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Roy, Radhika Ranjan

ANALYSIS OF MULTIHOP PACKET RADIO NETWORK -- CARRIER SENSE
MULTIPLE ACCESS WITH BUSY-TONE AND COLLISION DETECTION
(CSMA/BT-CD)

City University of New York

PH.D. 1984

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CARRIER SENSE MULTIPLE ACCESS WITH BUSY-TONE
AND COLLISION DETECTION
(CSMA/BT-CD)**

by

RADHIKA RANJAN ROY

A dissertation submitted to the Graduate Faculty of Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

1984

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1984

This manuscript has been read and accepted for the Graduate Faculty in Engineering in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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Abstract

Broadcast Packet Radio Network has advantages of both packet switching and broadcast communication. Packet switching is an efficient way of sharing the communication resources by many contending users of a very low duty cycle in which a short burst of data is sent or received by a longer quiescent interval after which additional traffic will again be present. The broadcast radio medium is suitable for multiple access and particularly suitable for communication with mobile users or where the wire-based communications are uneconomic.

In this dissertation we develop a mathematical model for multihop Packet Radio Network using nonpersistent Carrier Sense Multiple Access with Collision Detection and Busy-Tone (CSMA/BT-CD). The analysis is based on a continuous time Markov Chain model. Each node in the network has a finite buffer capacity. System capacity, throughput-delay trade-offs and blocking probabilities for the network as well as for the individual nodes can be obtained from the model. We have applied the model to networks with different topologies; a three-node chain network, a five-node ring network and a three dimensional network, such as, cube. As the number of nodes increases,

the number of network states increases tremendously. We have devised a technique to reduce the network states for efficient computations. We have also obtained upper- and lower bound in throughput and delay, respectively in heavy traffic situation. Point-to-point network using wire-based transmission facilities become a special case of this model. This model can also be applied to analyze local area-, satellite-, and mixed-media network.

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1. COMMUNICATION NETWORKS

Final years of this century is witnessing a tremendous explosive growth in data communication networks. Three main driving forces are acting behind this. The first one is that it is necessary to share the geographically distributed expensive resources like computers and data bases between many users. A second goal is to provide high reliability by having alternative sources of supply. The third one is that the cost of mini or micro computer used for switching is rapidly going down.

The communication needs can be viewed as a **bursty** process with high peak-to-average (ratios of 1000:1 are common) rate requirements. This implies that the demand on the communication resource tend to come in short bursts with long idle periods between them. The average load is fairly low (perhaps on the order of less than 10 bits per second), but during a transaction the data rate may be fairly high, possibly several thousand bits per second.

There have always been two fundamental and competing approaches to communications : pre-allocation and dynamic-allocation of transmission bandwidth. Early data communication services used the former approach. Towards the ends of sixties it was found that the network used in a pre-allocation mode was not capable of handling the large

volume of traffic that was beginning to arise, in a cost efficient manner. One of the main reasons for this is the bursty nature of the traffic [1]. With bursty traffic and pre-allocation mode, the expensive communication resource is tied up for the duration of the call, even though it is only being used perhaps 1% of the time [2].

Before advent of computers, data communication services used circuit-switched systems, where a fixed bandwidth is pre-allocated for the duration of a call. However, the rapid advances in computer technology over the last two decades have made feasible dynamic-allocation communications systems that are superior to pre-allocation systems in connect time, reliability and flexibility. This new communication technology, called **packet switching**, divides the input flow of information into small segments, or packets, of data which move through the communication subnet consisting of switching centers with store and forward capability at immensely higher speeds. Depending on the nature of the data traffic being transferred the packet switching approach is 3-100 times more efficient than pre-allocation techniques in reducing the wastage of available transmission bandwidth resources [3]. To do this, packet systems require both processing power and buffer storage resources at each switch in the network for each packet sent. The resulting economic trade-off is simple : if lines are cheap, use circuit

switching, if computing is cheap, use packet switching. Now packet packet switching is used almost exclusively in digital communication networks.

With circuit switching, any unused bandwidth on an allocated circuit is just wasted. With packet switching it may be utilized by other packets from unrelated sources going to unrelated destinations, because circuits are never dedicated. However, just because no circuits are dedicated, a sudden surge of input traffic may overwhelm a switching station, exceeding its storage capacity and causing it to lose packets.

In contrast with circuit switching, when packet switching is used, it is straight forward for the switching stations to provide speed and code conversion. Also they can provide error correction to some extent. However, in some packet-switched networks, packets may be delivered in the wrong order to the destination. Reordering of packets can never happen with circuit switching.

A final difference between the two methods is the charging algorithm. Packet carriers usually base their charge on both the number of bytes (or packets) carried and the connect time. Furthermore, transmission distance does not matter, except perhaps internationally. With circuit switching, the charge is based on the distance and time only, not the traffic.

In packet switching, two general categories of networks are often distinguished : terminal-oriented networks, those used to transmit various types of low-speed data; and computer networks, in which computers are interconnected into one network to provide more computer power than might otherwise be possible, to distribute computational loads more efficiently, and to provide a sharing of computational facilities. The ARPANET [4] is the largest such network in existence. Smaller networks are in existence or under development in the United States, France, Canada, England and Europe.

In most cases, the principles of network design are the same for both types of networks. Increasingly, however, networks are being called upon to handle a mix of data. These may vary in speed from 10 characters per second teletype to 50 kbits per second computer printout; the messages transmitted may be short, as is commonly the case for inquiry messages in many inquiry-response systems or they may be very long, as with data transmission involving file transfer. They may include voice data as well. The design of networks handling messages with a variety of speeds, length and rates of arrival is an area of great interest. This broad range of possible message statistics represents one fundamental distinction between data networks and the ubiquitous telephone networks transmitting primarily

voice information. In the latter case, message average three minutes long, and information bandwidths are limited at the entry to the network to less than 4 kilohertz [5].

Emergence of wideband fiber optics as a viable technology will force to rethink the relationship between switching and transmission. An intriguing possibility is to absorb the transmission terminal functions into future switching systems so that optical fibers carrying a multiplicity of channels and services can be directly terminated. This will require new technologies, topologies and capabilities. Fiber optics allows multiple channel services such as video, data, voice and others to co-reside on the same fiber as pure data communications. It has brought the concept of integrated services digital networks (ISDN) closer to reality.

It is also worth mentioning that a single optical fiber has more bandwidth than all the satellites ever launched, but because fibers are point-to-point rather than broadcast media, nearly all of the bandwidth is wasted. With a satellite, the bandwidth can be dynamically allocated precisely those users who need it. However, as time goes on, mixed-media networks using optical fibers, cable television, or the terrestrial telephone system for local distribution, and a satellite for the long-haul portion are becoming more and more common, thereby allowing small users to share a

single large satellite antenna.

Packet radio in broadcast mode offers a highly efficient way of using a multiple access radio channel with a potentially large number of mobile subscribers to support computer communication and to provide local distribution of information over a wide geographical area. We thus anticipate the growth of these kinds of facility possibly using carrier sense multiple access (CSMA) networks. The cost of digital technology and advanced signal processing is steadily decreasing. It is very reasonable to expect that digital technology will be married with the personal computer technology and that a very powerful network technology will emerge which will be capable of revolutionary impact on both the communications and computing fields [6].

1.1 Point-to-Point Networks

This kind of network consists of a collection of hosts, concentrators, Interface Message Processors (IMP), and terminals that are connected in some irregular topology by some point-to-point circuits. Each circuit connects exactly two locations. The classic example of this would be the ARPANET [4].

The main design issues of this network are how to route the packet within the network and to prevent congestion and deadlocks. Another important design issue is whether the fragmentation and reassembly of packets into messages should be done by the packet-switching system or by user computers. The latter point is related to an even more fundamental question having to do with type of service offered by the packet network. There are two major types of packet network service : datagram and virtual circuit. Loosely speaking, the datagram service does not provide any priori association among datagrams in the network. Each is delivered independently of the other and there is no enforced relationship between the order in which one computer enters datagrams into the network and the order in which these same datagrams are removed from the network and delivered to the user. That is, the host is taking on the responsibility for sequencing and error correction of the message. In virtual

circuit service, a dedicated path is established between the source and the destination and all packets are in order. In virtual circuit model, the subnet is doing the job for ordering and error correction. For example, the ARPANET offers both forms of service, where as the CYCLADE network offers only datagram [7]. The Canadian DATAPAC network offers only virtual-circuit service.

The routing problem for these networks is much more complicated specially if the topology is ditributed instead of centralized [8,9]. Most networks employ some form of adaptive routing to compensate for failures or to route around local congestion. Adaptive routing causes significant overhead due to additional traffic necessary to keep the routing tables current.

Packet switching has proved itself as a useful and important computer communication technology. There is a tremendous growth of packet switching networks now under way throughout the world. The extension of packet-switching concepts other than point-to-point networks has already provided formidable challenges to analyst, system designers, and engineers.

1.2 Broadcast Networks

Broadcast network, in contrast to the conventional

communication networks using transmission lines where each line connects exactly two locations, is a radically different kind of subnet. The broadcast network is one in which every packet sent is automatically received by every site within its range. Each receiver must select out that part of the input addressed to it. There is a single shared transmission medium for which the various stations contend. Only one packet may be in flight at any instant, which means that a high-bandwidth medium must be used to make the whole arrangement practical.

The first computer system to employ broadcast radio instead of point-to-point wires for its communication facility was the ALHOA system at the university of Hawaii [10]. In this scheme any node wishing to use the channel, does so with no regard to other users. If no other node attempt to use the channel at the same time, the packet will be received successfully. If, however, two or more nodes transmit at the same time, collision will occur, resulting in the loss of one or both of the transmitted packets. If packet was destroyed, the sender just waits a random amount of time and sends it again.

Carrier Sense Multiple Access (CSMA) is an obvious modification to the ALHOA scheme in which every node listens to the channel before transmitting. If the node senses a carrier on the channel it remains silent until the channel

becomes free or waits some random time and then resenses the carrier. If the channel is sensed idle, a station transmits its packet. If a collision occurs, the station waits a random amount of time and starts all over again. If all nodes are in range of each other and the propagation delay is small compared to the packet transmission time, we can achieve a throughput which is much higher than that of ALHOA scheme [11,12,13].

In certain situations packet radio (PR) system is very attractive as a method of communications. It is particularly attractive in mobile situation or in areas like where it may prove very difficult to build conventional wire-based communication network, such as, hostile mountain terrain, jungles, and desert.

The packet radio system is a store-and-forward network whose topology may or may not change. All nodes may not hear every transmission. It contains the complexities of both multiple-access and dedicated store-and-forward systems.

Another kind of network having a perimeter of few kilometers and sharing a high-bandwidth transmission medium in broadcast mode is known as Local Area Network (LAN). The transmission medium may be coaxial cable, twisted pairs or fiber optics. One reason in building a local area network is to connect together a collection of computers, terminals, and peripherals located in the same building or in adjacent

buildings, not only to allow them all to intercommunicate, but also to allow all of them to access a remote host or other network. In absence of local network, separate connections would be needed between the remote facility and each of the local machines, whereas with the LAN the remote facility need only tap onto the LAN in one place. This approach is typically motivated by the prior existence of a large collection of minicomputers that need to talk to each other and to some central computer center. The other reason there is interest in local networks is to exploit the advantages of functionally distributed computing. In this approach some of the machines are dedicated to perform specific functions, such as file storage, data base management, terminal handling, and so on. By having different machines perform different tasks, the goal is to make the implementation simpler or more efficient [14].

Recently satellite communications is gaining in popularity for data communications [15,16]. The great advantages are to cover a very large geographical area, reach isolated locations, and bridge oceans; because of its broadcasting capability. A satellite channel can be assigned proportions of the available bandwidth to users in a time or frequency multiplexing mode or used in random access mode such as ALHOA [15], so that any user can access the whole channel bandwidth on a contention basis. Another important

property of satellite packet broadcasting is that the sender can listen for his own packet, one round trip time after sending it. Since the sender can tell from this whether or not a collision has occurred, there is no need for explicit destination to source acknowledgements. If packet was garbled, the sender learns of the problem simultaneously with the receiver and can take appropriate action without having to be told.

Broadcast networks described above are conceptually similar to each other, although they are technically different. It is worth-mentioning some of the advantages it has over conventional point-to-point networks. First, there is no routing problem. Second, it is no longer possible for some lines to be badly congested while others are idle. Third, it is extremely easy for the network to expand when new facilities are added. Fourth, the very nature of broadcast networks allows redundancy. The failure of nodes in the network causes little or no performance degradation.

One major problem of broadcast networks is that issue of security and anti-jam protection, which is of special significance to the military. New coding techniques utilizing spread spectrum and programmable decoders allow a certain amount of anti-jam protection and added security. Encryption techniques have been improved tremendously and development of the same in broadcast network will enhance

the security problem.

LAN and PR network have comparatively smaller propagation delay (fraction of a packet length) with respect to satellite network. The principal disadvantages of satellite networks are the longer propagation times and the need for expensive antennas. Both LAN and fully connected PR network cannot cover large geographical area while satellite network can. Both satellite and PR network can accommodate mobile users without losing capability to communicate. One of the chief advantages of satellite network is that no topology optimization is required. That is, increasing the scale of the network is just a matter of adjusting one parameter, the satellite bandwidth rather performing a complicated heuristic topology optimization.

1.3 Mixed-Media Networks

The advantages of the ground network over the satellite network are as follows [7,12] :

- (i) Faster response under light to moderate input traffic load.
- (ii) Higher channel utilization.
- (iii) Greater stability.
- (iv) Less vulnerability.

The advantages of the satellite network over store-and-forward terrestrial networks are as follows :

- (i) Low-cost, high-bandwidth channel.
- (ii) Elimination of complex topological design and routing problems.
- (iii) Wide geographical coverage.
- (iv) Mobility of users.
- (v) Design insensitive to the addition of new users.
- (vi) Statistical load averaging.
- (vii) Reliability.

Probably the most undesirable features of the satellite network are its slow response and the vulnerability of the satellite transponder. However, its potentially good cost/performance, its broadband data communication capability, and other unique characteristics, such as its

multiaccess and broadcast features, are not to be given up so easily. Mixed-media network is built to combine these into a single entity so that they can complement each other. One such network is the connection of terrestrial ARPANET with packet satellite communication between the United States and the United Kingdom via INTELSAT IV [17]. This is a typical example of a mixed-media network is one using local access networks but using a satellite to connect the IMPs instead of a point-to-point backbone network. This kind of network has been discussed at length in [7]. Another example of a mixed media network is just the reverse : a common channel cable network is used for local distribution, but the long-haul portion uses a point-to-point backbone. Optimum topology design for mixed-media network is an open problem and research now tends to focus on how to find computationally efficient algorithms for topology design. In general, the problem of designing integrated local, regional, national, and international networks so that they can all be used for intermixed data, voice, facsimile, and television transmission are high on the agenda for the immediate future.

2. MULTIHOP PACKET RADIO NETWORKS

As mentioned earlier, the first implementation of a broadcast packet radio network was the ALHOA system at the University of Hawaii [10]. The Advanced Research Projects Agency of the Department of Defense (DARPA) have extended these ideas and developed the concept of packet radio network, wherein packets may take multiple hop paths in order to reach their destination [6]. Ground radio packet broadcasting stations have limited range, introducing the need for radio repeaters, which in turn affects the routing and acknowledgement schemes. One such multihop PR network has been built in the University of Hawaii covering the range upto 500 kilometers [11].

In multihop PR network all nodes are partially connected and we are thus faced with the problem similar to traditional store-and-forward multihop networks, except that a broadcast medium is used for transmissions. The most difficult problems in multihop networks are those of routing and flow control. The routing problem is especially hard if some of the nodes are mobile. This greatly complicates the work of the performance analyst and relatively little work has been done in this area.

If the nodes are fixed, we can know a reliable structure is there for communication using packet radios as

communication media. Any change in topology due to node failure can be taken into account by similar algorithms [18,19,20,21] used in conventional store-and-forward network. Many of the routing strategies used in point-to-point store-and-forward networks can be used in multihop PR network with little or no modifications. The goals of the routing procedures are the same in all networks, of course : to achieve a high probability of delivering packets to ultimate destination and to consume the minimum resources in the process. One of these routing strategies used in radio environment may be found in [22].

When the nodes become mobile, we are faced with a very complicated situation. We require that a reliable structure be acquired and maintained in the face of arbitrary topological changes due to node motion and/or failure. Such a structure may be achieved with a central or decentralized controller. In certain cases central controller may face difficulties to acquire and maintain such structure in mobile environment. Distributed Network Protocols [21] may be suitable to provide connectivity in such situation. A more detailed distributed algorithm that establishes and maintains such a connected architecture is also described in [23]. Due to mobility of the nodes and the propagation characteristics of radio frequency, the topology and connectivity of a dynamic computer network are very hard to

predict at any time especially if the network becomes very large. Extensive research is under way how to achieve a reliable communication subnetwork in dynamic computer networks. One such example for achieving a reliable communications subnetworks in dynamic environment may be found in [24].

2.1 Multiaccess Protocols

The need for multiaccess protocols arises whenever a resource is shared by many independent contending users. Two major factors contributed to such a situation : the need to share expensive resources in order to achieve their utilization, or the need to provide a high degree of connectivity for communication among independent subscribers or both. In broadcast environment a single transmission medium is shared by all subscriber; the medium is allocated to each subscriber for the time required to transmit a single packet. If a node transmits a packet, many other nodes hear the transmission irrespective of the fact whether it is addressed to them or not. In general, there is no simple way of deciding which node should access the shared resource (channel) at any time. We may , therefore, encounter collisions at the receiver, either when two nodes transmit to him at the same time, or when two or more nodes

in his hearing range transmit at the same time. So we need some way of controlling these conflicts and guarantees safe transmission of packets. Many multiaccess techniques exist for controlling channel. We may group into the following five categories [25] :

(i) Fixed assignment techniques (e.g. FDMA, TDMA, ATDMA, CDMA)

(ii) Random access techniques (e.g. ALHOA, CSMA/CD, BTMA, SSMA).

(iii) Centrally controlled demand assignment (e.g. SPADE, Polling, Adaptive Polling or Probing, SRMA, ALHOA-SRMA, GSMA).

(iv) Demand assignment with distributed control (e.g. Reservation-ALHOA, FIFO-ALHOA, Round-Robin-TDMA, MSAP, Assigned-Slot Listen-Before-Transmission, Tree-Algorithm, Control Token, Register Insertion).

(v) Mixed strategies (e.g. Urn-scheme, SPUC, PODA, FPODA, CPODA, MACS, GRA).

Multiaccess schemes are evaluated according to various criteria. The performance characteristics that are desirable are, first of all, high bandwidth utilization and low message delays. But a number of other attributes are just as important. The ability for an access protocol to simultaneously support traffic of different types, different priorities, with variable message lengths, and differing

delay constraints is essentially as higher bandwidth utilization is achieved by the multiplexing of all traffic types. Also, to guarantee proper operation of the schemes with distributed control, robustness, defined here as the insensitivity to errors resulting in misinformation, is also most desirable. No single access scheme can meet these requirements under all circumstances. Due to the bursty nature of the traffic, random access schemes are well suited and easy to implement. We now describing briefly some random access schemes that are available in broadcast packet radio environment.

2.1.1 ALHOA

The simplest random access scheme is **unslotted ALHOA**. This approach is named after the project at the University of Hawaii, which pioneered its use [10]. In its simplest form, no synchronization of station transmissions is used -- whenever a packet is ready to be sent, a station simply transmits it. If no other station is transmitting during this time (and no local noise errors occur at the receiver), the packet will be received successfully by the destination station. If one more other stations are transmitting, a conflict occurs due to destructive interference at the receiving transponder. The collision is resolved by the node

retransmitting the packet at some randomly chosen interval to minimize the probability of future conflicts, if no positive acknowledgement is received. Extensive analysis of this scheme can be found in [10,11,12], where it is determined that the maximum throughput is 18%. For traffic consisting of fixed-length packets, a factor-of-two improvement in performance can be achieved by synchronizing the burst starting times of all stations [11]. This is accomplished by **slotting** the channel using global timing in the same way as for fixed assignments, except that a frame is not needed. Under these circumstances a maximum throughput of approximately 36% can be achieved for traffic equally distributed among the stations.

A complication to either the unslotted or slotted method is the need to stabilize the channel. The random-access technique is inherently unstable if the retransmission intervals used are too small relative to the traffic rate. On the other hand, unnecessarily large intervals can result in excessive delays. Thus, a control mechanism is required which can adapt the rate of new transmissions and retransmissions to dynamic load changes while minimizing delay [12,26].

2.1.2 CSMA

In the Carrier Sense Multiple Access (CSMA) scheme, every node listens to the channel before transmission [27]. When a terminal learns that its transmission had incurred a collision, it reschedules the transmission of the packet according to the randomly distributed delay. At this new point in time, the transmitter senses the channel again and repeats the algorithm dictated by the protocol. If the propagation delay is smaller compared to the packet transmission time, we can achieve a throughput of about 80% of the channel bandwidth. In ground radio environments the channel can be characterized as wideband with a propagation delay between any source-destination pair that is small compared to the packet transmission time and CSMA is an attractive scheme to obtain a very high throughput. In certain local environments it is possible to detect collision by monitoring the channel constantly while transmitting [28]. The performance of CSMA can be enhanced by aborting conflicting transmissions, thus giving rise to the carrier sense multiple access schemes with collision detection (CSMA-CD). Performance analysis of CSMA-CD [29,31] shows that we can achieve a throughput of about 92% . It is shown that the throughput-delay characteristics of CSMA-CD

are better than the already efficient CSMA scheme.

In a large network, the propagation delay may become large enough to significantly degrade system performance, eventually reducing to ALHOA levels when the information gained by sensing the channel is so old as to be useless. It is precisely for this reason that CSMA is of no use in satellite networks, where the propagation delay is about 0.26 seconds. In multihop broadcast environments nodes are partially connected and we need to devise a new access scheme.

2.1.3 BTMA

Busy Tone Multiple Access (BTMA) scheme does not require that all users shall be in line-of-sight and within the range of each other. Typically, two terminals can be within range of the intended receiver, but out-of-range of each other or separated by some physical obstacle opaque to radio signals. In BTMA scheme, the available bandwidth is separated into two separate channels : a busy-tone channel and a message channel. The operation of BTMA [30] rests on the fact that, by definition, there exists a central station which is within range and in line of sight of all users. As long as the central stations senses carrier on the message channel it transmits a busy-tone signal on the busy-tone

channel. It is by sensing carrier on the busy-tone channel that the users' terminals determine the state of the message channel. In multihop networks the first assumption of a central station which is within range and in line of sight of all users is violated. More intelligent use of busy-tone in multihop environment will solve this problem. We must resort to find out a scheme for using busy tones which are generated by the receiver as soon as it detects an incoming transmission, which all nodes in his vicinity hear and realize that they should not transmit.

2.1.4 Overview

In the packet radio system, propagation delays fall between those in the local area network and in the satellite case. However, the packet radio network is a store forward system whose topology changes as the nodes move around. Thus, not all nodes hear every transmission. The packet radio units can often detect when the common radio channel is in use and not transmit during that time. So, in this broadcast environment CSMA is highly attractive scheme to implement. Moreover, CSMA scheme is already proven to be very efficient scheme because of its very high throughput, better throughput-delay characteristics and relatively more stable than other multiaccess schemes. In multihop

environment we need to clever use of Busy-Tone (BT) since nodes are partially connected. It is fair to say that the multihop packet radio system combines all of the most challenging features of multiple-access and dedicated store-and-forward system. In this dissertation we will define a new multiaccess protocol based on sensing of carrier as well as busy-tone suitable for partially connected multihop packet radio environment.

2.2 Acknowledgements

Acknowledgements are commonly used to indicate whether a transmission is successful. A user should know whether his transmission was successful so that he can decide his next action. In broadcast network it is necessary to have positive acknowledgement since collision occurs when two or more transmissions overlap in time. Fortunately, hop-by-hop (HOP) acknowledgement can normally be handled in passive manner in broadcast networks. That is, we do not have to actually transmit the acknowledgement. The sender listens to the channel until he hears the receiver retransmit the packet to be passed to the next repeater. This constitutes an acknowledgement. Two problems exist in passive acknowledgement. One is that the sender may not hear the retransmission due to other interference, in which case he

will retransmit the packet. Duplicate packets will be generated in the network. This may create a considerable problem. Intermediate or final destination node has to be equipped with appropriate protocols to discard duplicate packets. The other problem is that destination nodes do not retransmit the packet. These nodes must, therefore, send an active acknowledgements. Different schemes of active acknowledgement will have significant effects on system capacity. Detailed analysis can be found in [32,33,48]. End-to-End (ETE) acknowledgements are used to guarantee that the packet did not get lost in a repeater that died, or misrouted due to topology changes. If after some time out period, the sender has not received an ETE acknowledgement he sends the packet again. To set an actual optimum time out period for any particular network is a very important design parameter.

2.3 Previous Works

A two-hop broadcast network of ring topology around a station using slotted ALHOA protocol has been analyzed by Gitman [34]. The capacity of the network was determined, but delay was studied later by Tobagi [35]. A two-hop centralized packet radio network using ALHOA and CSMA schemes involving star and fully connected network was studied by Tobagi [36,37] considering only in-bound traffic. Multihop network of more general topologies such as chains, rings, and stars were presented by Boorstyn and Kershenbaum [38]. Throughput and blocking probability of multihop packet radio networks operating according to CSMA scheme were obtained assuming zero propagation (ZPD) and identical characteristics of all users. But actual throughput of individual node, delay, throughput-delay trade-offs, effects of buffer as well as of different transmission protocols were not provided by their mathematical model. Assumption of ZPD has seriously limited the geographical topology and the speed of the network. Later on, Tobagi and Brazio [39] has extended the mathematical model used in [38] for various access schemes but said limitations still exist.

2.4 Contributions of this Dissertation

In this dissertation we attempt to obtain the following:

(i) To develop a mathematical model for multihop packet radio network of any arbitrary topology using nonpersistent Carrier Sense Multiple Access with Busy-Tone and Collision Detection (CSMA/BT-CD) schemes. We consider non-zero propagation delay (non-ZPD) and each user has a finite buffer. Users' characteristics may or may not be identical. The analysis is based on continuous time Markov Chain Model [40,41].

(ii) To obtain throughput, delay, throughput-delay trade-offs for each node as well as for the whole network.

(iii) To apply the model to different network topologies, such as, chain, ring, and cube networks.

(iv) To devise a technique to reduce the number of network states and hence a reduction in the computational complexity [41].

(v) To obtain a lower bound in throughput and the corresponding upper bound in average packet delay for node as well as for the entire network [42].

3. GENERAL MODEL

We will consider a multihop network of any arbitrary topology operating according to nonpersistent CSMA/BT-CD scheme. Non-zero propagation delay (non-ZPD) and finite buffer for every terminal are considered. We do not consider the effects of perfect or imperfect capture. Busy-Tone is transmitted on a separate narrow band channel. By immediate first transmission (IFT) protocol, we mean that a terminal will initiate transmission immediately if any arrival occurs in an empty buffer. In case of delayed first transmission (DFT), all the packets are rescheduled for transmission. A terminal attempts to transmit its packet on first-come-first-serve (FCFS) basis. We assume that passive acknowledgements are always heard and ignore the effects of end-to-end acknowledgements discussed earlier.

Data packets received by a node from its neighbors is defined as the internal arrival. Any new packet generated in the node for transmission is defined as the external arrival. Terminals may either transmit or receive the internal arrival but they can be not do both simultaneously, while external arrival can occur at any time.

3.1 Carrier Sense Multiple Access with Busy-Tone and Collision Detection (CSMA/BT-CD) Scheme

In nonpersistent CSMA/BT-CD schemes, a terminal is defined to be idle if it does not transmit its packet or if it transmits busy-tone detecting transmission. A terminal with a packet ready for transmission senses the channel as well as the busy-tone and proceeds as follows:

1. If the channel as well as the busy-tone are sensed idle, the terminal initiates transmission of the packet;
2. If the channel is sensed busy or the busy-tone is detected then the terminal reschedules the transmission of the packet to some later time and repeats the algorithm; or
3. If a collision is detected during transmission, the transmission is aborted and the packet is scheduled for retransmission at some later time.

If a terminal is idle and detects transmission it proceeds as follows:

1. It transmits busy-tone to all neighbors except to the node from which it is receiving transmission as long as transmission continues.

A transmission from a node would be successful if the neighbors as well as the neighbors of the neighbors of the transmitting node remain idle. This definition of success

sets a severe constraint and gives a very pessimistic results of network performances. In general, transmission of one terminal can be heard by many other neighboring terminals. Routing will specify which terminal is to repeat the packet, if necessary. Topology will show the listing of the terminals which can hear each other. A collision is said to have occurred under the following circumstances:

1. If a node receives transmission or busy-tone from any one of its neighbors while transmitting.

2. If an idle node receives transmission from at least two of its neighbors simultaneously.

Some collision still may occur despite the strategy of sensing the carrier and the busy-tone due to propagation delay. This will occur under the following circumstances:

1. If a terminal initiates transmission before receiving transmission or busy-tone from its neighbors, or

2. If an idle terminal receives at least two transmissions simultaneously from its neighbors. This situation may arise if the neighbors of the neighbors of the transmitting node initiate transmissions before detection of busy-tone from the idle terminal. Receiving more than one transmission, the idle terminal transmits busy-tone in all directions including the terminals from which it is receiving transmissions. Receiving busy-tone, the transmitting terminals become aware of the fact that the

conflict has taken place.

The collided terminals are differentiated into the following two categories:

1. Those which sense conflict with other terminals while transmitting.
2. Those which sense conflict with other terminals while remaining idle.

The terminals in the second category transmit busy-tone in all directions including the terminals from which they are receiving transmissions to make them aware of the conflict. In this scheme, terminals sensing conflict proceed to truncate collision as follows:

1. If a transmitting terminal senses conflict, it jams the channel to ensure that all its neighbors detect the collision, and
2. If a terminal senses that the channel has been jammed, it stops all kinds of transmissions including busy-tone until the channel goes idle.

3.2 Heavy Traffic

We define heavy traffic situation when all neighbors as well as neighbor of the neighbors of the local node will always have a packet to be transmitted. The local node is considered as one for which performances are to be

determined in presence of maximum interference. We assume that the retransmission rate of the neighbors as well as the neighbors of the neighbors of the local node will always, at least, be the same rate of the local node and will never be less than the external arrival rate to the local node. In this situation we can find out the lower bound in throughput and the corresponding higher bound in delay for the local node as well as for the network.

3.3 Mathematical Analysis

We consider a multihop network having k nodes whose topology is yet to be specified. Let N^t be a vector of random processes which describes the state of the network at time t and can be represented as follows:

$$N^t = (h_1^t, h_2^t, \dots, h_k^t : n_1^t, n_2^t, \dots, n_k^t) \quad (1)$$

where h_i^t = the channel state for the i -th node at time t

n_i^t = the buffer state for the i -th node at time t

$i = 1, 2, \dots, k$

It is also defined :

$$N^t = (C^t : B^t) \quad (2)$$

where $C^t = (h_1^t, h_2^t, \dots, h_k^t)$

= state of the network channel at time t

$$B^t = (n_1^t, n_2^t, \dots, n_k^t)$$

= states of the network buffer at time t

Assuming the buffer of each node is finite, we can write:

$$0 \leq n_i^t \leq F_i \quad ; \quad i = 1, 2, \dots, k \quad (3)$$

where F^i = maximum capacity of the buffer of the i-th node.

The channel state of a node depends on the activity of the node itself as well as on the activities of the neighbors and those of the neighbors of the neighbors. Given that the topology is known, we can know the neighbors as well as the neighbors of the neighbors of each node. Consequently, we can specify the unique states of the channel at any particular instant of time. The unique channel state depends on the transmission protocols used in multihop environment. The following terms which are assumed exponentially distributed, are defined as follows:

(i) $1/\lambda_i$ is the mean external time to the i-th node.

(ii) $1/\lambda_{r_i}$ is the mean retransmission time of the

packet by the i-th node.

(iii) $1/\lambda_{d_i}$ is the mean transmission detection time by

all neighbors of the i -th node.

(iv) $1/\lambda_{b_i}$ is the mean busy-tone detection time by all

neighbors of the neighbors of the i -th node.

(v) $1/\lambda_c$ is the mean collision detection time of the

collided nodes.

(vi) $1/\lambda_t$ is the mean collision termination time of the

the

collided nodes.

(vii) $1/\mu_i$ is the mean service time of the packet of

the i -th node.

At present, for simplicity of analysis, we assume all are exponentially distributed (For non-exponential distribution method of stages -- Erlangian distribution [43] can be incorporated in this model). It is assumed that r_{ij} is the probability that the packet transmitted from node i is being

defined as the probability of an internal arrival of a packet to node j transmitted from node i . Problem of deadlock where all the buffers of the network become full and waiting for retransmission whose final destination are not the immediate neighbors, is not addressed here. It is rather assumed, by means of efficient buffer management or by some other techniques, no such situation arises. On the other hand, the probability that the packet departs from the network while transmitted from node i is given by:

$$\alpha_i = (1 - \sum_{j=1}^k r_{ij})$$

where k is the number of number of nodes in the network.

If a packet reaches its final destination, then it is assumed that it is lost from the network. The following is also assumed:

$$r_{ii} = 0 ; i = 1, 2, \dots k$$

For simplicity of analysis, it is assumed, if a packet is transmitted by a node then it is received by only one of its neighbors as determined by routing. If γ_i is the total arrival to node i , it can be shown:

$$\gamma_i = \lambda_i + \sum_{j=1}^k \gamma_j r_{ij} ; i = 1, 2, \dots k$$

The assumption of exponential arrival times for all packets and all of the detection times, implies that N^t is a continuous time, time homogeneous Markov Chain. The limiting state probabilities of this chain, defined as:

$$\Pi_j = \lim_{t \rightarrow \infty} P (N^t = j / N^S = i) \quad (4)$$

can be calculated (when they exist) using the following set of equations [43]:

$$q_{jj} \Pi_j + \sum_{k \neq j} q_{kj} \Pi_k = 0 ; \text{ for all } j \quad (5)$$

$$\sum_j \Pi_j = 1 \quad (6)$$

where q_{kj} denotes the rate of the transition from state k into state j .

Once the probabilities of all states are known we can find out throughput, delay, stability and other parameters of the network. Most importantly, this is not only true for broadcast packet radio environment, but also true for any other situations, such as, local area network, multihop communication networks based on wires or mixed-media network.

4. REGULAR TOPOLOGIES

4.1 Chain Network

Figure 1 shows the configuration a three-node chain network ($k=3$). Node 1 can hear node 2, but not node 3. Similarly, node 3 can hear node 2 but not node 1, while node 2 can hear both nodes 1 and 3. Nodes of the network are mutually independent and each other is communicating over a broadcast channel. Let us consider each terminal has a finite buffer capacity: M , N , and P for nodes 1, 2, and 3 respectively. Nodes 1 and 2 are considered neighbors of each other. Similar is the case for nodes 2 and 3. Node 3 is also the neighbor of the neighbor of node 1 and vice versa, while node 2 has two neighboring nodes 1 and 3 only.

The state of the network at any time t is given by:

$$N^t = (h_1^t, h_2^t, h_3^t : n_1^t, n_2^t, n_3^t) \quad (7)$$

where h_i^t = state of the channel of the i -th channel

at time t ; $i = 1, 2, 3$.

n_i^t = state of the buffer of the i -th channel

at time t ; $i = 1, 2, 3$.

Also we have:

$$0 \leq n_1^t \leq M$$

$$0 \leq n_2^t \leq N$$

$$0 \leq n_3^t \leq P$$

Let us define: $n_1^t \triangleq m$

$$n_2^t \triangleq n$$

$$n_3^t \triangleq p$$

The buffer state of the network can be classified as shown in Table-I. With the knowledge of the buffer states of all terminals at any given time, we may also find the channel states.

If we consider the case when the buffers of all nodes are nonempty, the channel state at time t is given by:

$$C^t = (h_1^t, h_2^t, h_3^t)$$

All possible states of the channel can be labeled as shown in Table-II depending on activities of all nodes of the network. Transitions of the channel from one state to another can be described as follows:

$$\text{Channel state, } C^t = (h_1^t, h_2^t, h_3^t)$$

Channel state, $(0,0,0)$: no terminal is transmitting if the channel remains in this state.

Channel state, $(1,0,0)$: node 1 transmission state. The channel transitions from $(0,0,0)$ to this state if node 1 is the first to begin transmitting on the channel. The channel remains in this state until (i) the transmission detection time expires, (ii) node 1 completes its transmission, or (iii) some other node begins transmitting. Similarly, we can also define the channel states $(0,0,1)$ and $(0,1,0)$ for node 3 and 2, respectively.

Channel state, $(D,0,0)$: the detection of transmission of node 1 by all its neighbors. The channel transitions from $(1,0,0)$ into this state when the safe detection time expires -- at which time all neighboring terminals of node 1 become aware of the transmission on the channel. All neighbors of

node 1 reschedule their transmissions allowing the transmission to continue without interference and busy-tone is being transmitted to their respective neighbors excluding the node from which transmission is being received. The channel remains in this state until (i) the transmission of node 1 is completed, (ii) the busy-tone detection time expires, or (iii) any node other than the neighbors of node 1 starts transmitting. In the same way we can define the channel states $(\emptyset, \emptyset, D)$ and $(\emptyset, D, \emptyset)$ for nodes 3 and 2, respectively.

Channel state, $(S, \emptyset, \emptyset)$: the safe transmission state for node 1. The channel transitions from $(D, \emptyset, \emptyset)$ into this state when the busy-tone detection time expires -- at which time all the neighbors of the neighbors of the transmitting node 1 receive busy-tone and any scheduled transmission attempts are postponed, allowing the transmission to continue without interference. The channel remains in this state until the transmission is completed. Similarly, we can also define the channel states $(\emptyset, \emptyset, S)$ and $(\emptyset, S, \emptyset)$ for nodes 3 and 2, respectively. It may be noted that the state $(\emptyset, D, \emptyset)$ is also the safe transmission for node 2. According to CSMA/BT-CD scheme every node has to transmit busy-tone after detecting transmission. So, node 2 has another safe transmission state, $(\emptyset, S, \emptyset)$.

Channel state, (C, C, C) : the detection state of the

channel. Transition of the channel may take place from several states. In CSMA/BT-CD scheme all the neighbors as well as the neighbors of the neighbors of a transmitting node will have to remain idle for safe transmission of a packet. If node 1 is in transmission state, then the channel transitions into this conflict state either (i) any neighbor or any neighbor of the neighbors of the transmitting node starts transmitting while the channel is in the state, $(1, \emptyset, \emptyset)$ or (ii) if any node of the neighbors of the transmitting node starts transmitting while the channel is in the state, $(D, \emptyset, \emptyset)$.

Similarly, we can define how the channel transitions into this state from states $(\emptyset, \emptyset, 1)$ or $(\emptyset, \emptyset, D)$ while node 3 is in transmission state. It may be noted that the channel transitions into state, (C, C, C) from state, $(\emptyset, 1, \emptyset)$ only if any neighbor of node 2 starts transmitting.

Channel state, (T, T, T) : the collision termination state of the channel. The channel transitions from (C, C, C) into this state if the collision detection time expires.

4.1.1 State-Transition-Rate Diagram

Both channel and buffer states can be incorporated together as defined in equation (7). If we consider the case of nonempty buffer, then the states of the network can be

defined as shown in Table-III. Figure 2 shows the state transition rate diagram for the network at time t . Transition between the states is indicated by the arrows. For example,

$$(\emptyset, \emptyset, \emptyset:m, n, p) \rightarrow (1, \emptyset, \emptyset:m, n, p) \rightarrow (D, \emptyset, \emptyset:m, n, p) \rightarrow (S, \emptyset, \emptyset:m, n, p) \rightarrow (\emptyset, \emptyset, \emptyset:m-1, n, p).$$

represents a successful transmission of a packet by node 1 and the packet has left the network as it has reached its final destination. On the otherhand,

$$(\emptyset, \emptyset, \emptyset:m, n, p) \rightarrow (1, \emptyset, \emptyset:m, n, p) \rightarrow (D, \emptyset, \emptyset:m, n, p) \rightarrow (S, \emptyset, \emptyset:m, n, p) \rightarrow (\emptyset, \emptyset, \emptyset:m-1, n+1, p).$$

represents a successful transmission of a packet by node 1 and the packet has been received by the neighbor of the transmitting node for forwarding to the next destination depending on routing. In this case the packet has been received by node 2 for forwarding to the next destination. Transition from:

$$(\emptyset, \emptyset, \emptyset:m, n, p) \rightarrow (1, \emptyset, \emptyset:m, n, p) \rightarrow (C, C, C:m, n, p) \rightarrow (T, T, T:m, n, p).$$

represents the collision of two or more packets transmitted at the same time. The sequence :

$$(T, T, T:m, n, p) \rightarrow (\emptyset, \emptyset, \emptyset:m, n, p).$$

represents that the channel goes to idle state after termination of collision.

It can be shown that the other states of the network

will be similar to those states if some buffers are empty. If any arrival occurs to an empty buffer it would be immediately transmitted if the channel and the busy-tone are sensed idle in case of IFT protocol, or it could be delayed if we use DFT protocol.

4.1.2 Throughput and Delay Analysis

We can write the global-balance equations (5) from the state-transition-rate diagram shown in Figure 2 and calculate the state probability, Π_1 . We are also using similar argument to find the throughput as that used in [31] for single-hop network. If the channel is in state, $(D, \emptyset, \emptyset: m, n, p)$ which occurs with probability, $\Pi_5 = P(D, \emptyset, \emptyset: m, n, p)$ the time spent in this state represents successful transmission of information if the next transition on the channel is either departure of the packet or detection of busy-tone by all neighbors of the neighbors of the transmitting node. Since the parameters are exponentially distributed, the contribution of this state to successful transmissions is given by:

$$\frac{(\lambda_{b_1} + \mu_1)}{E} [P(D, \emptyset, \emptyset: m, n, p)] \quad (8)$$

where $E = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_{r_3} + \lambda_{b_1} + \mu_1$

If the channel is in state, $(1, \emptyset, \emptyset: m, n, p)$ which occurs with probability, $\Pi_2 = P(1, \emptyset, \emptyset: m, n, p)$ the time spent in this

state represents successful transmission of information if the next transition on the channel is either departure of the packet or detection of this transmission by all neighbors of the transmitting node and no transmission by any neighbor of the neighbors of the transmitting node. It may be noted that the contribution to successful transmission once the transmission is detected, is similar to what we have accounted in equation (8). Hence, the contribution of state, $(1, \emptyset, \emptyset: m, n, p)$ to successful transmission is:

$$\left[\frac{\mu_1}{F} + \frac{\lambda_{d_1}}{F} \cdot \frac{(\lambda_{b_1} + \mu_1)}{E} \right] \cdot [P(1, \emptyset, \emptyset: m, n, p)] \quad (9)$$

where $F = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_{r_2} + \lambda_{r_3} + \lambda_{d_1} + \mu_1$

It may be noted that the above results ignore the contribution, if any, by external arrival to successful transmission assuming the fact that λ_{d_i} or λ_{b_i} is much larger than λ_i for any practical network in order to simplify the calculation. This may give the pessimistic result of the throughput. Should it be not small we should take this into account, as it has been done in case of

transmission and busy-tone detection rate.

If the channel is in state, $\Pi_8 = P(S, \emptyset, \emptyset : m, n, p)$ a successful transmission is taking place. Hence, the contribution of this state to the channel throughput is the probability of the state itself. Combining these three successful mechanisms, the throughput for node 1 when its buffer content is m :

$$S_1(m) = \sum_{n=0}^N \sum_{p=0}^P \mu_1 \left[\{ P(I, \emptyset, \emptyset : m, n, p) \} \left\{ \frac{\mu_1}{F} + \frac{\lambda_{d1}}{F} \cdot \left(\frac{\lambda_{b1} + \mu_1}{E} \right) \right\} \right. \\ \left. + \{ P(D, \emptyset, \emptyset : m, n, p) \} \cdot \left\{ \frac{\lambda_{b1} + \mu_1}{E} \right\} + P(S, \emptyset, \emptyset : m, n, p) \right] \quad (10)$$

The throughput of node 1 is given by:

$$S_1 = \sum_{m=0}^M S_1(m) \quad (11)$$

The expected number of packets at node 1 is obtained from:

$$Q_1 = \sum_{m=0}^M \sum_{n=0}^N \sum_{p=0}^P [m \left\{ \sum_{h_1, h_2, h_3} P(h_1, h_2, h_3 : m, n, p) \right\}] \quad (12)$$

Using Little's result [44], the expected time a packet spends at node 1 or the delay at node 1, is given by:

$$D_1 = Q_1/S_1 \quad (13)$$

Blocking probability at node 1 is given by:

$$B_1 = 1 - S_1/\lambda_1 \quad (14)$$

Similarly, we can find throughput, delay, and blocking probability for nodes 2 and 3. The throughput of the network is given by:

$$S = \sum_{i=1}^k S_i \quad (15)$$

The expected number of packets in the network is given by:

$$Q = \sum_{i=1}^k Q_i \quad (16)$$

The expected delay in the network is given by:

$$D = Q/S \quad (17)$$

The blocking probability in the network is given by:

$$B = 1 - S/\lambda_s \quad (18)$$

where

$$\lambda_s = \sum_{i=1}^k \lambda_i \quad (19)$$

4.1.3 Reduction of States

We have just shown how we can calculate the state probabilities of the network. Consequently, one can find throughput, delay, and blocking probability for each node as well as for the entire network. If we could reduce the network state by taking advantage of symmetry of the state transitions, with the given knowledge of topology as well as state-transition graph, it would improve the computational efficiency especially when the network is large. To explore symmetry in transition, we shall have to make some assumptions, such as, each node should have the same external arrival rate, transmission detection rate,

busy-tone detection rate and packet service rate. A simple example will make it clear how we can take the advantage of symmetry for reducing the network states.

Example :

Figure 3 shows a two-node network operating according to CSMA strategy and IFT protocol. We assume that transmission is heard by their neighbor instantaneously and no collision takes place. We also consider, each has one packet buffer and the same arrival and retransmission rate.

Let us assume, λ , λ_r , and μ be arrival rate, retransmission rate, and packet service rate respectively. Table IV shows the possible network states. Figure 4 shows the state-transition-rate diagram. Appendix A shows the solutions for the state probabilities, the throughput and the delay. It is interesting to note that $\Pi_2 = \Pi_3$. Moreover, Π_2 and Π_3 are the steady state probabilities of network states $(0,0:1,0)$ and $(0,0:0,1)$, respectively. Figure 4 shows clearly there is a symmetry in transition, bearing the fact in mind, nodes 1 and 2 have also topological symmetry among themselves. The same thing is true for other network states.

We have then combined the symmetrical states into one

(Table V) and drawn a new state transition diagram (Figure 5). Appendix B shows the solutions for the state probabilities, the throughput and the delay for the network. Results are very surprising. We note the following:

$$\begin{aligned}\Pi_1^* &= \Pi_1 \\ \Pi_2^* &= 2 \Pi_2 \\ \Pi_3^* &= 2 \Pi_4 \\ \Pi_4^* &= 2 \Pi_6\end{aligned}$$

Results of the throughput and the delay are the same in both cases, that is, $TH^* = TH$ and $D^* = D$. We see here that that seven states have been reduced to four. Resultant state transition diagram is also simpler. To draw the resultant state diagram it requires a little caution. In a bigger network it will require more skill and experience. Computer programs similar to those developed in [45,46] would be very helpful to generate the state transition rate diagram for large networks.

We shall now apply the same technique in three-node chain network. We define the following:

$$\left. \begin{aligned}\lambda_i &= \lambda \\ \lambda_{r_i} &= \lambda_r \\ \lambda_{d_i} &= \lambda_d \\ \lambda_{b_i} &= \lambda_b \\ \mu_i &= \mu \\ F_i &= F\end{aligned} \right\} \quad i=1,2, \dots, k \quad (20)$$

To simplify our calculation we shall further assume that the buffer capacity of each node is unity and once the packet is successfully transmitted by a node is lost from the network. We, therefore, can write:

$$\left. \begin{array}{l} \gamma_i = \lambda \\ \alpha_i = 1 \end{array} \right\} \quad i=1,2, \dots k \quad (21)$$

since $r_{ij} = 0; \quad i, j = 1, 2, \dots$

If we analyze the states of this network, it can be shown that there is only 52 states as listed in Table VI. Careful examination of the state transition rate diagram will reveal the fact there is a symmetry in transition among some states. For example, transitions of the states, $(1,0,0:1,0,0)$ and $(0,0,1:0,0,1)$ has a complete symmetry. In other words we can say, the probabilities of these two states are the same, that is, $P(1,0,0:1,0,0) = P(0,0,1:0,0,1)$ or $\Pi_9 = \Pi_{11}$ (Numerical results can be seen in Table VIA, VIB, and VIC). If we combine these two states into one, the new resultant state would be simply twice of the value what had been in the previous case. In

the same way we can find out all other similar states of the network. The reduced states are shown in Table-VII. We would have to solve for 52 states and 52 X 52 transition matrix, had the states not been reduced. Now we have to solve 33 states and 33 X 33 transition matrix.

4.1.4 Determination of Parameters

In CSMA/BT-CD protocol a node will initiate transmission if it senses channel idle while no busy-tone is detected. In a three-node chain network (Figure 1) if node 1 initiates transmission, then it is clear that it takes, at most, one end-to-end propagation delay τ , for the packet to reach its neighbors; beyond this time the channel is expected to be sensed busy as long as data transmission is in process. As soon as transmission reaches to its neighbors, all of them start transmitting busy-tone to their respective neighbors except the transmitting node as long as transmission continues. Propagation delay of busy-tone to the neighbors of the neighbors of the transmitting node is assumed to be another, τ , relative to the time of start of transmission of the busy-tone by the neighbors of the transmitting node.

We define collision if all the neighbors as well as the neighbors of the neighbors of the transmitting node are not idle. Given that node 1 is in transmission state, $C2=(1,0,0)$ then the channel transitions to the collision state, $C11=(C,C,C)$ either (a) node 2 starts transmitting before detection of transmission, or (b) node 3 starts transmitting before receiving busy-tone. Given the situation in (a) it will take, at most, one additional end-to-end propagation

delay, that is, 2τ relative to the time of start of transmission by node 1, before interference reaches between the neighboring nodes and the transmitting node. Let ζ denote the time it takes a terminal to detect collision once the later has reached it. In other words $2\tau + \zeta$ may be the total time to detect collision for situation described in (a) from the time node 1 has started transmission. In case of (b), idle node 2 will detect the transmission from node 3, at least, within another end-to-end propagation delay. In this scheme idle node 2 has to transmit busy-tone in all directions including the transmitting node from which it is receiving transmission to make them aware that the collision has taken place. This busy-tone will take another end-to-end propagation delay to reach to the transmitting nodes which are yet to detect collision. In this situation $3\tau + \zeta$ may be the total time to detect collision by all collided nodes from the time node 1 has started transmission. So, collision detection time may vary from $\tau + \zeta$ to $3\tau + \zeta$.

According to this protocol all the transmitting nodes which has just detected collision, jams the channel. We define β as the period used for collision consensus reenforcement. Given that a collision has been detected, the channel is again sensed idle after a period of $\beta + \tau$. This period is defined as the collision termination time and

depends on implementation and can be as small as few bits of transmission time [47].

If the channel is in the state, $C5=(D,0,0)$ then transition to state, $C11=(C,C,C)$ will only take place if node 3 starts transmitting before receiving busy-tone. Receiving more than one transmission simultaneously, node 2 will come to realize that it is in collision state. It will then start transmitting busy-tone in all directions to make all the transmitting nodes aware that they are in collision state. In this situation, collision detection time will vary from $2\tau + \zeta$ to $3\tau + \zeta$ after the time of detection of transmission by node 2.

One can easily show that similar is the situation if we consider any other nodes and values of those parameters remain within limits as discussed above. In the beginning, we have assumed all the parameters such as transmission detection time, busy-tone detection time, collision detection time and collision termination time are exponentially distributed with their mean values of $1/\lambda_d$, $1/\lambda_b$, $1/\lambda_c$ and $1/\lambda_t$, respectively. In other words, the mean values of the parameters depend on the the configuration of the network as well as on the implementation of the protocol. We may choose the mean values of the parameters within the above specified limits.

4.1.5 Numerical Results and Discussions

Results have been normalized with respect to the period of the packet length. It is assumed that the mean length of the packet is unity (i.e. $1/\mu = T = 1$) and accordingly all other parameters have been normalized. Depending on distance between the nodes, the propagation delay is determined. Given the propagation delay, the parameters λ_d , λ_b , λ_c , and λ_t can be determined. Throughput and delay can be found at various values of retransmission rates λ_r .

Figure 6 displays the throughput-delay curves for the partially connected three-node chain network of Figure 1 operating according to nonpersistent CSMA/BT-CD scheme. The scheme has been evaluated with $a=\tau/T=0.01$, $\mu=1$, $\lambda_d=100$, $\lambda_b=100$, $\lambda_c=50$, $\lambda_t=100$ using IFT protocol at various values of retransmission rate, λ_r .

It is observed that, for a fixed value of λ_r , the channel exhibits a maximum achievable throughput which depends on that value. The optimum-delay performance is obtained by taking lower envelope of all fixed λ_r -curves. The maximum throughput obtained by CSMA/BT-CD is around 92%. For this random access scheme, the fact that the throughput drops toward zero as the retransmission rate increases indefinitely, is indicative of unstable behavior. Figure 7

shows, with CSMA/BT-CD scheme, the channel has the ability to maintain a throughput relatively high and has also the ability of sustaining proper behavior when the channel load exceeds that for which the system has been optimized with respect to λ_r .

If we examine the delay-throughput curves (Figure 6) for the retransmission rates ranging from 0.001 to 0.1, we observe that there is a peak indicating the maximum delay in between very low and high throughput for each retransmission rate. We can explain this phenomenon, if we examine the steady state probabilities of the network. Let us consider one such delay-throughput curve when retransmission rate is 0.001. Tables VIB and VIC show the distribution of all steady state probabilities of the network at throughputs of 0.05 and 0.47, respectively at the said retransmission rate. Probabilities of remaining idle while there are packets in the network (i.e. Π_2 , Π_3 , Π_4 , Π_5 , and Π_6) and probabilities of collision (i.e. Π_{45} , Π_{46} , and Π_{47}) are considerably higher in case of the former than the latter. This has contributed to increase the delay for the former. Once the packet is collided it will be retransmitted after a considerable amount of delay, since retransmission rate is very low (in this case $\lambda_r=0.001$). It is obvious that the probability of new arrival in the network is much higher for the latter than the former, since the arrival rates are 0.03

and 0.90, when the throughputs are 0.05 and 0.47, respectively. If the system is idle and a new arrival occurs in the empty buffer, it will immediately be transmitted due to IFT protocol. Under these circumstances, this new arrival has higher probability of success. As a result the expected delay is reduced and the throughput of the network also increases. That is why we see delay is considerably less in case of the latter than the former. Had there been no IFT protocol, we would not observe these peaks (Figure 13 shows that no such peaks in the delay-throughput curves if DFT protocol is used). As the retransmission rate increases further the peaks will disappear and the contribution by IFT protocol will not be so much significant (we shall see later, Figure 17, that both IFT and DFT protocols behave almost similarly if the retransmission rate becomes higher).

Let us consider the performance of the individual node. Figure 8 shows that the throughput of node 2 is little higher than that of node 1 or 3 as expected while those of nodes 1 and 3 are the same proving that all activities of these two nodes are similar and they have the same steady state probabilities. Inspection of the network states (Table VI) will also reveal the similarities among the states. It is interesting to note that at higher channel traffic (range of λ_r from 100 to 1000) the throughput of node 2 has not dropped off as sharply as that of node 1 or

3. This significant difference is due to the fact that node 2 has no neighbor of the neighbors and no busy-tone is required to be transmitted by its neighbors to refrain those nodes from transmitting. Consequently, node 2 is performing much better in presence of higher interference.

Figure 9 shows the curves for blocking probabilities versus throughput at various retransmission rates. It shows that the blocking probability increases as the throughput increases for a fixed- λ_r .

4.2 Ring Network

Let us consider a network consists of five-node ($k=5$) uniformly distributed around the circumstances of a circle as shown in Figure 10. Node 1 can hear its neighboring nodes 2 and 5, but not nodes 3 or 4. Similar is the case for each node in the network. Nodes of the network are mutually independent and each other is communicating over a common broadcast channel as described earlier. We assume each terminal has a finite buffer capacity: $M, N, P, Q,$ and R for nodes 1, 2, 3, 4, and 5, respectively.

The state of the network at any time t is given by:

$$N^t = (h_1^t, h_2^t, \dots, h_5^t; n_1^t, n_2^t, \dots, n_5^t) \quad (22)$$

Also we have:

$$0 \leq n_1^t \leq M$$

$$0 \leq n_2^t \leq N$$

:

$$0 \leq n_3^t \leq P$$

$$0 \leq n_4^t \leq Q$$

$$0 \leq n_5^t \leq R$$

Let us define:

$$n_1^t \stackrel{\Delta}{=} m$$

$$n_2^t \stackrel{\Delta}{=} n$$

$$n_3^t \stackrel{\Delta}{=} p$$

$$n_4^t \stackrel{\Delta}{=} q$$

$$\text{and } n_5^t \stackrel{\Delta}{=} r$$

If we consider the case of nonempty buffer, the states of the network at any time t can be described as shown in Table VIII . Transitions of the channel from one state to another is similar to those what have been explained in case of the chain network.

4.2.1 State Transition Rate Diagram

Figure 11 shows the state transition rate diagram for the network at time t . Transition between the states is indicated by arrows and the same explanation is true what we have discussed in case of the chain network.

4.2.2 Throughput and Delay Analysis

Figure 11 shows the state transition diagram for node 1 when all buffers of the network are nonempty. Again we can write the global balance equation (5) from the state transition rate diagram and calculate the state probability, Π_i . Combining the successful mechanisms, the throughput for node 1 when its buffer content is m , is given by:

$$S_1(m) = \sum_{n=0}^N \sum_{p=0}^P \sum_{q=0}^Q \sum_{r=0}^R \mu_1 \left\{ \Pi_2 \left\{ \frac{\mu_1}{G} + \frac{\lambda_{b_1} + \mu_1}{E} \cdot \frac{\lambda_{d_1}}{G} \right\} + \Pi_3 \left\{ \frac{\lambda_{b_1} + \mu_1}{E} \right\} + \Pi_4 \right\} \quad (23)$$

The throughput of node 1 is given by:

$$S_1 = \sum_{m=0}^M S_1(m) \quad (24)$$

The expected number of packets at node 1 is given by:

$$Q_1 = \sum_{m,n,p,q,r} m \left\{ \sum_i \Pi_i \right\} \quad (25)$$

Using Little's result, the expected time a packet spends or delay at node 1 is given by:

$$D_1 = Q_1 / S_1 \quad (26)$$

The blocking probability in node 1 is given by:

$$B_1 = 1 - S_1 / \lambda_1 \quad (27)$$

Similarly, we can find the throughput, the delay and the blocking probability for all other nodes. The throughput of the network is given by:

$$S = \sum_{i=1}^k S_i \quad (28)$$

The expected number of packets in the network is given by:

$$Q = \sum_{i=1}^k Q_i \quad (29)$$

The expected delay in the network is expressed as:

$$D = Q / S \quad (30)$$

The blocking probability in the network is given by:

$$B = 1 - S / \lambda_s \quad (31)$$

where $\lambda_s = \sum_{i=1}^k \lambda_i$

4.2.3 Reduction of States

We assume that each node has the same external arrival rate, transmission detection rate, busy-tone detection rate and packet service rate. So, we can write as follows:

$$\left. \begin{aligned} \lambda_i &= \lambda \\ \lambda_{r_i} &= \lambda_r \\ \lambda_{d_i} &= \lambda_d \\ \lambda_{b_i} &= \lambda_b \\ \mu_i &= \mu \\ F_i &= F \end{aligned} \right\} i=1,2, \dots, k \quad (32)$$

At present, we assume that once the packet is successful transmitted by a node is lost from the network. So, we have:

$$\left. \begin{array}{l} \gamma_i = \lambda \\ \alpha_i = 1 \end{array} \right\} \quad i=1,2, \dots, k \quad (33)$$

since $r_{ij} = 0$; $i, j = 1, 2, \dots$

If we assume that the buffer size is unity for each node, then the states of the network would be 254 and we have to solve 254 X 254 transition matrix. We can reduce these states into 50 by combining the symmetrical states. The resultant states have been shown in Table IX. We have to solve for 50 states and 50 X 50 transition matrix. We can now determine the parameters λ_d , λ_b , λ_c , and λ_t once we know the distance between the nodes of the uniform ring. We have discussed in detail how to determine those parameters of multihop network operating according to CSMA/BT-CD scheme in case of chain network.

Figure 12 shows some examples how DFT and IFT transmission protocols influence the state transition diagram.

4.2.4 Single Buffer: Discussions of Numerical Results for DFT and IFT Transmission Protocols

We observe from (27) that the throughput of the

network, S is a concave function of λ_r which maximizes S . From (30) and (31) we note that D and B are convex function of λ_r . We do not give any analytical proof for those above statements, but later on, we can see these are true when curves are plotted. So, it may be clear that the value of λ_r which maximizes S , minimizes D and B .

We have normalized our results with respect to the period of the packet length. It is assumed that the mean length of the packet is unity (i.e. $1/\mu = T = 1$) and accordingly all other parameters have been normalized. Depending on distance between the nodes, the propagation delay is determined. Given the propagation delay, the parameters λ_d , λ_b , λ_c , and λ_t can be determined. The throughput, the delay and the blocking probability are found at various values of retransmission rate λ_r .

Figures 13, 14, and 15 display the throughput-delay curves for the partially connected five-node ring operating according to nonpersistent CSMA/BT-CD scheme. We evaluate the scheme with $a = \tau/T = 0.01$, $\mu = 1$, $\lambda_d = 100$, $\lambda_c = 50$ and $\lambda_t = 100$ using DFT and IFT transmission protocols at various values of retransmission rate λ_r .

Once again we observe that, for a fixed value of λ_r , the channel exhibits a maximum achievable throughput which depends on that value. The system becomes unstable if the retransmission rate increases indefinitely. In this work we

do not address the problem of controlling the unstable behaviour of the channel of multihop network. If we compare the performances of DFT (Figure 13) with those of IFT (Figure 14), we do not observe any peaks indicating the maximum delay in between low and high throughput whether retransmission rate is high or low in case of DFT as predicted, but IFT does have the peaks as we have seen earlier. The same explanation holds good what has been described in Section 4.1.5.

Figures 16, 17, and 18 show the optimum throughput, the throughput/blocking probability and delay versus retransmission rate. We observe that throughput S , delay D , and blocking probability B are not too sensitive to λ_r . and IFT protocol is superior to DFT in all respects. Moreover, performances of DFT becomes almost equal to those of IFT as λ_r increases.

In Figure 19, we plot S (maximized over λ_r with kept constant) versus λ . We also observe that S , optimized with respect to λ_r , is a monotonic function of λ .

4.2.5 Lower Bound in Throughput

Let us refer node 1 of Figure 10 as our local node. If we consider heavy traffic situation, then all neighbors as well as neighbors of the neighbors of the local node will always have a packet to be transmitted. Moreover, retransmission rate of all nodes (except the local node) will not be less than the external arrival rate to the local node. In this situation the local node will face maximum interference.

4.2.5.1 Single Buffer : IFT Protocol

In heavy traffic situation, we do not need to know the state of the buffers except the local node since the buffer state of all those nodes remains the same at all times. Table X shows the states of the networks in heavy traffic situation for five node ring network.

Figure 20 shows some examples of the state transition rate diagram in heavy traffic situation for single buffer. It can be shown easily that the throughput of the local node can be given as follows:

$$S_1 = \mu \left\{ \frac{1}{H} \left\{ \mu + \frac{\lambda_d (\lambda_b + \mu)}{H} \right\} \Pi_{1,1} + \frac{(\lambda_b + \mu)}{J} \Pi_{2,1} + \Pi_{3,1} \right\} \quad (34)$$

where $H = 4 \lambda'_r + \lambda_d + \lambda_s$

$$J = 2 \lambda_r + \lambda_d + \lambda_s$$

λ'_r = retransmission rate of the neighbor or the neighbor of the neighbor of the local node.

The average number of the packets in the local node is given by:

$$Q'_1 = \sum_n n \left[\sum_{i,j} \Pi_{i,j} \right] \quad (35)$$

The expected delay in the local node is given by:

$$D'_1 = Q'_1 / S_1 \quad (36)$$

The blocking probability in the local node is given by:

$$B'_1 = 1 - S'_1 / \lambda \quad (37)$$

The throughput of the network is expressed as:

$$S' = k S'_1 \quad (38)$$

The expected delay (for transmission of a packet one-hop

away) and the blocking probability of the network are $D = D'$ and $B = B'$, respectively. S' represents the lower bound in throughput and D' represents corresponding the higher bound in delay of the network.

Figure 21 shows delay versus throughput for both heavy and normal traffic situation. Comparing the heavy traffic case with that of the normal traffic, we find some interesting results. The maximum throughput of the network in heavy traffic situation increases as the retransmission rate increases from low to high. If the retransmission rate increases further the maximum throughput starts decreasing. If we compare the retransmission rate at which this maximum throughput is achieved under heavy traffic situation with that of the normal traffic, we can draw a very useful conclusion. Retransmission rate for maximum throughput in normal traffic situation is comparatively much higher than that of the heavy traffic case.

Figure 22 displays the optimum throughput and delay versus retransmission rate for both heavy and normal traffic situations. It clearly shows that the throughput in heavy traffic situation is the lower bound with respect to the normal traffic of the network and the corresponding delay is the higher bound. Similarly, we can find the lower bound in throughput and the corresponding higher bound in delay for any other configurations of the networks.

4.2.5.2 Multibuffer : IFT Protocol

Table XI shows the states of the network in heavy traffic situation in the multibuffer case. We can find the lower bound in throughput and the corresponding upper bound in delay as before once we solve the global balance equations (5). It may be one of the most important observations that there would be no explosion in state equations. Moreover, we can also find the close expressions for throughput and delay by taking Z -transformation. In this work we have not shown any of those expressions. However, we have solved for multibuffer case when the buffer contents of the local node is 2 and 3 to understand the effects of the buffer in multihop network in heavy traffic situation using IFT transmission protocol.

In Figure 23 we plot the optimum throughput and delay versus retransmission rate in heavy traffic situation. It shows a significant increase in throughput of the network by going from $F=1$ to $F=2$. Increasing F to 3, however, offers no further appreciable improvement. We also observe that the network delay has increased with larger F . This is due to the additional queueing time incurred in the node. The increase in delay going from $F=2$ to $F=3$ is greater than that of from $F=1$ to $F=2$. It implies if F is made

larger, it will cause an increase in delay more rapidly while there will be no appreciable increase in the throughput.

In a similar manner the effect of multibuffer can also be found for other configurations of the networks.

4.3 Cube Network

We shall now attempt to apply our model in three dimensional topology, such as, cube network. Figure 24 shows a regular cube network. Node 1 has three neighbors (2, 4, and 5) and three neighbors of the neighbors (3, 6, and 8). All other nodes has the same situation.

4.3.1 Network States

Number of buffer states is given by $(1+L)^k$, where L and k are the buffer capacity (assuming each node has equal number of buffers) and number of nodes in the network, respectively. To find the total number of network states, we have to multiply the number of buffer states to that of the channel states.

If we consider that the expected number of channel states would be 12 (we could see that there would be 15 channel states for each node if buffer is nonempty, but some

of those states might not exit while buffer is empty). Even for unity buffer case, the approximate number of network states would be 3,072. To analyze the state-transition rate diagram even for this single buffer situation is a colossal task. Moreover, if we reduce the states by observing the symmetry as discussed earlier, we would obtain nearly 768 network states in normal traffic situation. This would have been also a very serious task to perform. We obtain 56 network states, if we consider heavy traffic situation. This is some what within our effort for detailed analysis. Table XII shows the states of the cube network in heavy traffic situation.

4.3.2 Discussions of Numerical Results

Figure 25 shows the delay-throughput curves for cube network in heavy traffic situation. The characteristics of the curves have the similarity what we have observed earlier. Most surprising result is that the throughput per node is considerably higher than that of what we have found in five-node ring network although the latter has lesser number of the neighbors and the neighbors of the neighbors for each node. Apparent reason is that two off-diagonal nodes of the cube can transmit simultaneously while only one node can transmit at a time in case of the five-node

ring. Another reason is that if a node of the former is in safe transmission state and the other off-diagonal node wants to transmit, then the probability of success is almost certain. These two important phenomena have contributed to increase the throughput of the cube network.

5. CONCLUSIONS

5.1 Normal Traffic

Figure 6 and 14 display the delay-throughput curves at various retransmission rates for three-node chain and five-node ring network, respectively. We observe that the shapes of all curves are similar, as if, these have been shifted by some scale factors. This is one of the important observations. It may be noted that a node has only one neighbor and one neighbor of the neighbor (except the middle node) for the former, where as, there are two neighbors and two neighbors of the neighbor for each node in case of the latter. These are the main important factors which have contributed to cause differences in the throughput-delay curves for the same retransmission rate. In other configurations, such as cube, the connectivity among the nodes will also play an important part to influence the throughput-delay characteristics of the network.

In normal traffic situation, the network state increases tremendously as the topology becomes complex containing large number of nodes. Reduction of states by taking advantage of the similarity among the states will be of great help for computation in case of simple topology, but we can not expect too much for a network having a large

number of hops.

5.2 Heavy Traffic

In heavy traffic situation we do not need to know the states of the buffers except the local node. This reduces the network state very significantly. It is required to know the channel state only. Moreover, we can again take the advantage of symmetry and reduce the network state further. This has been proved very useful. Figures 21 and 25 display the delay-throughput characteristics for the five-node ring and the cube network, respectively. If we examine carefully, we find that the shapes of the throughput-delay curves are similar in heavy traffic situation, especially if the throughput per node exceeds 0.05 .

It is very interesting to note that the capacity per node of the cube network is significantly higher than that of the five-node ring network. The apparent reason is that the former has the higher degrees of connectivity than the latter. We predict that the other regular topologies having higher degrees of connectivity, such as, tetrahedron, octahedron, decahedron, icosahedron etcetra will perform relatively better under CSMA/BT-CD scheme. It may also be interesting to investigate, in future, how far connectivity may be beneficial for increasing the capacity for regularly

structured broadcast networks. Moreover, Figure 23 shows, in a five-node ring network, more than two buffers does not increase the throughput appreciably while delay increases rapidly. We believe the same may be true for any other multihop topologies.

5.3 Practical Considerations

In our foregoing examples we have considered final destination of the traffic is only one-hop. In multihop network the traffic has to be routed through many hops to reach final destination. Routing and traffic matrix will play a significant role to determine the delay-throughput characteristics. To know the actual network throughput in multihop environment we have to divide the network throughput (as found earlier) by the average path length [2,43]. Average path length is influenced by the routing algorithm and the traffic matrix. Detailed calculations for finding the average path length can be found in [2,43]. Silvester and Kleinrock [49] has shown that the traditional optimal routing algorithms, such as, the flow deviation algorithm [50] may be difficult to apply for broadcast multihop packet radio networks. To devise proper algorithms to find optimal routes for broadcast networks is an active area of research.

5.4 Suggestions for Future Research

Many aspects of multihop broadcast network have arisen during the course of this dissertation which need further study. It is intended that the following phenomena will be suitably modelled in order that their effects on the throughput, the delay, and the throughput-delay trade-offs of multihop networks operating according to nonpersistent CSMA/BT-CD scheme can be studied:

5.4.1 Routing Algorithm

Distributed routing algorithm is desirable from reliability and efficiency point of view in a real network. Routing algorithm used in point-to-point network may be difficult to implement [49]. The situation becomes more difficult if the nodes become mobile. More frequent routing updates around the network is required in mobile situation. The topology changes due to mobility will occur every time a device leaves the range of its nearest repeaters. How to handle the rapidly changing topologies in routing algorithm would be a very interesting work.

5.4.2 Acknowledgement

In this work perfect acknowledgement has been assumed. In real situation passive acknowledgement can be used. We have mentioned earlier that there could be two problems, such as, duplicate packets sent when the sender does not hear the retransmission due to some interference and active acknowledgement sent by the destination node, since it does not retransmit the packet. Both of these effects have been ignored in this dissertation. Effects of acknowledgement will have a significant influence on the performances of the network. We find some works to consider the effects of acknowledgement in multihop broadcast networks in [48]. One particular interest would be to incorporate the hop-by-hop or end-to-end acknowledgement scheme in our model.

5.4.3 Effects of Capture

Here we have assumed, when two packets collide, both will be lost. In fact, this overly pessimistic, since many FM receiver are able to extract the stronger of two overlapping packets without error known as capture. To see how this influences the system performance, let us imagine there be two classes of stations, one broadcasting at high power, one at low power, or one group close by and one group

far away, both at the same power. If two overlapping packets both originating from the same group, the receiver can not disentangle them, and both are lost. If, however, they originate from different groups, the stronger one will be accepted. In half the cases, what was previously counted as a collision is now a success. It may be a good research topics how to incorporate this in our model.

5.4.4 Nonexponential Distribution of System Parameters

For simplicity of analysis we have assumed exponential distribution of system parameters. In real situation the distribution may not be exponential. In case of nonexponential situation, the method of stages -- Erlangian distribution [43] can be used. This can be incorporated in our model, but number of network states will increase than before. Study of nonexponential distribution will help us to deal with any arbitrary distributions of retransmission rate, transmission detection rate, collision detection rate, and collision termination rate.

5.4.5 Algorithm to Reduce the Network State

It may be very useful to devise a suitable algorithm to reduce the states of the network of different topologies operating according to CSMA/BT-CD scheme. In heavy traffic situation it may be possible to obtain a few number of states of the network by exploring symmetry among the states for any number of hops.

5.4.6 Analysis of Broadcast Networks having Large Number of Hops

One of the important limitations of our model is that the network state increases tremendously when the network becomes large. We have seen that the state reduces significantly, if we consider heavy traffic situation. The actual analysis of large network is far beyond our reach due to increase in states even under heavy traffic assumption. It is observed that the performances of a node are primarily affected by its neighbors and neighbors of the neighbors. Influence of the other nodes may start decreasing if the hop distance increases from the node. In other words performances of a node may not depend too much on the

activities of the other nodes which are far away in hop distances. In a large network it may be possible to study the performance of a node by taking only a certain portion of the network whose states are well within computational capacity and then we can estimate the performance of the whole network. What the optimum number of hops around a node would be considered for such analysis would be very interesting topic for future research. This may lead us to an analogous situation, to simplify the complexities of calculation, Kleinrock [51] announced the 'Independent Assumption' of the nodes of the conventional communication networks based on wire.

5.4.7 Mixed-Media Network

In mixed-media environment there may be one using local access networks by using a satellite to connect the IMP's instead of a point-to-point backbone network. In other case, a common channel cable network may be used for local distribution, but long haul portion uses a point-to-point backbone. Our model may also be applied in this situation. Analysis of mixed-media network using mathematical model developed in this dissertation will be a very interesting topic for future investigation.

Finally, it is seen that the analysis of continuous time

Markov Chain model of multihop packet radio networks operating according to CSMA/BT-CD scheme can be studied by incorporating routing algorithms, congestion, acknowledgement, and other features essential for multihop environment. In collision free environment this model becomes almost equivalent to that of the conventional communication networks. It is hoped that some practical work on development of multihop network operating according to the CSMA/BT-CD schemes will consolidate the theoretical analysis.

APPENDIX A

Global balance equations (5) for the state transition rate diagram shown in Figure 4 will give the following equations written in a matrix form:

$$\begin{bmatrix}
 0 & 0 & \lambda + \lambda_r & 0 & 0 & -\mu & 0 \\
 0 & \lambda + \lambda_r & 0 & 0 & 0 & 0 & -\mu \\
 -\lambda & -\lambda_r & 0 & \lambda + \mu & 0 & 0 & 0 \\
 -\lambda & 0 & -\lambda_r & 0 & \lambda + \mu & 0 & 0 \\
 0 & 0 & -\lambda & -\lambda & 0 & \mu & 0 \\
 0 & -\lambda & 0 & 0 & -\lambda & 0 & \mu \\
 1 & 1 & 1 & 1 & 1 & 1 & 1
 \end{bmatrix}
 \begin{bmatrix}
 \Pi_1 \\
 \Pi_2 \\
 \Pi_3 \\
 \Pi_4 \\
 \Pi_5 \\
 \Pi_6 \\
 \Pi_7
 \end{bmatrix}
 =
 \begin{bmatrix}
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 1
 \end{bmatrix}
 \quad (\text{A.1})$$

Solving the equations we obtain:

$$\Pi_1 = 1 / (1 + 2\lambda \{ 1 + \lambda(\lambda + \mu + \lambda_r) / \mu \lambda_r \} / \mu) \quad (\text{A.2})$$

$$\Pi_2 = (\lambda^2 / \mu \lambda_r) \cdot \Pi_1 \quad (\text{A.3})$$

$$\Pi_3 = \Pi_2 \quad (\text{A.4})$$

$$\Pi_4 = (\lambda / \mu) \cdot \Pi_1 \quad (\text{A.5})$$

$$\Pi_5 = \Pi_4 \quad (\text{A.6})$$

$$\Pi_6 = (\lambda^2 \{ 1 + \lambda / \lambda_r \} / \mu^2) \cdot \Pi_1 \quad (\text{A.7})$$

$$\Pi_7 = \Pi_6 \quad (\text{A.8})$$

Throughput of the network is given by:

$$TH = \mu (\Pi_4 + \Pi_5 + \Pi_6 + \Pi_7) \quad (A.9)$$

One can show after little algebra:

$$TH = 2 \lambda (1 + \lambda (1 + \lambda/\lambda_r) / \mu) \cdot \Pi_1 \quad (A.10)$$

Average numbers of packets in the network is:

$$A = 2 \lambda (\lambda/\mu \lambda_r + 1/\mu + \lambda (1 + \lambda/\lambda_r) / \mu^2) \cdot \Pi_1 \quad (A.11)$$

Expected delay in the network:

$$D = (\lambda/ \mu \lambda_r + 1/\mu + \lambda (1 + \lambda/\lambda_r) / \mu^2) / (1 + \lambda (1 + \lambda/\lambda_r) / \mu) \quad (A.12)$$

APPENDIX B

Global balance equations (5) for the state transition rate diagram shown in Figure 5 will give the following equations written in a matrix form:

$$\begin{bmatrix} -2\lambda & \mu+\lambda & 0 & -\lambda_r \\ 0 & -\lambda & \mu & -\lambda \\ 0 & 0 & -\mu & \lambda+\lambda_r \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \Pi_1^* \\ \Pi_2^* \\ \Pi_3^* \\ \Pi_4^* \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (\text{B.1})$$

Solving we obtain:

$$\Pi_1^* = 1 / (1 + 2\lambda(1 + \lambda(\lambda + \mu + \lambda_r) / \mu\lambda_r) / \mu) \quad (\text{B.2})$$

$$\Pi_2^* = 2(\lambda / \mu) \cdot \Pi_1^* \quad (\text{B.3})$$

$$\Pi_3^* = 2(\lambda^2(1 + \lambda/\lambda_r) / \mu^2) \cdot \Pi_1^* \quad (\text{B.4})$$

$$\Pi_4^* = 2(\lambda^2 / \mu\lambda_r) \cdot \Pi_1^* \quad (\text{B.5})$$

Throughput of the network:

$$\text{TH}^* = \mu(\Pi_2^* + \Pi_3^*) \quad (\text{B.6})$$

Computing the values of the steady state probabilities:

$$\text{TH}^* = 2\lambda(1 + \lambda(1 + \lambda/\lambda_r) / \mu) \cdot \Pi_1^* \quad (\text{B.7})$$

Average numbers of packets in the network is given by:

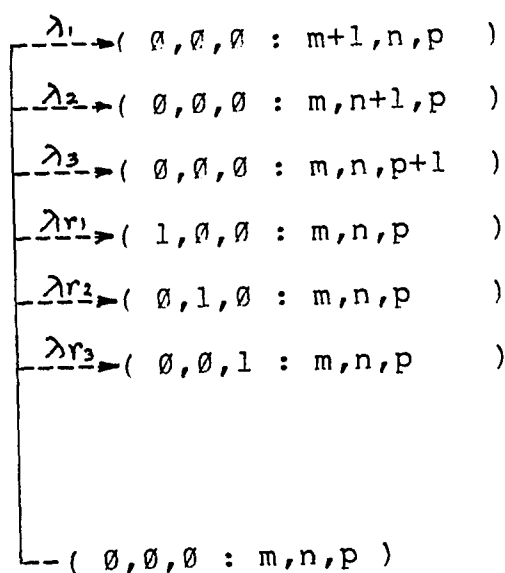
$$A^* = 2 \lambda \left(\frac{\lambda}{\mu \lambda_r} + \frac{1}{\mu} + \frac{\lambda}{\mu^2} (1 + \frac{\lambda}{\lambda_r}) \right) \cdot \Pi_1^* \quad (B.8)$$

Expected delay in the network is as follows:

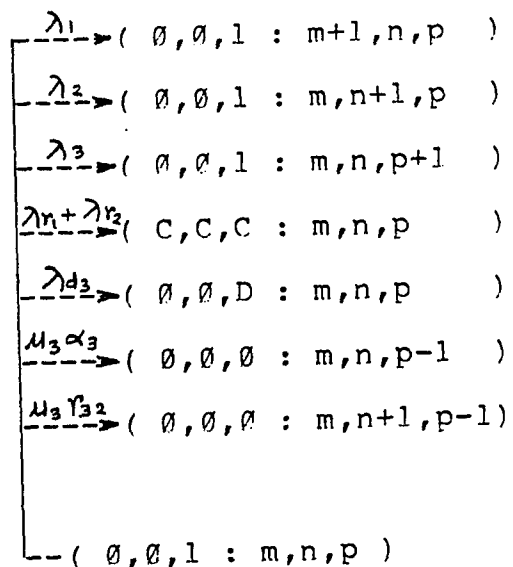
$$D^* = A^* / TH^* \quad (B.9)$$



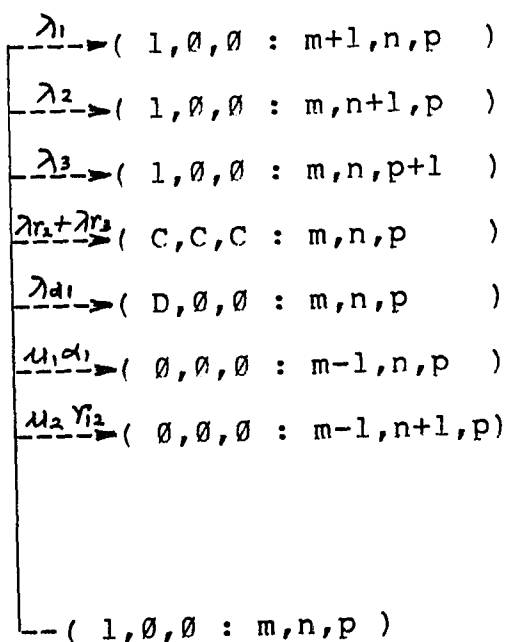
Figure 1: Three-Node Chain Network



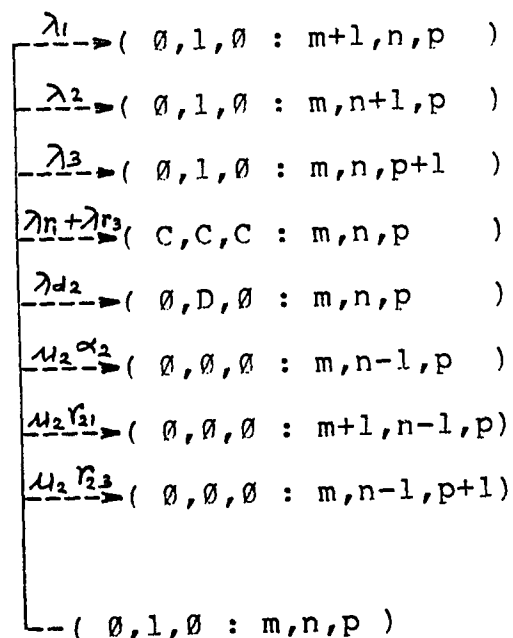
[a]



[c]

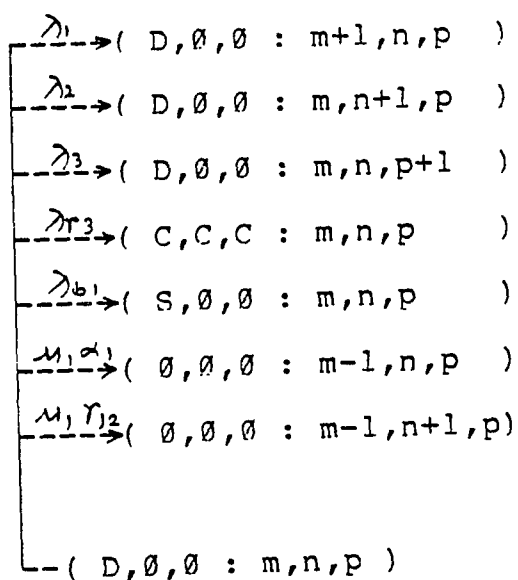


[b]

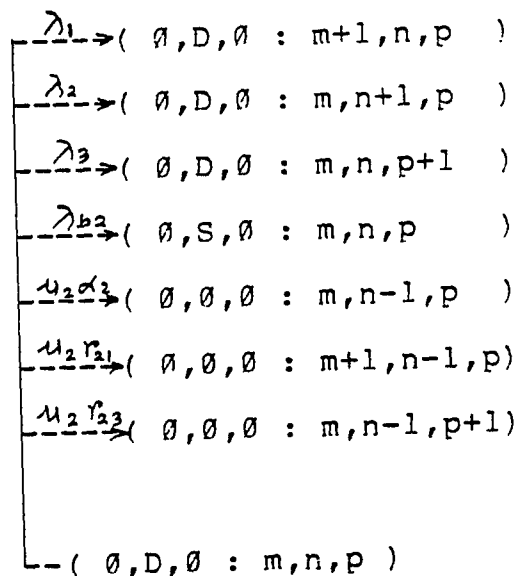


[d]

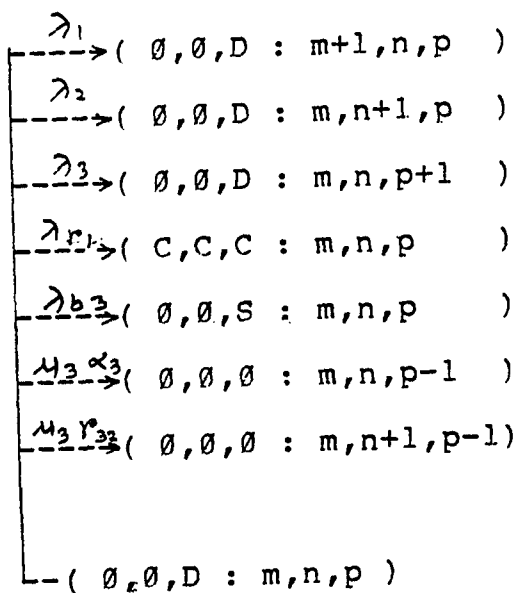
Figure 2: State Transition Rate Diagram for Nonempty Buffer: Chain Network



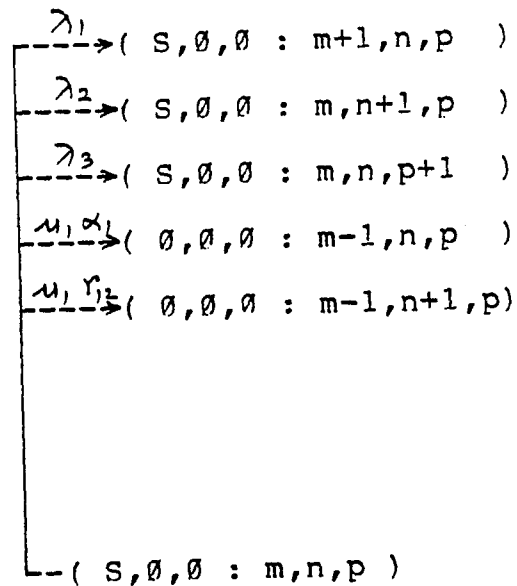
[e]



[f]

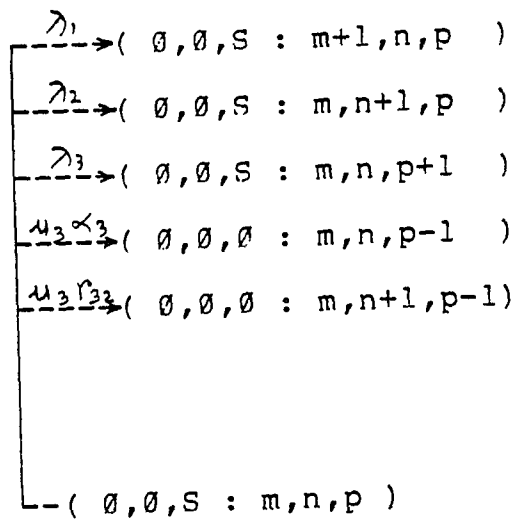


[g]

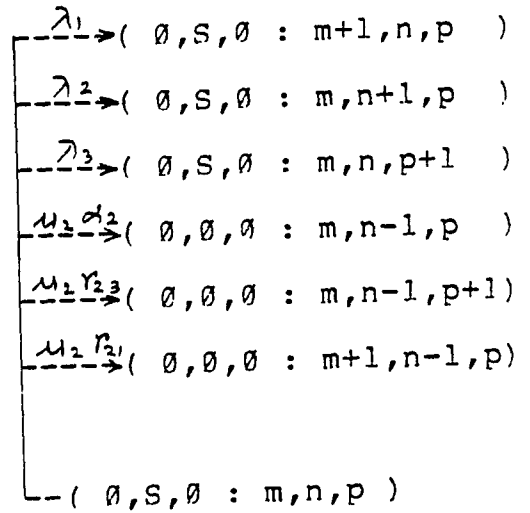


[h]

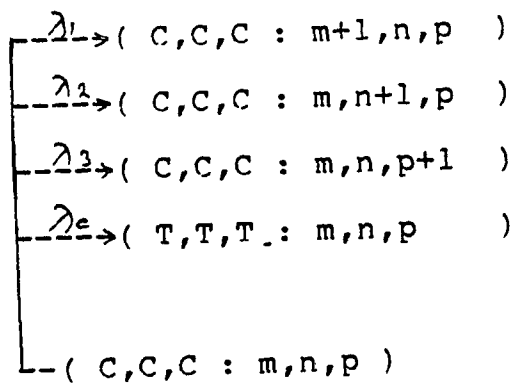
Figure 2 (Contd.)



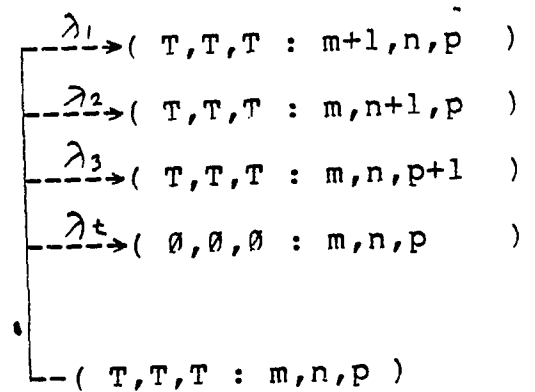
[i]



[j]



[k]



[l]

Figure 2 (Contd.)



Figure 3: Two-Node Network [Example 1]

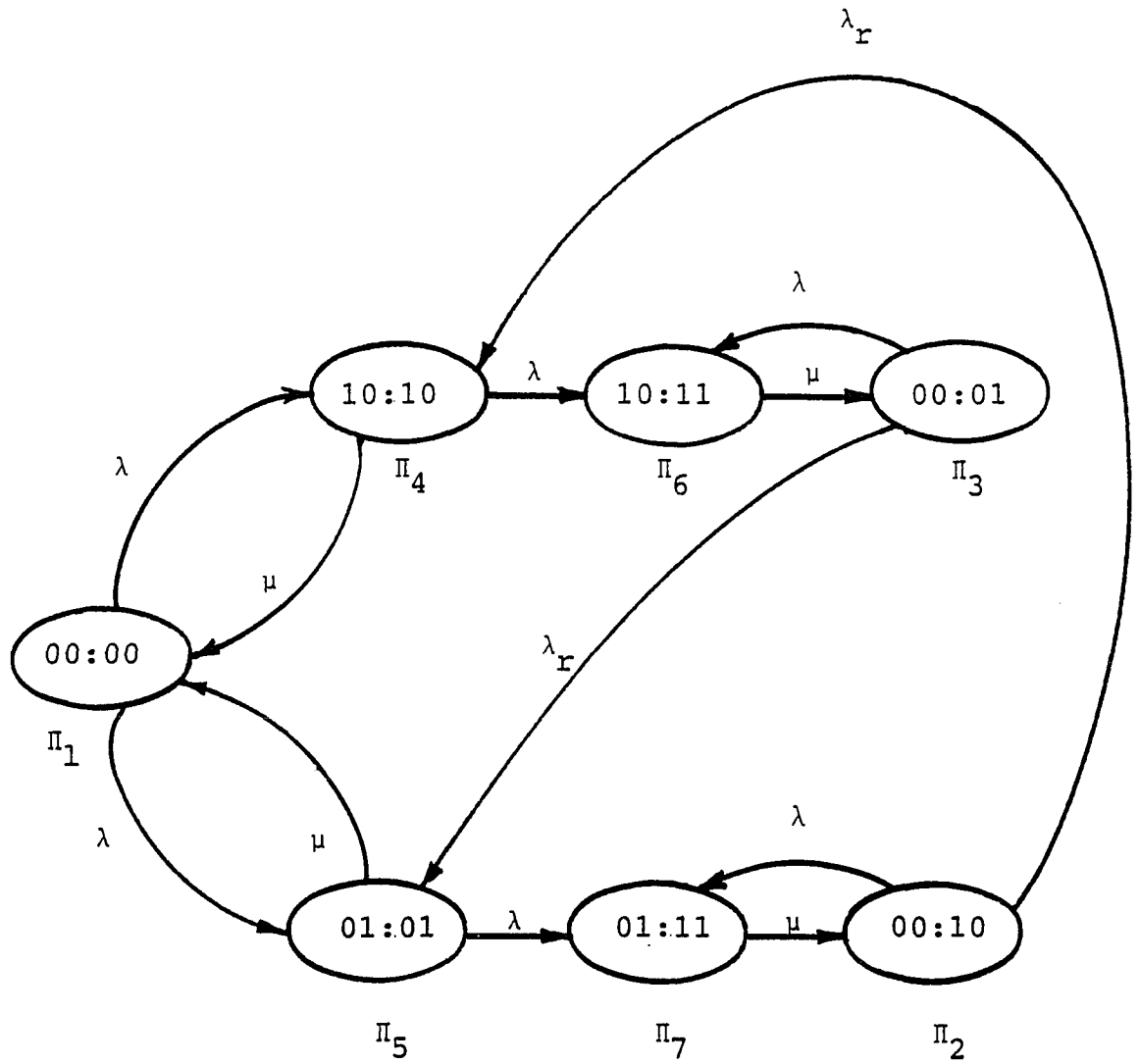


Figure 4: State Transition Rate Diagram for Two-Node Network (Figure 3: Example 1)

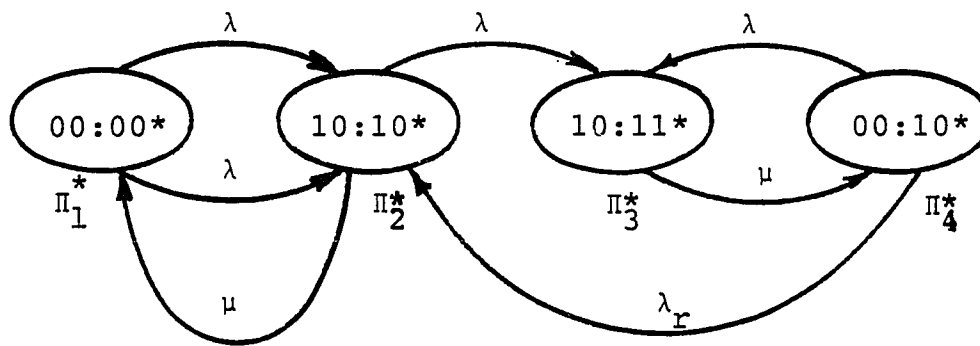


Figure 5: State Transition Rate Diagram for Reduced Network State (Table V: Example 1)

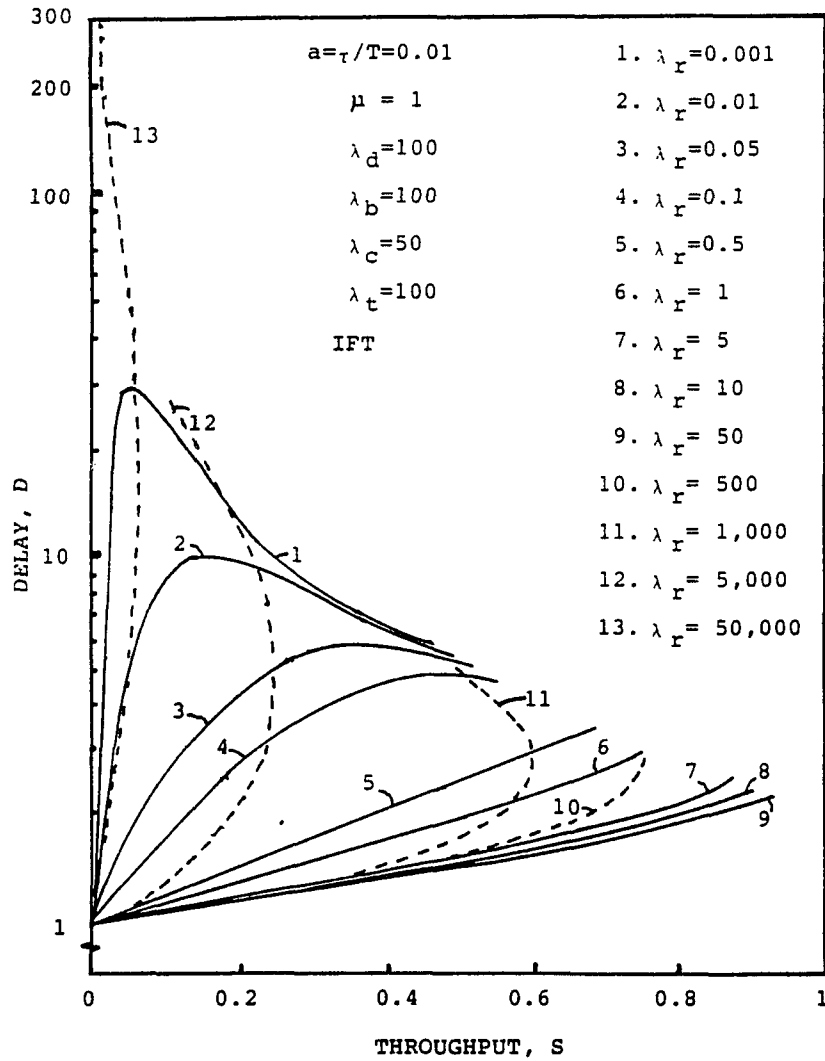


Figure 6: Effects of Retransmission Rate: Delay versus Throughput: Chain Network

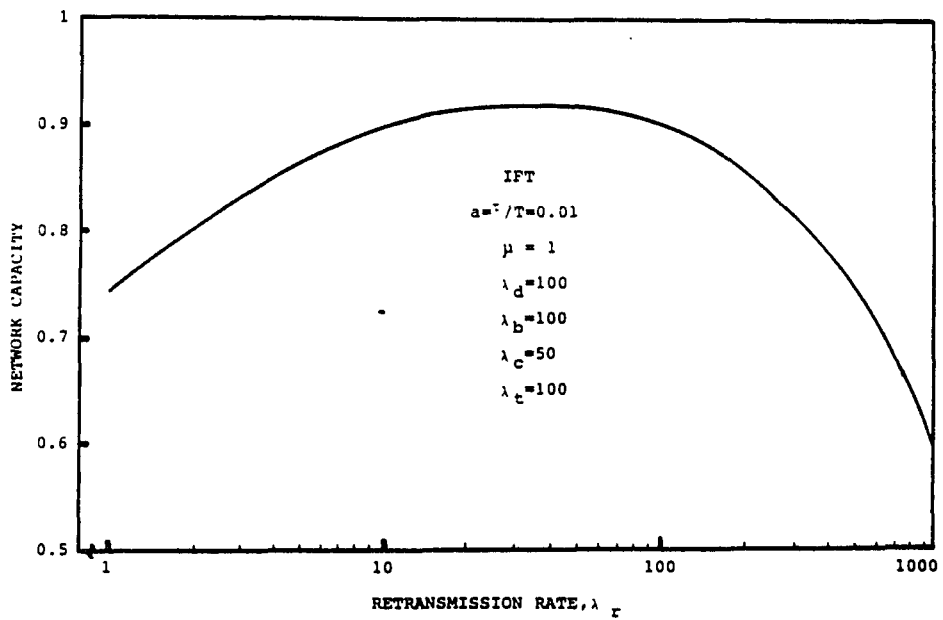


Figure 7: Network Capacity versus Retransmission Rate: Chain Network

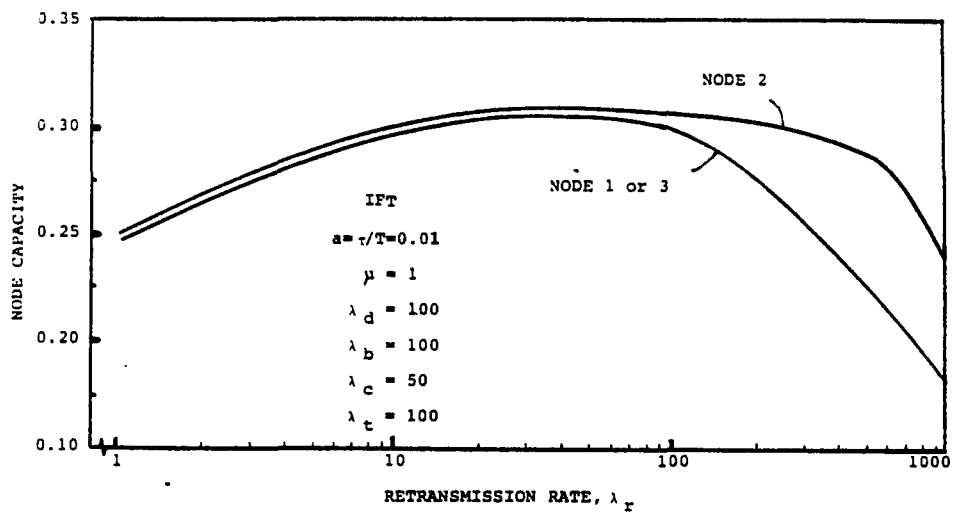


Figure 8: Node Capacity versus Retransmission Rate: Chain Network

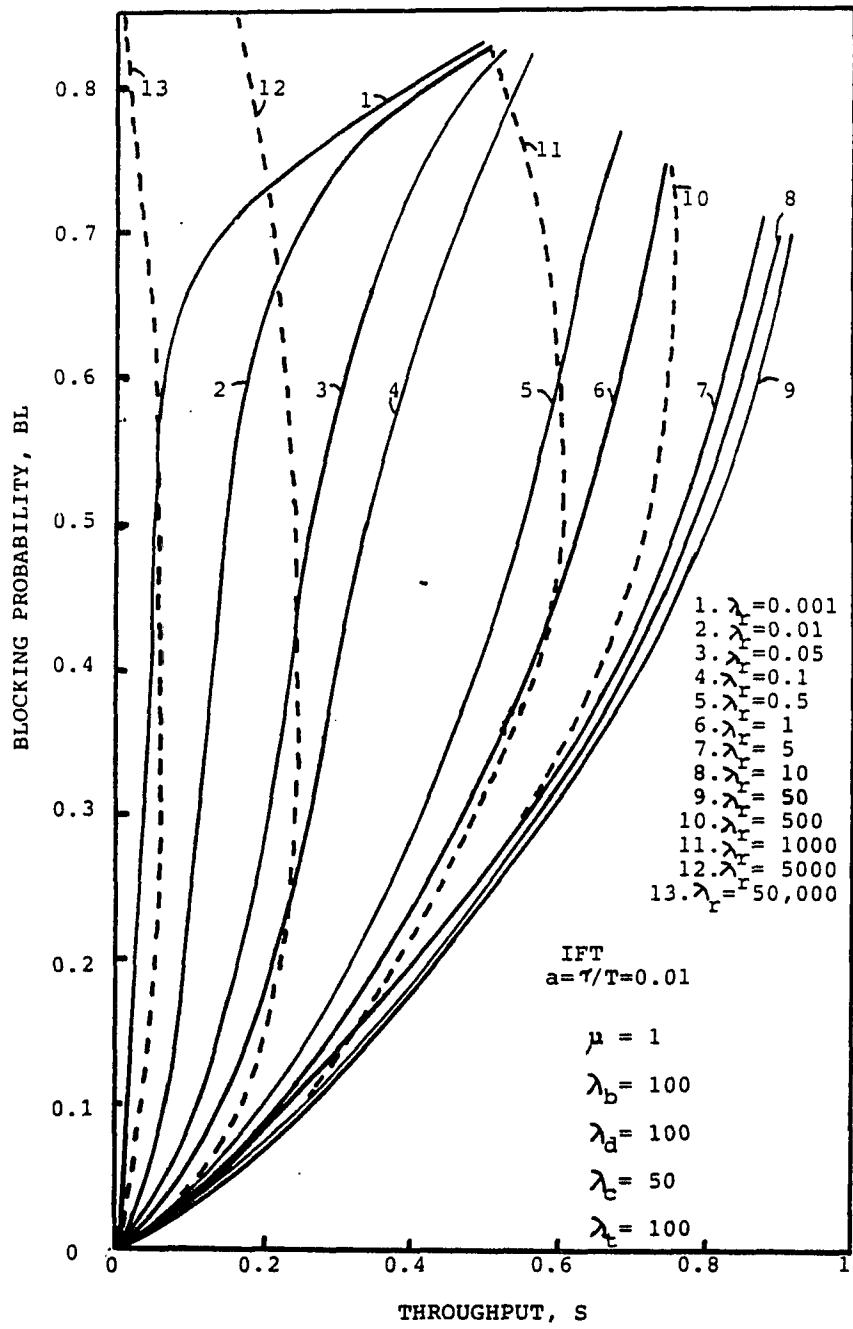


Figure 9: Blocking Probability versus Throughput:
Chain Network
100

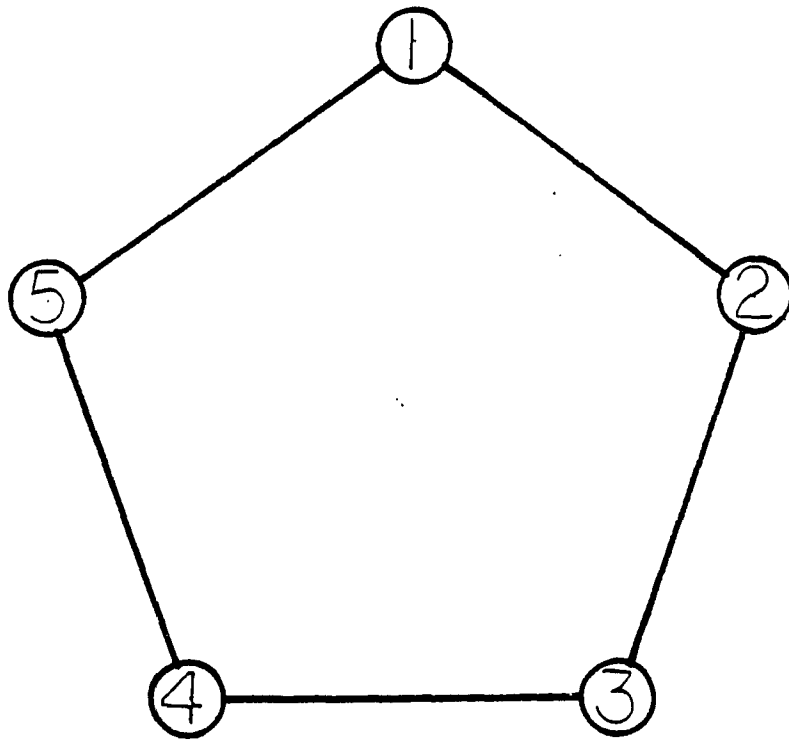
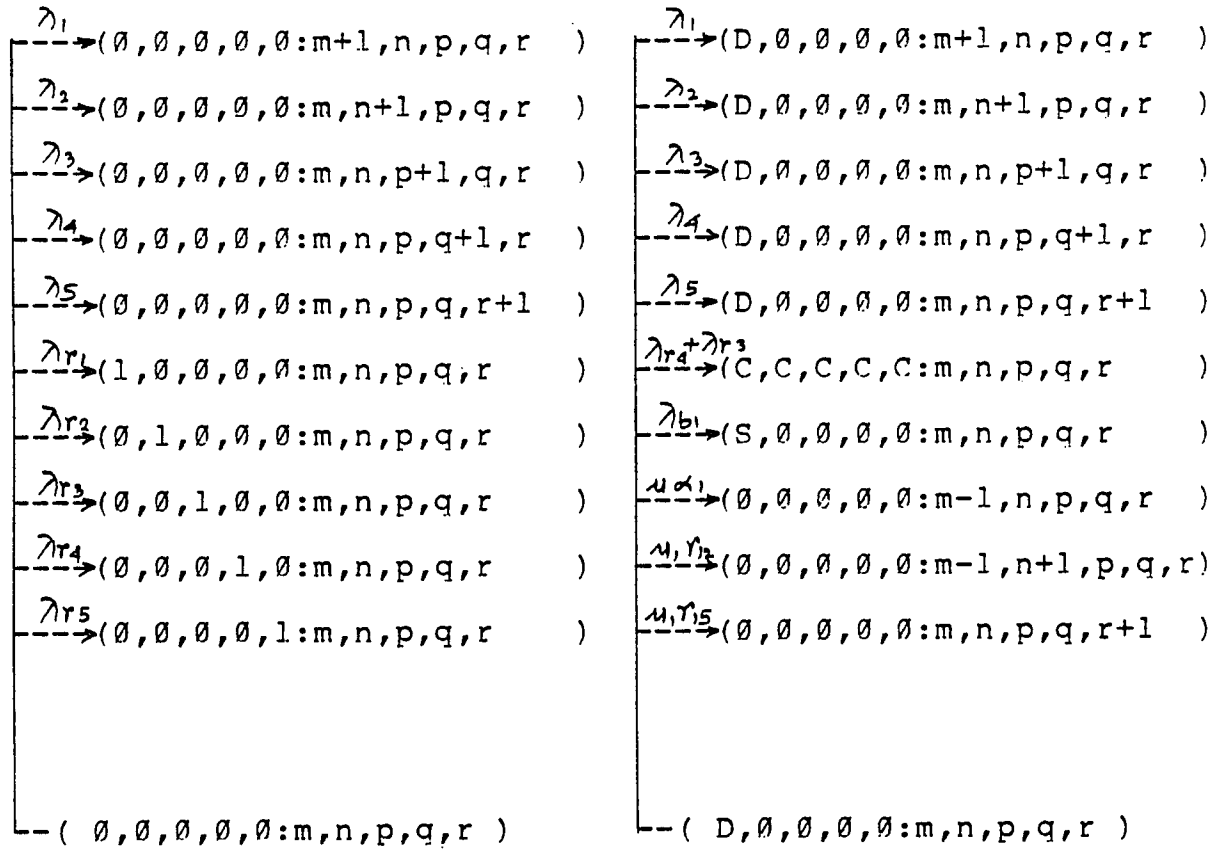


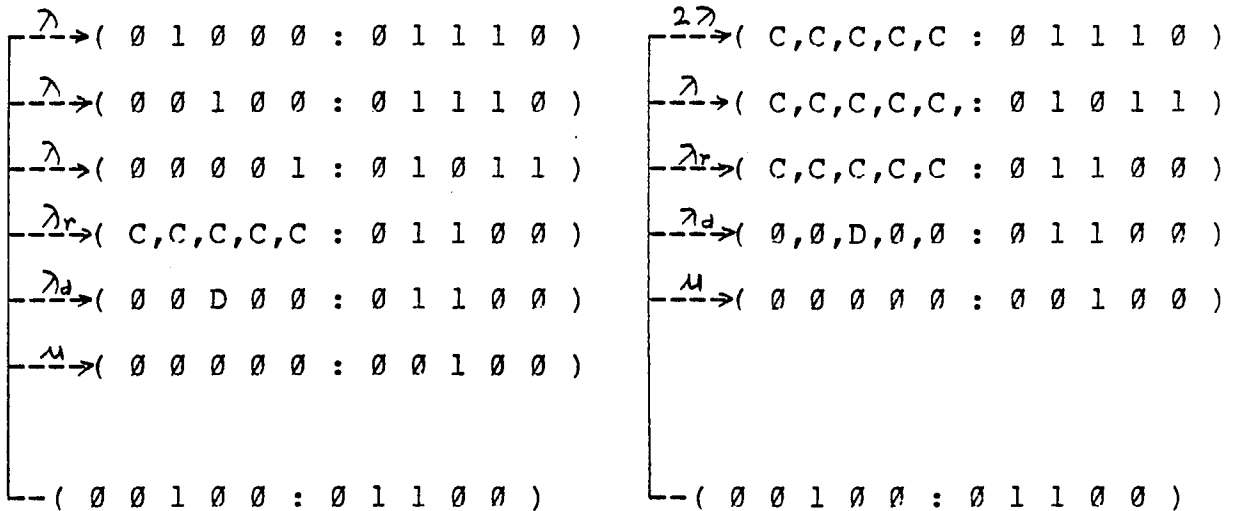
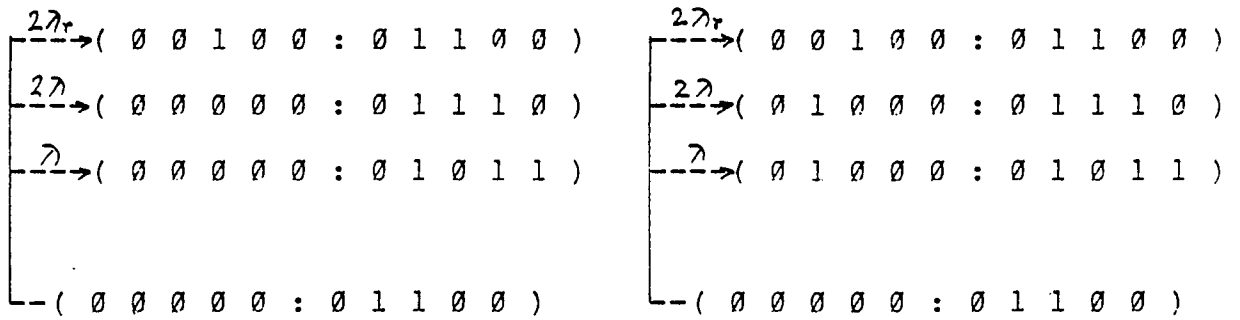
Figure 10: Five-Node Regular Ring Network



[a]

[b]

Figure 11: State Transition Rate Diagram for Node 1:
Nonempty Buffer: Ring Network



[a] DFT Protocol

[b] IFT Protocol

Figure 12: Some Examples: How DFT and IFT Protocols Influence the State Transition Rate Diagram: Ring Network

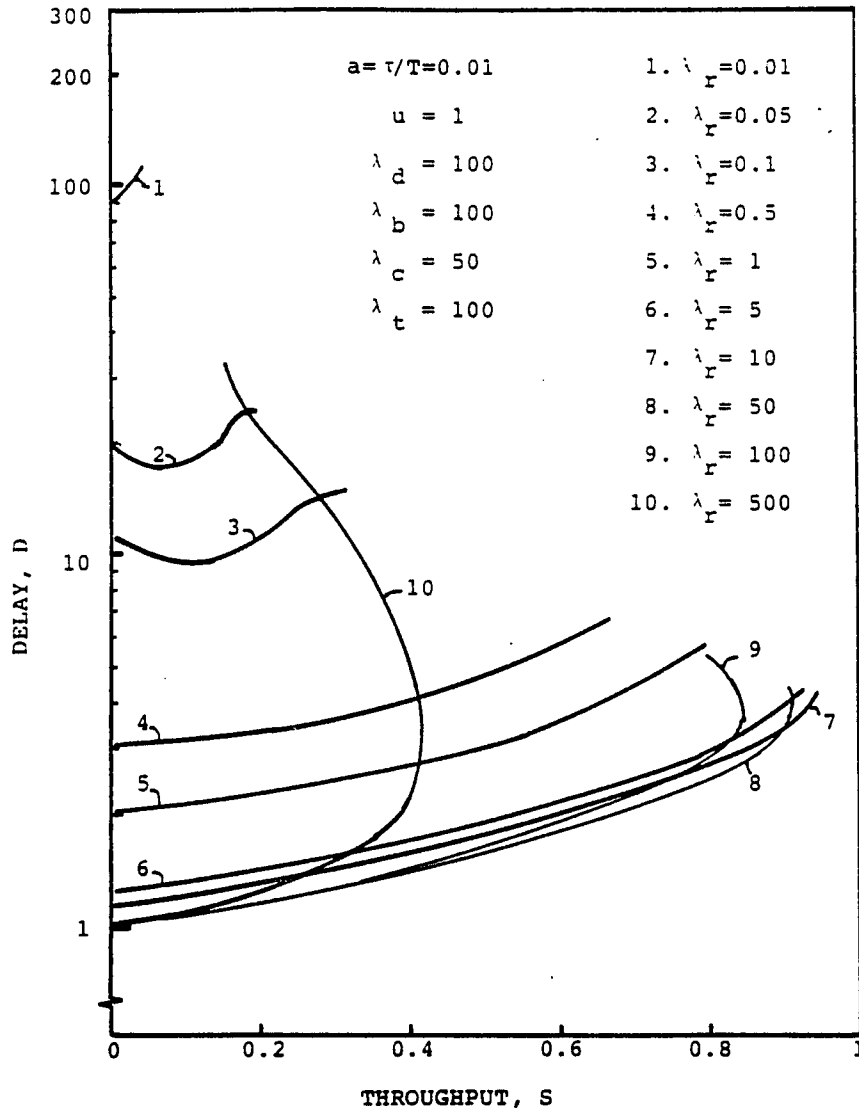


Figure 13: Delay versus Throughput: DFT Protocol:
Ring Network

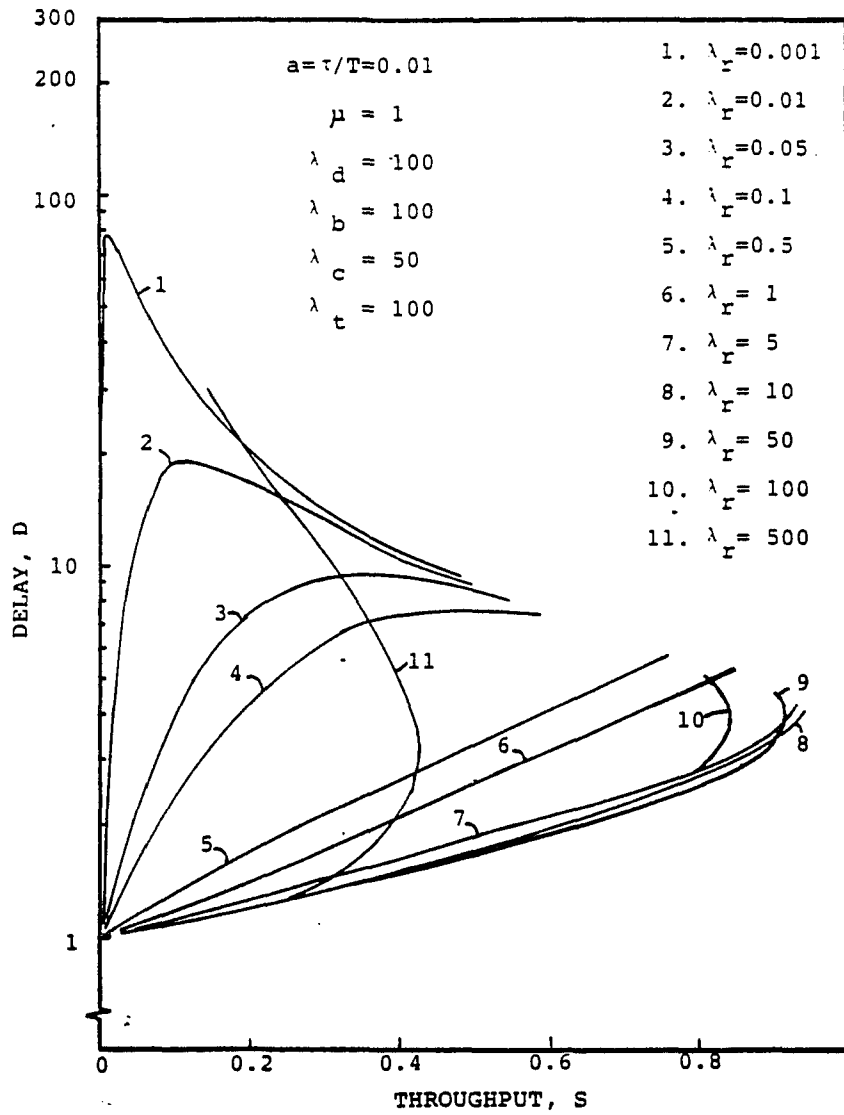


Figure 14: Delay versus Throughput: IFT Protocol:
Ring Network

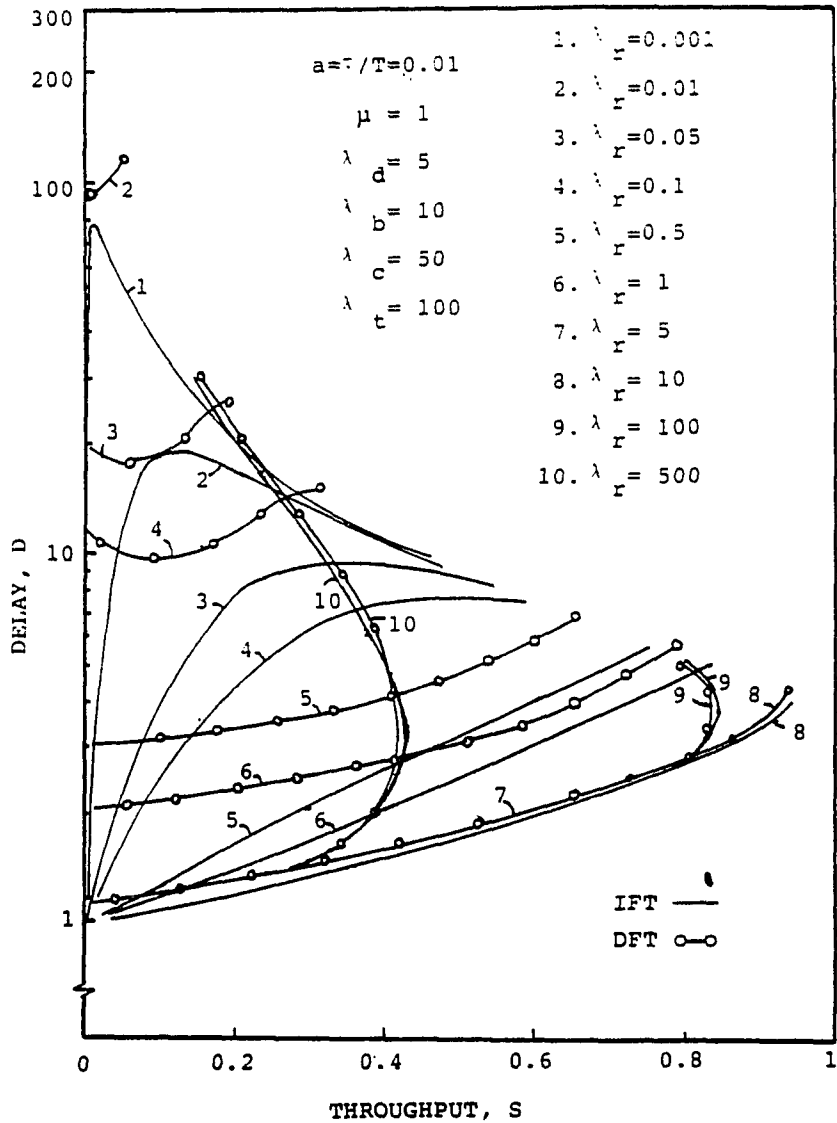


Figure 15: Delay versus Throughput: Comparison of DFT and IFT Protocols: Ring Network

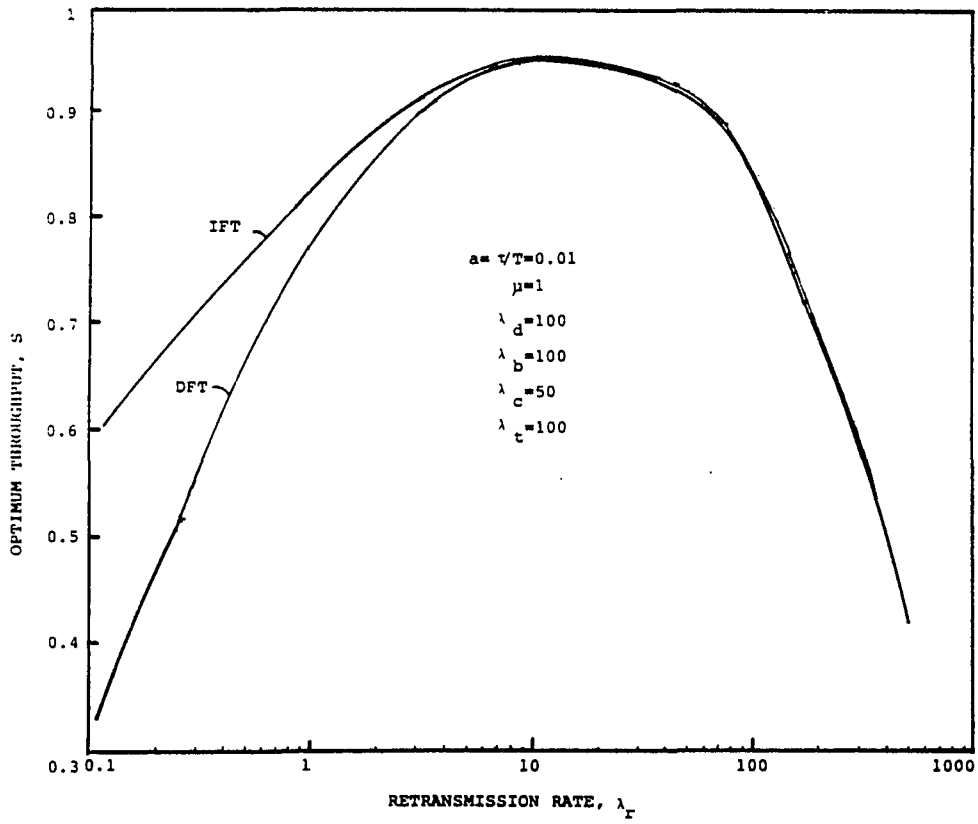


Figure 16: Optimum Throughput versus Retransmission Rate: Ring Network

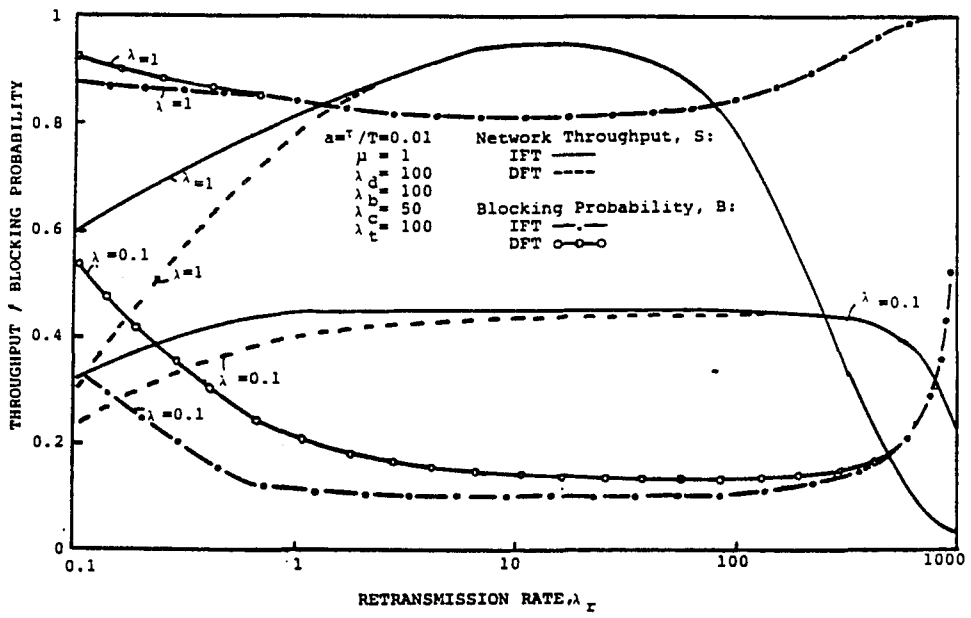


Figure 17: Throughput / Blocking Probability versus Retransmission Rate:
Ring Network

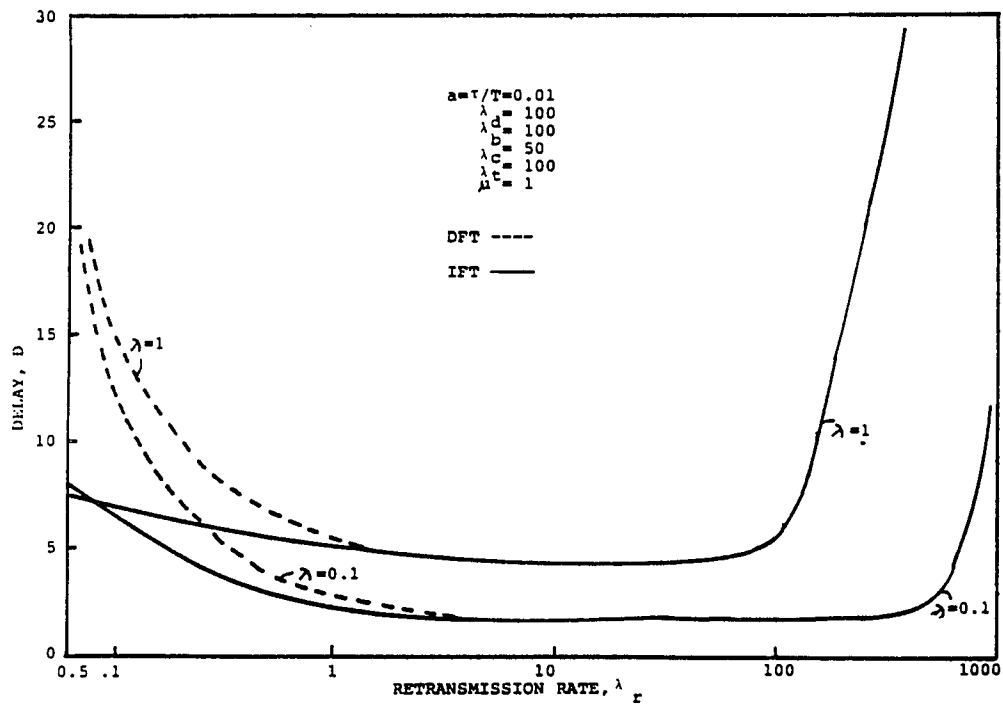


Figure 18: Delay versus Retransmission Rate: Ring Network

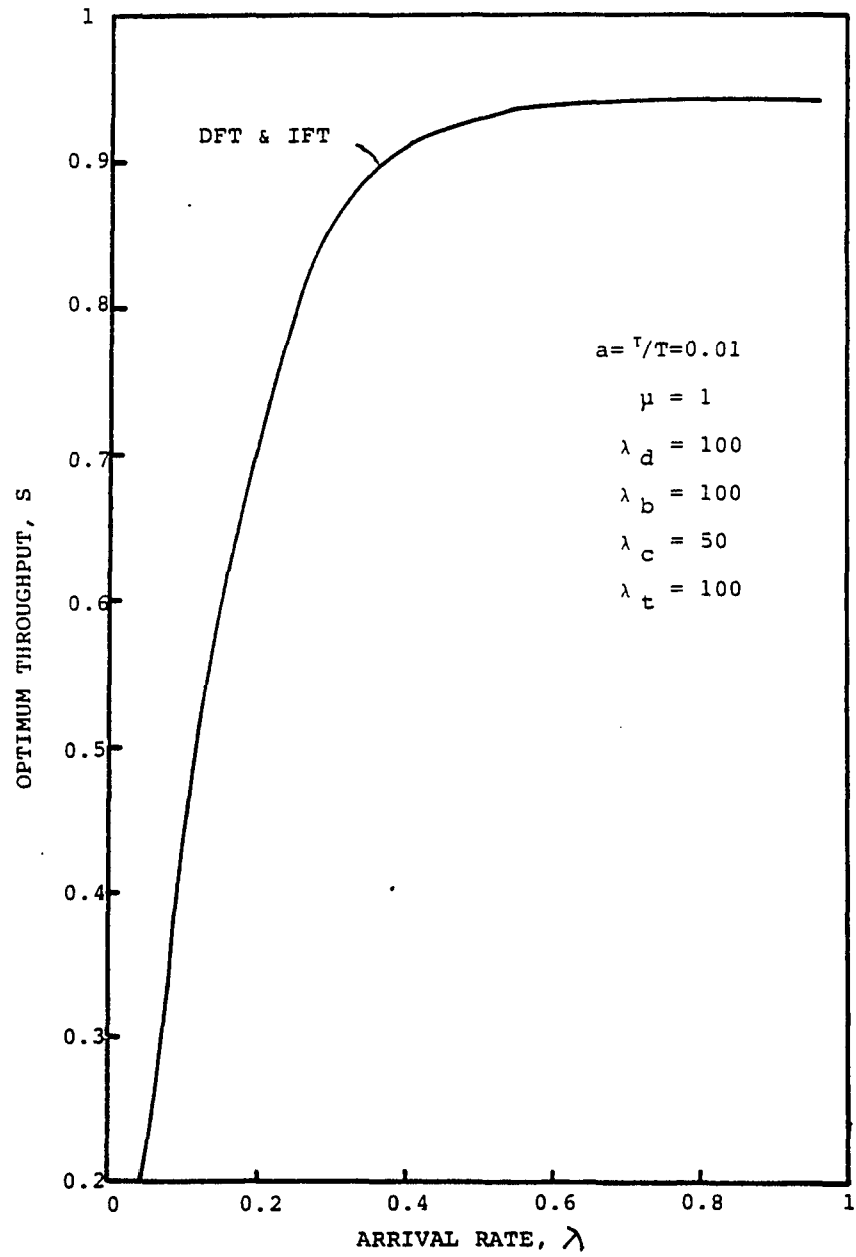


Figure 19: Optimum Throughput versus Arrival Rate:
Ring Network

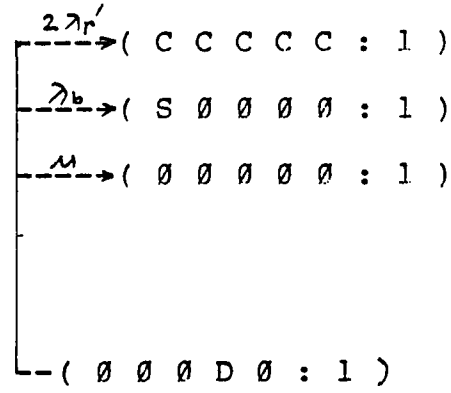
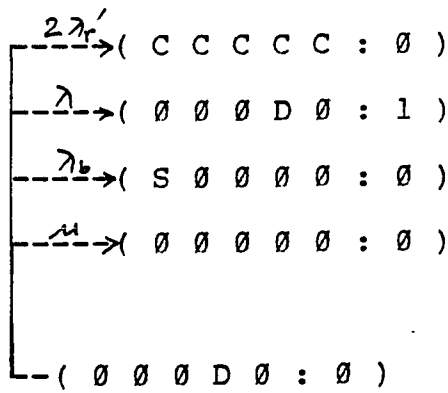
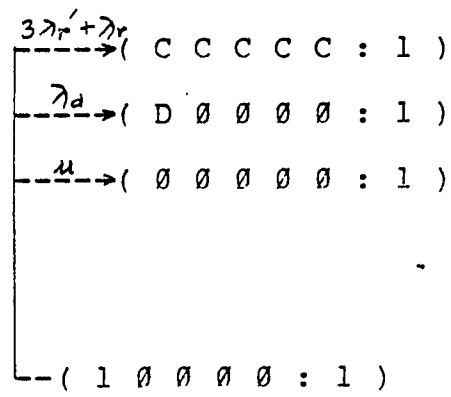
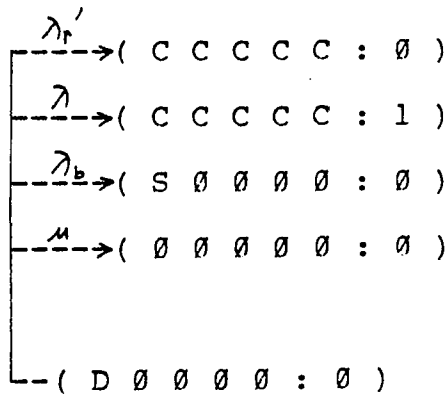
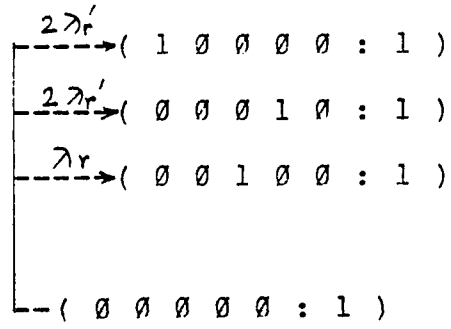
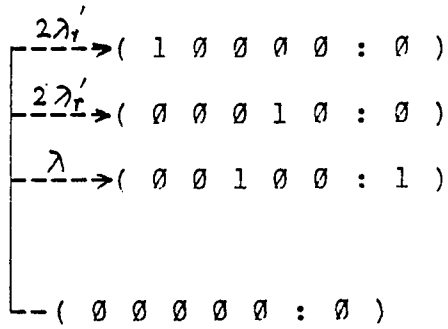


Figure 20: Some Examples of State Transition Rate Diagram in Heavy Traffic Situation: Single Buffer: IFT Protocol: Ring Network

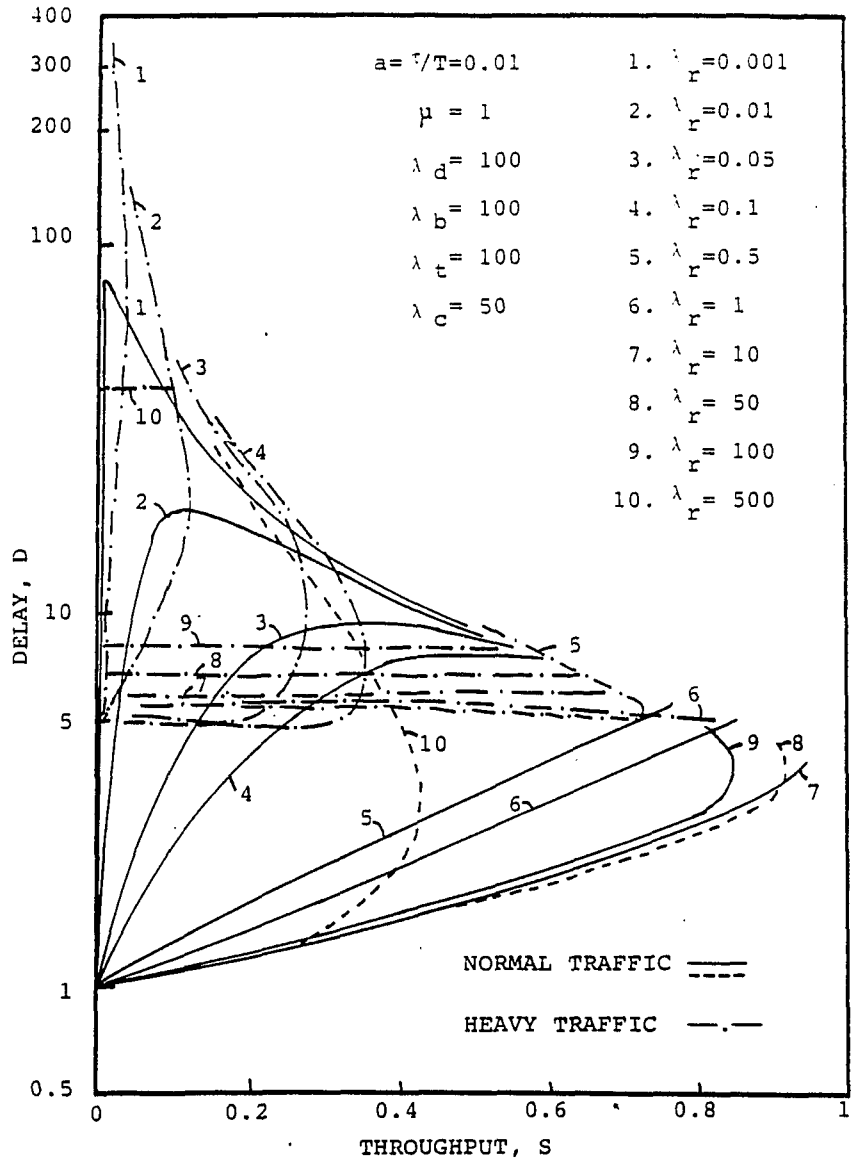


Figure 21: Delay versus Throughput: Single Buffer:
Heavy & Normal Traffic: Ring Network

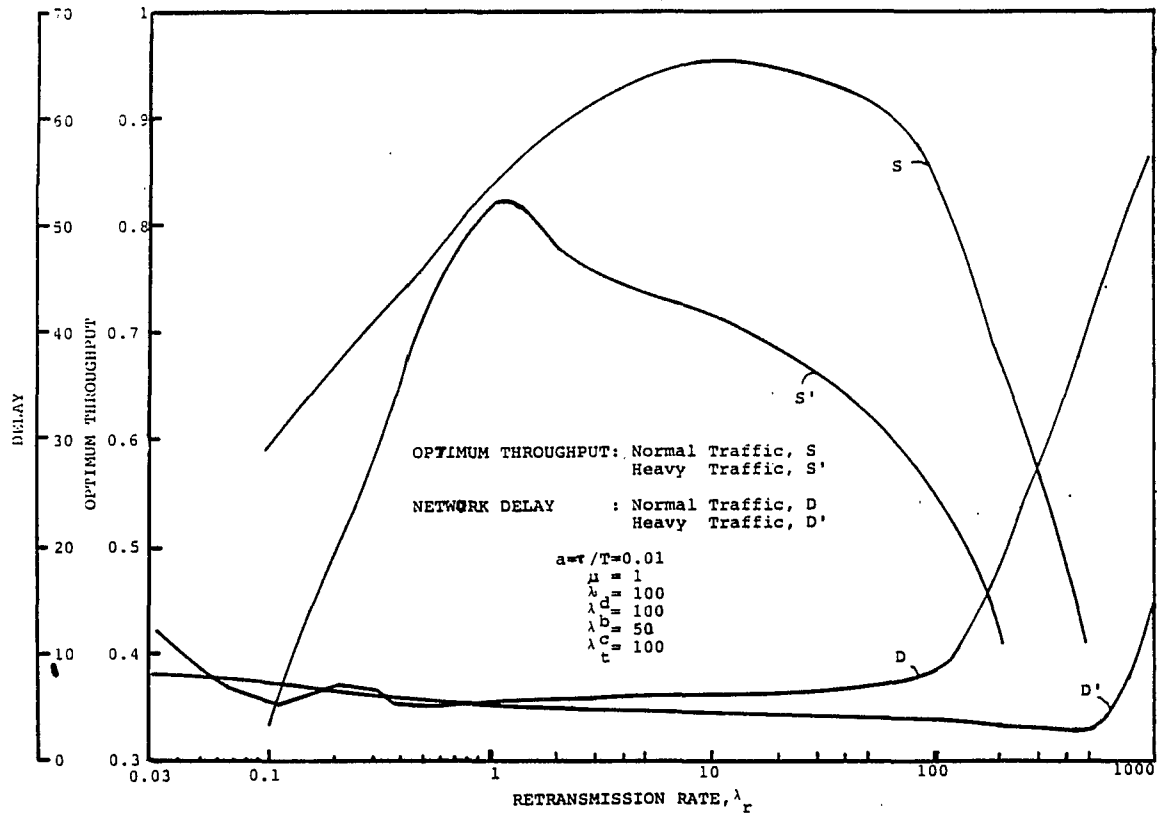


Figure 22: Optimum Throughput/Delay versus Retransmission Rate: Single Buffer: Heavy Traffic & Normal Traffic: Ring Network

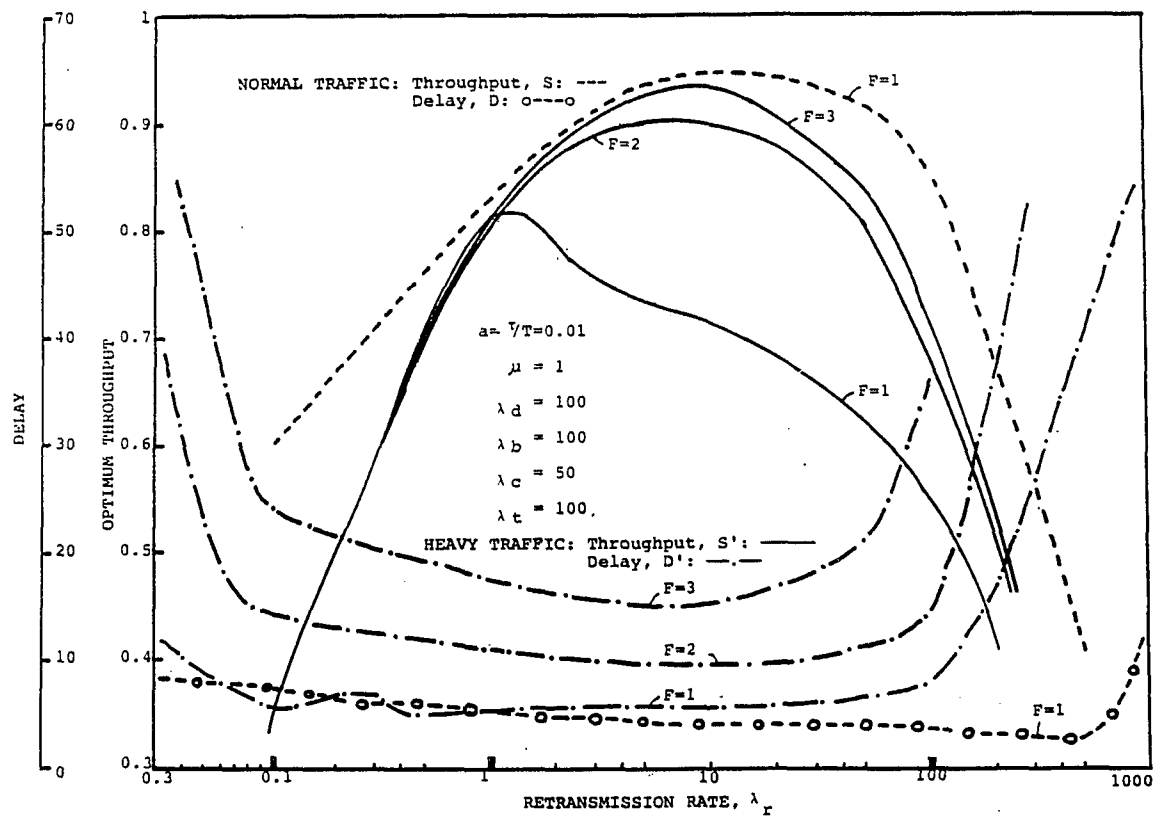


Figure 23: Optimum Throughput/Delay versus Retransmission Rate: Multibuffer: Heavy Traffic: Ring Network

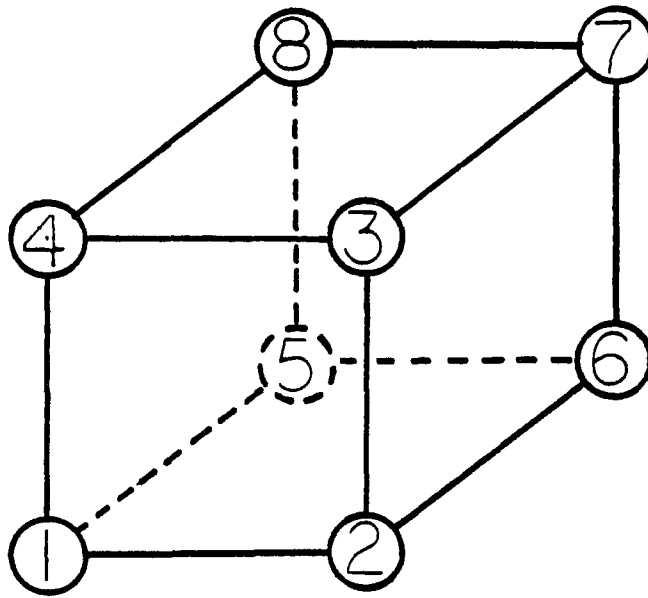


Figure 24: Cube Network

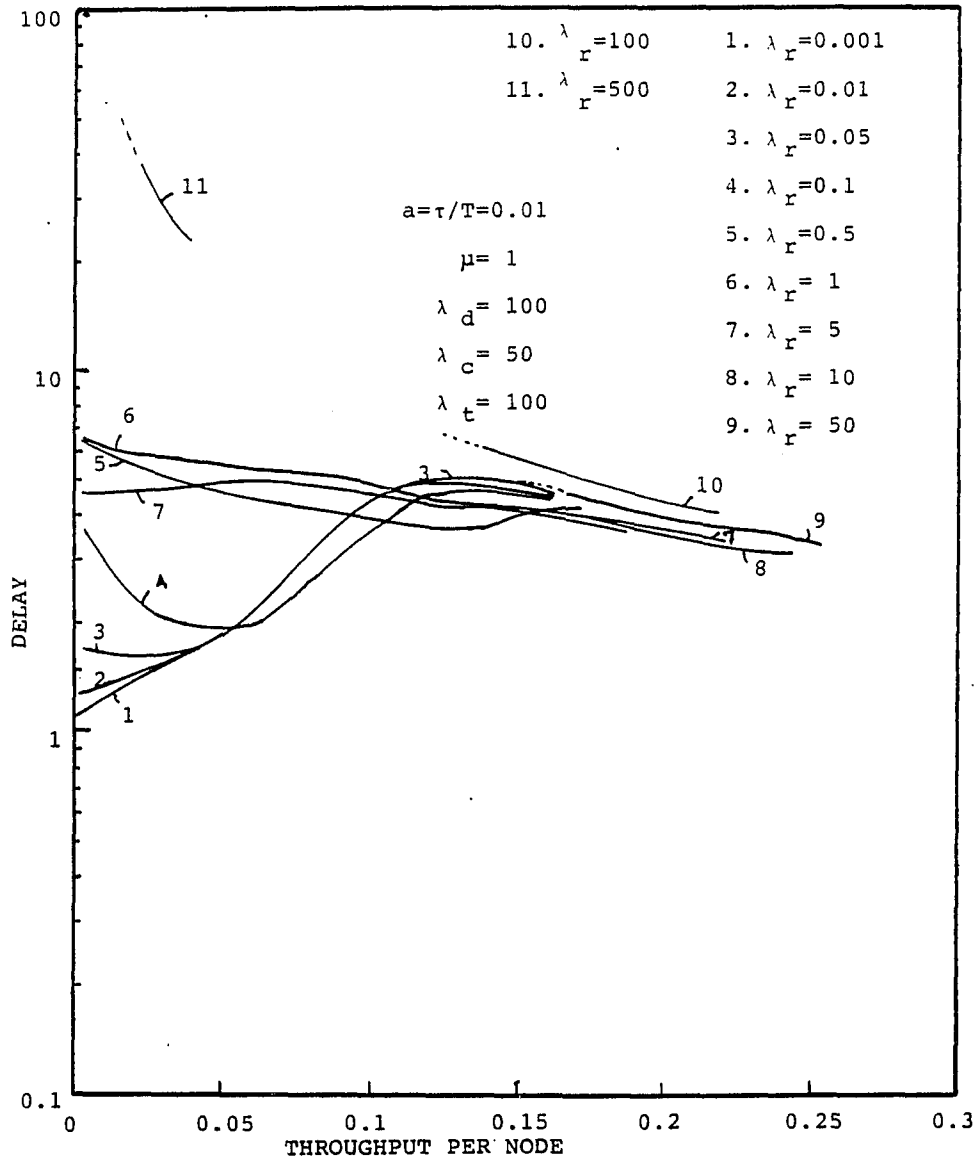


Figure 25: Delay versus Throughput per Node: Single Buffer: Heavy Traffic: Cube Network

**Table I: Classification of Buffer State:
Chain Network**

Buffer State	Buffer State of Each Node		
(Classification)	Node 1	Node 2	Node 3
B1	NE	NE	NE
B2	∅	NE	NE
B3	NE	NE	∅
B4	NE	∅	NE
B5	NE	∅	NE
B6	∅	∅	NE
B7	∅	NE	∅
B8	∅	∅	∅

NE = Nonempty

∅ = Empty

Table II: Channel State: Chain Network

Channel State	Channel State of Each Node		
	Node	Node	Node
	1	2	3
C1	∅	∅	∅
C2	1	∅	∅
C3	∅	∅	1
C4	∅	1	∅
C5	D	∅	∅
C6	∅	∅	D
C7	∅	D	∅
C8	S	∅	∅
C9	∅	∅	S
C10	∅	S	∅
C11	C	C	C
C12	T	T	T

∅= Idle State
 1= Transmission State
 D= Detection State
 S= Safe Transmission State
 C= Collision State
 T= Collision Termination State

**Table III: Network State for Nonempty Buffer: Chain
Network**

Probability of Network State	Network State					
	Channel State of Each Node			Buffer State of Each Node		
	Node	Node	Node	Node	Node	Node
	1	2	3	1	2	3
Π_1	\emptyset	\emptyset	\emptyset	m	n	p
Π_2	1	\emptyset	\emptyset	m	n	p
Π_3	\emptyset	\emptyset	1	m	n	p
Π_4	\emptyset	1	\emptyset	m	n	p
Π_5	D	\emptyset	\emptyset	m	n	p
Π_6	\emptyset	\emptyset	D	m	n	p
Π_7	\emptyset	D	\emptyset	m	n	p
Π_8	S	\emptyset	\emptyset	m	n	p
Π_9	\emptyset	\emptyset	S	m	n	p
Π_{10}	\emptyset	S	\emptyset	m	n	p
Π_{11}	C	C	C	m	n	p
Π_{12}	T	T	T	m	n	p

Table IV: Network State for Two-Node Network

(Figure 3: Example 1)

Probability of Network State	Network State			
	Channel State		Buffer State	
	Node	Node	Node	Node
	1	2	1	2
Π_1	0	0	0	0
Π_2	0	0	1	0
Π_3	0	0	0	1
Π_4	1	0	1	0
Π_5	0	1	0	1
Π_6	1	0	1	1
Π_7	0	1	1	1

Table V: Resultant Network State for Two-Node Network
 (Figure 3: Example 1)

Probability of Network State	Network State
Π_1^*	00:00*
Π_2^*	10:10*
Π_3^*	10:11*
Π_4^*	00:10*

Table VI: Complete Network State: Single Buffer:
Chain Network

Probability of Network State	Network State					
	Channel State of Each Node			Buffer State of Each Node		
	Node 1	Node 2	Node 3	Node 1	Node 2	Node 3
	II	III	IV	V	VI	VII
Π_1	0	0	0	0	0	0
Π_2	0	0	0	1	0	0
Π_3	0	0	0	0	1	0
Π_4	0	0	0	0	0	1
Π_5	0	0	0	1	1	0
Π_6	0	0	0	1	0	1
Π_7	0	0	0	0	1	1
Π_8	0	0	0	1	1	1
Π_9	1	0	0	1	0	0
Π_{10}	0	1	0	0	1	0

Table VI: (Contd.)

I	II	III	IV	V	VI	VII
Π_{11}	\emptyset	\emptyset	1	\emptyset	\emptyset	1
Π_{12}	1	\emptyset	\emptyset	1	1	\emptyset
Π_{13}	\emptyset	1	\emptyset	1	1	\emptyset
Π_{14}	1	\emptyset	\emptyset	1	\emptyset	1
Π_{15}	\emptyset	\emptyset	1	1	\emptyset	1
Π_{16}	\emptyset	1	\emptyset	\emptyset	1	1
Π_{17}	\emptyset	\emptyset	1	\emptyset	1	1
Π_{18}	1	\emptyset	\emptyset	1	1	1
Π_{19}	\emptyset	1	\emptyset	1	1	1
Π_{20}	\emptyset	\emptyset	1	1	1	1
Π_{21}	D	\emptyset	\emptyset	1	\emptyset	\emptyset
Π_{22}	\emptyset	D	\emptyset	\emptyset	1	\emptyset
Π_{23}	\emptyset	\emptyset	D	\emptyset	\emptyset	1
Π_{24}	D	\emptyset	\emptyset	1	1	\emptyset
Π_{25}	\emptyset	D	\emptyset	1	1	\emptyset
Π_{26}	D	\emptyset	\emptyset	1	\emptyset	1
Π_{27}	\emptyset	\emptyset	D	1	\emptyset	1
Π_{28}	\emptyset	D	\emptyset	\emptyset	1	1

Table VI: (Contd.)

I	II	III	IV	V	VI	VII
Π_{29}	\emptyset	\emptyset	D	\emptyset	1	1
Π_{30}	D	\emptyset	\emptyset	1	1	1
Π_{31}	\emptyset	D	\emptyset	1	1	1
Π_{32}	\emptyset	\emptyset	D	1	1	1
Π_{33}	S	\emptyset	\emptyset	1	\emptyset	\emptyset
Π_{34}	\emptyset	S	\emptyset	\emptyset	1	\emptyset
Π_{35}	\emptyset	\emptyset	S	\emptyset	\emptyset	1
Π_{36}	S	\emptyset	\emptyset	1	1	\emptyset
Π_{37}	\emptyset	S	\emptyset	1	1	\emptyset
Π_{38}	S	\emptyset	\emptyset	1	\emptyset	1
Π_{39}	\emptyset	\emptyset	S	1	\emptyset	1
Π_{40}	\emptyset	S	\emptyset	\emptyset	1	1
Π_{41}	\emptyset	\emptyset	S	\emptyset	1	1
Π_{42}	S	\emptyset	\emptyset	1	1	1
Π_{43}	\emptyset	S	\emptyset	1	1	1

Table VI: (Contd.)

I	II	III	IV	V	VI	VII
Π_{44}	\emptyset	\emptyset	S	1	1	1
Π_{45}	C	C	C	1	1	\emptyset
Π_{46}	C	C	C	1	\emptyset	1
Π_{47}	C	C	C	\emptyset	1	1
Π_{48}	C	C	C	1	1	1
Π_{49}	T	T	T	1	1	\emptyset
Π_{50}	T	T	T	1	\emptyset	1
Π_{51}	T	T	T	\emptyset	1	1
Π_{52}	T	T	T	1	1	1

Table VIA: Steady State Probabilities of Network States

($\lambda = 0.0005$)

Throughput of the Network, $S = 0.0015$

Retransmission Rate, $\lambda_r = 0.001$

$\lambda_d=100, \lambda_b=100, \lambda_c=50, \lambda_t=100, \mu = 1$

$S=0.0015, D=2.03, BL=0.001$

$S_1=0.0005, D_1=2.03, BL_1=0.001$

$S_2=0.0005, D_2=2.027, BL_2=0.001$

$S_3=0.0005, D_3=2.03, BL_3=0.001$

$\Pi_1 = 0.996979415416$	$\Pi_2 = 0.000501272268$	$\Pi_3 = 0.000501270871$
$\Pi_4 = 0.000501271802$	$\Pi_5 = 0.000004113559$	$\Pi_6 = 0.000006562451$
$\Pi_7 = 0.000004113558$	$\Pi_8 = 0.000002784401$	$\Pi_9 = 0.000004940437$
$\Pi_{10} = 0.000004940437$	$\Pi_{11} = 0.000004940436$	$\Pi_{12} = 0.000000002522$
$\Pi_{13} = 0.000000002522$	$\Pi_{14} = 0.000000002546$	$\Pi_{15} = 0.000000002546$
$\Pi_{16} = 0.000000002522$	$\Pi_{17} = 0.000000002522$	$\Pi_{18} = 0.000000000047$
$\Pi_{19} = 0.000000000060$	$\Pi_{20} = 0.000000000047$	$\Pi_{21} = 0.000004891475$
$\Pi_{22} = 0.000004891473$	$\Pi_{23} = 0.000004891473$	$\Pi_{24} = 0.000000002521$
$\Pi_{25} = 0.000000002521$	$\Pi_{26} = 0.000000002521$	$\Pi_{27} = 0.000000002521$
$\Pi_{28} = 0.000000002521$	$\Pi_{29} = 0.000000002521$	$\Pi_{30} = 0.000000000047$
$\Pi_{31} = 0.000000000059$	$\Pi_{32} = 0.000000000047$	$\Pi_{33} = 0.000488658435$
$\Pi_{34} = 0.000488658901$	$\Pi_{35} = 0.000488659366$	$\Pi_{36} = 0.000000496227$
$\Pi_{37} = 0.000000496228$	$\Pi_{38} = 0.000000496204$	$\Pi_{39} = 0.000000496205$
$\Pi_{40} = 0.000000496227$	$\Pi_{41} = 0.000000496227$	$\Pi_{42} = 0.000000005243$
$\Pi_{43} = 0.000000006444$	$\Pi_{44} = 0.000000005243$	$\Pi_{45} = 0.000000000048$
$\Pi_{46} = 0.000000000196$	$\Pi_{47} = 0.000000000098$	$\Pi_{48} = 0.000000000001$
$\Pi_{49} = 0.000000000049$	$\Pi_{50} = 0.000000000098$	$\Pi_{51} = 0.000000000049$
$\Pi_{52} = 0.000000000083$		

Table VIB: Steady State Probabilities of Network States

($\lambda = 0.03$)

Throughput of the Network, $S = 0.05$

Retransmission Rate, $\lambda_r = 0.001$

$\lambda_d = 100, \lambda_b = 100, \lambda_c = 50, \lambda_t = 100, \mu = 1$

$S = 0.05, D = 28.90, BL = 0.4644$

$S_1 = 0.0160, D_1 = 28.97, BL_1 = 0.4650$

$S_2 = 0.0161, D_2 = 28.75, BL_2 = 0.4631$

$S_3 = 0.0160, D_3 = 28.97, BL_3 = 0.4650$

$\Pi_1 = 0.0083292782306$	$\Pi_2 = 0.150020062923$	$\Pi_3 = 0.149741351604$
$\Pi_4 = 0.150028049945$	$\Pi_5 = 0.137752950191$	$\Pi_6 = 0.139395117759$
$\Pi_7 = 0.137763142585$	$\Pi_8 = 0.003800554899$	$\Pi_9 = 0.000026210240$
$\Pi_{10} = 0.000026207475$	$\Pi_{11} = 0.000026210283$	$\Pi_{12} = 0.000045827429$
$\Pi_{13} = 0.000045910186$	$\Pi_{14} = 0.000045928827$	$\Pi_{15} = 0.000045926441$
$\Pi_{16} = 0.000045912616$	$\Pi_{17} = 0.000045827458$	$\Pi_{18} = 0.000040956510$
$\Pi_{19} = 0.000041441249$	$\Pi_{20} = 0.000040953513$	$\Pi_{21} = 0.000025935281$
$\Pi_{22} = 0.000025932560$	$\Pi_{23} = 0.000025935354$	$\Pi_{24} = 0.000045367822$
$\Pi_{25} = 0.000045449764$	$\Pi_{26} = 0.000045460095$	$\Pi_{27} = 0.000045457738$
$\Pi_{28} = 0.000045452179$	$\Pi_{29} = 0.000045367924$	$\Pi_{30} = 0.000040564103$
$\Pi_{31} = 0.000041057937$	$\Pi_{32} = 0.000040561120$	$\Pi_{33} = 0.002446730621$
$\Pi_{34} = 0.002446472644$	$\Pi_{35} = 0.002446740167$	$\Pi_{36} = 0.004475910216$
$\Pi_{37} = 0.004483856260$	$\Pi_{38} = 0.004484865814$	$\Pi_{39} = 0.004484653472$
$\Pi_{40} = 0.004484102129$	$\Pi_{41} = 0.004475928843$	$\Pi_{42} = 0.004325240850$
$\Pi_{43} = 0.004374839365$	$\Pi_{44} = 0.004324935376$	$\Pi_{45} = 0.000000033265$
$\Pi_{46} = 0.000000066190$	$\Pi_{47} = 0.000000033265$	$\Pi_{48} = 0.000000226276$
$\Pi_{49} = 0.000000016627$	$\Pi_{50} = 0.000000033085$	$\Pi_{51} = 0.000000016627$
$\Pi_{52} = 0.000000114091$		

Table VIC: Steady State Probabilities for Network States

($\lambda = 0.90$)

Throughput of the Network, $S = 0.47$

Retransmission Rate, $\lambda_r = 0.001$

$\lambda_d = 100, \lambda_b = 100, \lambda_c = 50, \lambda_t = 100, \mu = 1$

$S = 0.47, D = 5.29, BL = 0.8265$

$S_1 = 0.1555, D_1 = 5.32, BL_1 = 0.8271$

$S_2 = 0.1574, D_2 = 5.24, BL_2 = 0.8250$

$S_3 = 0.1555, D_3 = 5.32, BL_3 = 0.8265$

$\Pi_1 = 0.000000131514$	$\Pi_2 = 0.000213462612$	$\Pi_3 = 0.000212172672$
$\Pi_4 = 0.000213528663$	$\Pi_5 = 0.171907603740$	$\Pi_6 = 0.174113512039$
$\Pi_7 = 0.172014474868$	$\Pi_8 = 0.012903127819$	$\Pi_9 = 0.000000003227$
$\Pi_{10} = 0.000000003215$	$\Pi_{11} = 0.000000003228$	$\Pi_{12} = 0.000003560931$
$\Pi_{13} = 0.000003572325$	$\Pi_{14} = 0.000003594557$	$\Pi_{15} = 0.000003593975$
$\Pi_{16} = 0.000003573960$	$\Pi_{17} = 0.000003561983$	$\Pi_{18} = 0.001532898982$
$\Pi_{19} = 0.001551602734$	$\Pi_{20} = 0.001531944843$	$\Pi_{21} = 0.000000003139$
$\Pi_{22} = 0.000000003127$	$\Pi_{23} = 0.000000003140$	$\Pi_{24} = 0.000003494562$
$\Pi_{25} = 0.000003505742$	$\Pi_{26} = 0.000003527499$	$\Pi_{27} = 0.000003526927$
$\Pi_{28} = 0.000003507347$	$\Pi_{29} = 0.000003495593$	$\Pi_{30} = 0.001517737284$
$\Pi_{31} = 0.001536302935$	$\Pi_{32} = 0.001516792690$	$\Pi_{33} = 0.000000112141$
$\Pi_{34} = 0.000000111705$	$\Pi_{35} = 0.000000112163$	$\Pi_{36} = 0.000183977666$
$\Pi_{37} = 0.000184565898$	$\Pi_{38} = 0.000185711236$	$\Pi_{39} = 0.000185681070$
$\Pi_{40} = 0.000184650270$	$\Pi_{41} = 0.000184032018$	$\Pi_{42} = 0.152106523513$
$\Pi_{43} = 0.153962552547$	$\Pi_{44} = 0.152012050151$	$\Pi_{45} = 0.000000000254$
$\Pi_{46} = 0.000000000505$	$\Pi_{47} = 0.000000000254$	$\Pi_{48} = 0.000000757426$
$\Pi_{49} = 0.000000000125$	$\Pi_{50} = 0.000000000250$	$\Pi_{51} = 0.000000000125$
$\Pi_{52} = 0.000000387256$		

**Table VII: Resultant Network State: Single Buffer:
Chain Network**

Probability of Network state	Network State					
	Channel State			Buffer State		
I	II	III	IV	V	VI	VII
Π_1	0	0	0	0	0	0
Π_2^*	0	0	0	1	0	0
Π_3	0	0	0	0	1	0
Π_4^*	0	0	0	1	1	0
Π_5	0	0	0	1	0	1
Π_6	0	0	0	1	1	1
Π_7^*	1	0	0	1	0	0
Π_8	0	1	0	0	1	0
Π_9^*	1	0	0	1	1	0

* Indicate the Resultant State after Combining the
Symmetrical States having the same Probability.

Table VII (Contd.)

I	II	III	IV	V	VI	VII
Π_{10}^*	0	1	0	1	1	0
Π_{11}^*	1	0	0	1	0	1
Π_{12}^*	1	0	0	1	1	1
Π_{13}	0	1	0	1	1	1
Π_{14}^*	D	0	0	1	0	0
Π_{15}	0	D	0	0	1	0
Π_{16}^*	D	0	0	1	1	0
Π_{17}^*	0	D	0	1	1	0
Π_{18}^*	D	0	0	1	0	1
Π_{19}^*	D	0	0	1	1	1
Π_{20}	0	D	0	1	1	1

Table VII (Contd.)

I	II	III	IV	V	VI	VII
Π_{21}^*	S	\emptyset	\emptyset	1	\emptyset	\emptyset
Π_{22}	\emptyset	S	\emptyset	\emptyset	1	\emptyset
Π_{23}^*	S	\emptyset	\emptyset	1	1	\emptyset
Π_{24}^*	\emptyset	S	\emptyset	1	1	\emptyset
Π_{25}^*	S	\emptyset	\emptyset	1	\emptyset	1
Π_{26}^*	S	\emptyset	\emptyset	1	1	1
Π_{27}	\emptyset	S	\emptyset	1	1	1
Π_{28}^*	C	C	C	1	1	\emptyset
Π_{29}	C	C	C	1	\emptyset	1
Π_{30}	C	C	C	1	1	1
Π_{31}^*	T	T	T	1	1	\emptyset
Π_{32}	T	T	T	1	\emptyset	1
Π_{33}	T	T	T	1	1	1

**Table VIII: Network States for Nonempty Buffer:
Ring Network**

Probability of Network State	Network State									
	Channel State of Each Node					Buffer State of Each Node				
	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
	1	2	3	4	5	1	2	3	4	5
I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Π_1	\emptyset	\emptyset	\emptyset	\emptyset	\emptyset	m	n	p	q	r
Π_2	1	\emptyset	\emptyset	\emptyset	\emptyset	m	n	p	q	r
Π_3	D	\emptyset	\emptyset	\emptyset	\emptyset	m	n	p	q	r
Π_4	S	\emptyset	\emptyset	\emptyset	\emptyset	m	n	p	q	r
Π_5	\emptyset	1	\emptyset	\emptyset	\emptyset	m	n	p	q	r
Π_6	\emptyset	D	\emptyset	\emptyset	\emptyset	m	n	p	q	r
Π_7	\emptyset	S	\emptyset	\emptyset	\emptyset	m	n	p	q	r
Π_8	\emptyset	\emptyset	1	\emptyset	\emptyset	m	n	p	q	r
Π_9	\emptyset	\emptyset	D	\emptyset	\emptyset	m	n	p	q	r

Table VIII: (Contd.)

I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Π_{10}	\emptyset	\emptyset	S	\emptyset	\emptyset	m	n	p	q	r
Π_{11}	\emptyset	\emptyset	\emptyset	l	\emptyset	m	n	p	q	r
Π_{12}	\emptyset	\emptyset	\emptyset	D	\emptyset	m	n	p	q	r
Π_{13}	\emptyset	\emptyset	\emptyset	S	\emptyset	m	n	p	q	r
Π_{14}	\emptyset	\emptyset	\emptyset	\emptyset	l	m	n	p	q	r
Π_{15}	\emptyset	\emptyset	\emptyset	\emptyset	D	m	n	p	q	r
Π_{16}	\emptyset	\emptyset	\emptyset	\emptyset	S	m	n	p	q	r
Π_{17}	C	C	C	C	C	m	n	p	q	r
Π_{18}	T	T	T	T	T	m	n	p	q	r

Table IX: Resultant Network State: Ring Network

Probability of Network State	Network State	
	Channel State	Buffer State
1. All Nodes are Empty		
Π_1	0 0 0 0 0	0 0 0 0 0
2. Only One Node has a Packet		
Π_2	0 0 0 0 0	0 0 1 0 0
2.1 Node having Empty Neighbors and Neighbors of the Neighbors, is in Transmission		
Π_3	0 0 1 0 0	0 0 1 0 0
Π_4	0 0 D 0 0	0 0 1 0 0
Π_5	0 0 S 0 0	0 0 1 0 0
3. Only Two Nodes have Packets		

Table IX: (Contd.)

3.1 Two Adjacent Nodes have Packets

Π_6	0 0 0 0 0	0 1 1 0 0
Π_7	C C C C C	0 1 1 0 0
Π_8	T T T T T	0 1 1 0 0

3.1.1 Node having Neighbor and neighbor of the Neighbors in One Side and Nonempty neighbor but Nonempty Neighbor of the Neighbor to the other side, is in Transmission

Π_9	0 0 1 0 0	0 1 1 0 0
Π_{10}	0 0 D 0 0	0 1 1 0 0
Π_{11}	0 0 S 0 0	0 1 1 0 0

3.2 Two Nodes not Adjacent to Each Other have Packets

Π_{12}	0 0 0 0 0	0 1 0 1 0
Π_{13}	C C C C C	0 1 0 1 0
Π_{14}	T T T T T	0 1 0 1 0

3.2.1 Node having Empty Neighbor but Nonempty Neighbor of the Neighbor in One Side and Empty Neighbor and Neighbor of the Neighbor

Table IX: (Contd.)

to the Other Side, is in Transmission		
Π_{15}	0 1 0 0 0	0 1 0 1 0
Π_{16}	0 D 0 0 0	0 1 0 1 0
Π_{17}	0 S 0 0 0	0 1 0 1 0
4. Only Three Nodes Have Packet		
4.1 Three Adjacent Nodes have Packets		
Π_{18}	0 0 0 0 0	0 1 1 1 0
Π_{19}	C C C C C	0 1 1 1 0
Π_{20}	T T T T T	0 1 1 1 0
4.1.1 Node having Nonempty Neighbor and Neighbor of the Neighbor in One Side and Empty Neighbor and Neighbor of the Neighbor to the Other side, is in Transmission		
Π_{21}	0 1 0 0 0	0 1 1 1 0
Π_{22}	0 D 0 0 0	0 1 1 1 0
Π_{23}	0 S 0 0 0	0 1 1 1 0
4.1.2 Nodes having Nonempty Neighbors but Empty Neighbors of the Neighbors, is in		

Table IX: (Contd.)

Transmission		
Π_{24}	0 0 1 0 0	0 1 1 1 0
Π_{25}	0 0 D 0 0	0 1 1 1 0
Π_{26}	0 0 S 0 0	0 1 1 1 0
4.2 Two Adjacent and One Non-Adjacent Nodes have Packets		
Π_{27}	0 0 0 0 0	0 1 0 1 1
Π_{28}	C C C C C	0 1 0 1 1
Π_{29}	T T T T T	0 1 0 1 1
4.2.1 Node having Empty Neighbors and Nonempty Neighbors of the Neighbors, is in Transmission		
Π_{30}	0 1 0 0 0	0 1 0 1 1
Π_{31}	0 D 0 0 0	0 1 0 1 1
Π_{32}	0 S 0 0 0	0 1 0 1 1
4.2.2 Node having Empty Neighbor but Nonempty Neighbor of the Neighbor in one side and Nonempty Neighbor but Empty Neighbor of the Neighbor to the Other Side, is in Transmission		

Table IX: (Contd.)

Π_{33}	0 0 0 0 1	0 1 0 1 1
Π_{34}	0 0 0 0 D	0 1 0 1 1
Π_{35}	0 0 0 0 S	0 1 0 1 1
5. Only Four Nodes have Packets		
Π_{36}	0 0 0 0 0	1 1 1 1 0
Π_{37}	C C C C C	1 1 1 1 0
Π_{38}	T T T T T	1 1 1 1 0
5.1 Node having Empty Neighbor but Nonempty Neighbor in One Side and Nonempty Neighbor and Neighbor of the Neighbor to the Other side, is in Transmission		
Π_{39}	0 0 0 1 0	1 1 1 1 0
Π_{40}	0 0 0 D 0	1 1 1 1 0
Π_{41}	0 0 0 S 0	1 1 1 1 0
5.2 Node having Nonempty Neighbor and Neighbor of the Neighbor in one side and Nonempty Neighbor but Empty Neighbor of the Neighbor to the Other Side, is in Transmission		
Π_{42}	0 1 0 0 0	1 1 1 1 0
Π_{43}	0 D 0 0 0	1 1 1 1 0
Π_{44}	0 S 0 0 0	1 1 1 1 0
6. All Nodes are Nonempty		

Table IX: (Contd.)

Π_{45}	0 0 0 0 0	1 1 1 1 1
Π_{46}	C C C C C	1 1 1 1 1
Π_{47}	T T T T T	1 1 1 1 1
6.1 Node having Nonempty Neighbors and Neighbors of the Neighbors, is in Transmission		
Π_{48}	0 0 1 0 0	1 1 1 1 1
Π_{49}	0 0 D 0 0	1 1 1 1 1
Π_{50}	0 0 S 0 0	1 1 1 1 1

**Table X: Network States in Heavy Traffic Situation:
Single Buffer: Ring Network**

Probability of Network State	Network State	
	Channel State	Buffer State
1. Empty Local Node		
$\Pi_{0,0}$	0 0 0 0 0	0
$\Pi_{9,0}$	C C C C C	0
$\Pi_{10,0}$	T T T T T	0
1.1 Neighbor of the Neighbor of the Local Node is in Transmission		
$\Pi_{4,0}$	1 0 0 0 0	0
$\Pi_{5,0}$	D 0 0 0 0	0
$\Pi_{6,0}$	S 0 0 0 0	0
1.2 Neighbor of the Local Node is in Transmission		

Table X: (Contd.)

$\Pi_{7,0}$	0 0 0 1 0	0
$\Pi_{8,0}$	0 0 0 D 0	0
2. Nonempty Local Node		
$\Pi_{0,1}$	0 0 0 0 0	1
$\Pi_{9,1}$	C C C C C	1
$\Pi_{10,1}$	T T T T T	1
2.1 Local Node is in Transmission		
$\Pi_{1,1}$	0 0 1 0 0	1
$\Pi_{2,1}$	0 0 D 0 0	1
$\Pi_{3,1}$	0 0 S 0 0	1
2.2 Neighbor of the Neighbor of the Local Node is in Transmission		
$\Pi_{4,1}$	1 0 0 0 0	1
$\Pi_{5,1}$	D 0 0 0 0	1
$\Pi_{6,1}$	S 0 0 0 0	1
2.3 Neighbor of the Local Node is in Transmission		

Table X: (Contd.)

$\Pi_{7,1}$	0 0 0 1 0	1
$\Pi_{8,1}$	0 0 0 D 0	1

**Table XI: Network States in Heavy Traffic Situation:
Multibuffer: Ring Network**

Probability of Network State	Network State	
	Channel State	Buffer State
1. Empty Local Node		
$\Pi_{0,0}$	0 0 0 0 0	0
$\Pi_{4,0}$	1 0 0 0 0	0
$\Pi_{5,0}$	D 0 0 0 0	0
$\Pi_{6,0}$	S 0 0 0 0	0
$\Pi_{7,0}$	0 0 0 1 0	0
$\Pi_{8,0}$	0 0 0 1 0	0
$\Pi_{9,0}$	C C C C C	0
$\Pi_{10,0}$	T T T T T	0
2. Nonempty Local Node		
$\Pi_{0,n}$	0 0 0 0 0	n
$\Pi_{1,n}$	0 0 1 0 0	n

Table XI: (Contd.)

$\Pi_{2,n}$	0 0 D 0 0	n
$\Pi_{3,n}$	0 0 S 0 0	n
$\Pi_{4,n}$	1 0 0 0 0	n
$\Pi_{5,n}$	D 0 0 0 0	n
$\Pi_{6,n}$	S 0 0 0 0	n
$\Pi_{7,n}$	0 0 0 1 0	n
$\Pi_{8,n}$	0 0 0 D 0	n
$\Pi_{9,n}$	C C C C C	n
$\Pi_{10,n}$	T T T T T	n

n = Buffer Content of the Local Node

**Table XII: Network States in Heavy traffic Situation:
Single Buffer: Cube Network**

Prabability of Network State	Network State	
	Channel State	Buffer State
1. Empty Local Node		
1.1 No Transmission by Any Node		
Π_1	$\emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, \emptyset$	\emptyset
1.2 A Neighbor of the Local Node Transmitting		
Π_2	$\emptyset, 1 \emptyset \emptyset, \emptyset \emptyset \emptyset, \emptyset$	\emptyset
Π_3	$\emptyset, D \emptyset \emptyset, \emptyset \emptyset \emptyset, \emptyset$	\emptyset
Π_4	$\emptyset, S \emptyset \emptyset, \emptyset \emptyset \emptyset, \emptyset$	\emptyset
1.3 A Neighbor of the Local Node Transmitting		
Π_5	$\emptyset, \emptyset \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	\emptyset
Π_6	$\emptyset, \emptyset \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	\emptyset

Table XII: (Contd.)

Π_7	$\emptyset, \emptyset \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	\emptyset
1.4 Off-Diagonal Node (i.e other than the Neighbor or the neighbor of the Neighbor of the Local Node) Transmitting		
Π_8	$\emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, 1$	\emptyset
Π_9	$\emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, D$	\emptyset
Π_{10}	$\emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, S$	\emptyset
1.5 Two Off-Diagonal Nodes (other than the off-diagonal Node of the Local Node) Transmitting		
Π_{11}	$\emptyset, 1 \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	\emptyset
Π_{12}	$\emptyset, D \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	\emptyset
Π_{13}	$\emptyset, S \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	\emptyset
Π_{14}	$\emptyset, 1 \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	\emptyset
Π_{15}	$\emptyset, D \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	\emptyset
Π_{16}	$\emptyset, S \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	\emptyset
Π_{17}	$\emptyset, 1 \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	\emptyset
Π_{18}	$\emptyset, D \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	\emptyset
Π_{19}	$\emptyset, S \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	\emptyset

Table XII: (Contd.)

1.6 Collision State		
Π_{20}	C, C C C, C C C, C	0
1.7 Collision Termination State		
Π_{21}	T, T T T, T T T, T	0
2. Nonempty Local Node		
2.1 No Transmission by Any Node		
Π_{22}	0, 0 0 0, 0 0 0, 0	1
2.2 Local Node Transmitting		
Π_{23}	1, 0 0 0, 0 0 0, 0	1
Π_{24}	D, 0 0 0, 0 0 0, 0	1
Π_{25}	S, 0 0 0, 0 0 0, 0	1
2.3 A Neighbor of the Local Node Transmitting		
Π_{26}	0, 1 0 0, 0 0 0, 0	1
Π_{27}	0, D 0 0, 0 0 0, 0	1

Table XII: (Contd.)

Π_{28}	$\emptyset, S \emptyset \emptyset, \emptyset \emptyset \emptyset, \emptyset$	1
2.4 A Neighbor of the Neighbor of the Local Node Transmitting		
Π_{29}	$\emptyset, \emptyset \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	1
Π_{30}	$\emptyset, \emptyset \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	1
Π_{31}	$\emptyset, \emptyset \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	1
2.5 Off-Diagonal Node (other than the Neighbor or Neighbor of the Neighbor of the Local Node) Transmitting		
Π_{32}	$\emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, 1$	1
Π_{33}	$\emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, D$	1
Π_{34}	$\emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, S$	1
2.6 Two Off-Diagonal Nodes (other than the off-diagonal Node of the Local Node) Transmitting		
Π_{35}	$\emptyset, 1 \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	1
Π_{36}	$\emptyset, D \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	1
Π_{37}	$\emptyset, S \emptyset \emptyset, 1 \emptyset \emptyset, \emptyset$	1

Table XII: (Contd.)

Π_{38}	$\emptyset, 1 \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	1
Π_{39}	$\emptyset, D \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	1
Π_{40}	$\emptyset, S \emptyset \emptyset, D \emptyset \emptyset, \emptyset$	1
Π_{41}	$\emptyset, 1 \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	1
Π_{42}	$\emptyset, D \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	1
Π_{43}	$\emptyset, S \emptyset \emptyset, S \emptyset \emptyset, \emptyset$	1
<p>2.7 Local- and its Off-Diagonal Node are Transmitting</p>		
Π_{44}	$1, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, 1$	1
Π_{45}	$D, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, 1$	1
Π_{46}	$S, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, 1$	1
Π_{47}	$1, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, D$	1
Π_{48}	$D, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, D$	1
Π_{49}	$S, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, D$	1
Π_{50}	$1, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, S$	1
Π_{51}	$D, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, S$	1
Π_{52}	$S, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset, S$	1
<p>2.8 Collision State</p>		

Table XII: (Contd.)

Π_{53}	C, C C C, C C C, C	1
2.9 Collision Termination State		
Π_{54}	T, T T T, T T T, T	1

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