIS SUBROUTINE.
C  IY - A RESULTANT INTEGER RANDOM NUMBER REQUIRED FOR
C       THE NEXT ENTRY TO THIS SUBROUTINE. THE RANGE OF
C       THIS NUMBER IS BETWEEN ZERO AND 2**31
C  YFL- THE RESULTANT UNIFORMLY DISTRIBUTED, FLOATING
C       POINT RANDOM NUMBER IN THE RANGE 0 TO 1.0
C
C ...................................................
C
      SUBROUTINE RANDU(IX,IY,YFL)
      IY=IX*65539
      IF(IY)5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END
```

APPENDIX 'C'

FINITE BUFFER BEHAVIOR WITH POISSON ARRIVALS AND RANDOM SERVER INTERRUPTIONS [34]

We consider finite buffer behavior, with Poisson arrivals, synchronous transmission and single output channel with Bernoulli interruptions and the output from the buffer is controlled by the switch S. This situation is depicted in Fig. C.1.

The following assumptions are made:

(1) Arrival of packets at the buffer is Poisson distributed.

(2) One channel slot is provided during each clock time interval and its duration is one unit of service time.

(3) Departures from the buffer occur before any arrivals during a unit service interval, i.e. the buffer is operated at the end of each service interval, and

(4) Departures from the buffer are according to First In First Out (FIFO) queue discipline.

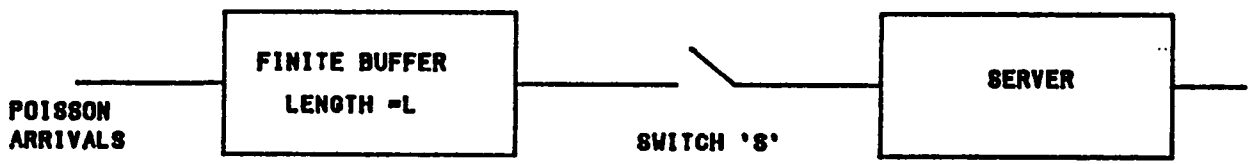


Figure C.1. Kekre and Saxena model for Poisson arrivals and random server interruptions.

Now Let

L = buffer length (packets)

p_{s1} = steady state probability of the switch in state 1 (switch closed)

p_{s0} = steady state probability of the switch in state 0.

and

Service interval = τ sec.

Average output/service interval = p_{s1} packets

Average input/service interval = $\alpha = \rho\, p_{s1}$ packets (4.27)

where $\rho(< 1)$ is the traffic intensity to the buffer.

The probability, Θ_k, of k packets arriving during a service interval (τ sec) is

$$\Theta_k = \frac{\alpha^k e^{-\alpha}}{k!}, \quad k = 0, 1, \ldots, \infty \qquad (C.1)$$

Let the probability $p_i(j)$ of buffer occupancy $B(j) = i$ at the end of jth service interval be defined as

$$p_i(j) \triangleq P[B(j) = i] \quad i = 0, 1, \ldots L$$

Now

$$\underline{P}(j+1) = p_{s1}\, \underline{C} \cdot \underline{P}(j) + p_{s0}\, \underline{D} \cdot \underline{P}(j) \qquad (C.2)$$

where $\underline{P}(j)$ is the (L+1)- dimensional vector

$$\underline{P}^t(j) = [p_0(j) \quad p_1(j) \quad \ldots\ldots \quad p_L(j)] \tag{C.3}$$

and $\underline{C}$ and $\underline{D}$ are (L+1) x (L+1) matrices defined as

$$\underline{C} = \begin{bmatrix} \Theta_0 & \Theta_0 & 0 \;\text{----} & 0 & 0 \\ \Theta_1 & \Theta_1 & \Theta_0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Theta_{L-1} & \Theta_{L-1} & \Theta_{L-2} & \Theta_1 & \Theta_0 \\ [1-\sum_{i=0}^{L-1}\Theta_i] & [1-\sum_{i=0}^{L-1}\Theta_i] & [1-\sum_{i=0}^{L-2}\Theta_i] & [1-\sum_{i=0}^{1}\Theta_i] & [1-\Theta_0] \end{bmatrix}$$

$$\underline{D} = \begin{bmatrix} \Theta_0 & 0 & 0 \;\text{----} & 0 & 0 \\ \Theta_1 & \Theta_0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Theta_{L-1} & \Theta_{L-2} & \Theta_{L-3} & \Theta_0 & 0 \\ [1-\sum_{i=0}^{L-1}\Theta_i] & [1-\sum_{i=0}^{L-2}\Theta_i] & [1-\sum_{i=0}^{L-3}\Theta_i] & [1-\Theta_0] & 1 \end{bmatrix}$$

When $j \to \infty$, $\underline{P}(j+1) = \underline{P}(j) = \underline{P}$ where $\underline{P}$ is a vector of steady state probabilities, thus Eqn. (C.2) reduces to

$$\underline{P} = p_{s1}\,\underline{C}\,\underline{P} + p_{so}\,\underline{D}\,\underline{P} \tag{C.4}$$

or

$$\underline{R}\,\underline{P} = \underline{0} \tag{C.5}$$

where

$$\underline{R} = \underline{I} - p_{s1}\,\underline{C} - p_{s0}\,\underline{D} \tag{C.6}$$

The matrix $\underline{R}$ will be of the form

$$\underline{R} = \begin{bmatrix} r_{00} & r_{01} & 0 \;\text{----} & 0 & 0 \\ r_{10} & r_{11} & r_{12} \;\text{----} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{L-1,0} & r_{L-1,1} & r_{L-1,2} \;\text{--} & r_{L-1,L-1} & r_{L-1,L} \\ r_{L,0} & r_{L,1} & r_{L,2} \;\text{----} & r_{L,L-1} & r_{L,L} \end{bmatrix} \tag{C.7}$$

Since (L+1) component equations obtained from Eqn. (C.5) are not linearly independent, first L component equations from Eqn. (C.5) are solved together with the normalizing condition

$$\underline{U}^t \cdot \underline{P} = \underline{1} \tag{C.8}$$

where $\underline{U}$ is (L+1) dimensional unit vector. (L+1) components of $\underline{P}$ can now be solved using a recursion method by defining an (L+1) dimensional vector $\underline{Y}$ as

$$y_i \triangleq \frac{p_i}{p_0} \tag{C.9}$$

so that

$$y_0 = \frac{p_0}{p_0} = 1 \tag{C.10}$$

In general

$$y_k = \frac{p_k}{p_0} = \frac{-\sum_{i=0}^{k-1} r_{k-1,i}\, y_i}{r_{k-1,k}} \quad , \; k = 1,\ldots, L \tag{C.11}$$

Equation (C.11) gives p_k ($k = 1,2,\ldots L$) in terms of y_k and p_0 whereas p_0 is given by

$$p_0 = \frac{1}{\sum_{i=0}^{L} y_i} \tag{C.12}$$

Thus all values of p_k ($k = 0, 1,\ldots, L$) are evaluated through Eqns. (C.11) and (C.12). The probability, β, of a packet being transmitted during each service

interval is given by

$$\beta = p_{s1} (1 - p_0) \tag{C.13}$$

Therefore, the expected load carried during each service interval is β. The average load offered during each service interval is given by Eqn. (C.1). The overflow probability P_{of} is defined as

$$P_{of} \triangleq \frac{\text{Average offered load} - \text{Average carried load}}{\text{Average offered load}}$$

Thus

$$P_{of} = \frac{\alpha - \beta}{\alpha}$$

or

$$P_{of} = 1 - \frac{\beta}{\alpha} \tag{C.14}$$

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