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PERFORMANCE ANALYSIS OF AN ASYNCHRONOUS SPREAD SPECTRUM PACKET NETWORK

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PERFORMANCE ANALYSIS OF AN ASYNCHRONOUS SPREAD SPECTRUM PACKET NETWORK

by

AHMED H. ABDELMONEM

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

1987

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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

PERFORMANCE ANALYSIS OF AN ASYNCHRONOUS
SPREAD SPECTRUM PACKET NETWORK
BY
AHMED H. ABDELMONEM

Adviser: Professor Tarek N. Saadawi

A Continuous time Markov chain models for asynchronous communication spread spectrum code division multiple access network and a Markov chain model for CDMA with busy tone and code sensing for asynchronous channel are developed. The network is composed of N stations, the message generation process at the stations is assumed to be poisson.

Spreading code protocols are discussed, the receiver-based code is considered; a station with a packet to send looks up the destination's code and transmits on that code. Our approach is based on a two-dimensional Markov chain model for the asynchronous code division multiple access network (CDMA) and is used to evaluate throughput-delay tradeoffs.

Stead28Hystate results for throughput versus offered traffic and the delay versus throughput are obtained. The model is illustrated by examples; stability of the network is discussed. Comparison between ALOHA and CDMA is discussed; the discussion is illustred by examples.

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CHAPTER 1

SPREAD SPECTRUM

I. Introduction

The problem of multiple accessing the channel arises when a number of users transmits the signal over the same channel. Circuit switching is relatively inefficient for computer communication especially over long distances. Moreover if a high-speed point-to-point channel is used, the channel utilization may be extremely low since the channel is idle most of the time. On the other hand, if a low-speed channel is used, the transmission delay is large. By the law of large numbers in probability theory, the total demand at any instant from a large population of independent users is, with high probability, approximately equal to the sum of their average demands. Thus if a channel is dynamically shared in some fashion among many users, the required channel bandwidth to satisfy a given delay constraint may be much less than if the users are given dedicated channels [3].

If the total bandwidth available is small compared to the average total required data rate, resource sharing may be highly contentious. If the reverse is true, various interesting design options may be explored to assign individual channels that are roughly equivalent in bandwidth to individual user data rates. The three principle options are: 1) To divide time into small increments (channels), during each of which a single user

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transmitter shall be assigned the entire available bandwidth (TDMA). 2) To divide the bandwidth into many narrow-band channels, each of which is comparable to the average data rate(FDMA). 3) To use one or more signals, each of whose bandwidths greatly exceeds the average data rate of any individual user. These signals which have some orthogonality in code space (CDMA). Fixed assignments (FDMA, TDMA) can lead to poor channel utilization if individual traffic duty cycles are low. In this case contention access (ALOHA, carrier sense) among such users leads to more efficient utilization and a variety of digital radio systems, including packet radio, use this approach. Carrier sense protocols reduce the number of packet collisions and are much more efficient than ALOHA protocols.

Demand assignment, or reservation protocols are more efficient than ALOHA protocols and are commonly used in heavy traffic environments, by using a side channel to transmit time reservation packets and thus eliminate contention.

WHY SPREAD SPECTRUM

The above mentioned protocols (FDMA, ALOHA) cannot allow to overlap the signals both in time and frequency domain. Any slight overlap of transmission from different stations causes the destruction of all data packets involved, therefore the advantages of using Spread Spectrum are: 1) Spread spectrum (SS) protocol, on the other hand, allows overlap of signals both in

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time and frequency by CDMA (code division multiple access). 2) CDMA can provide higher throughput than ALOHA or FDMA and CSMA. 3) Spread spectrum are very effective against jamming, and multipath interference 4) Its resistance to interception yields privacy and secure communication 5) It requires neither time scheduling nor individual allocation to specified frequency. More detailed discussion will be given in section (1.2).

SPREAD SPECTRUM APPLICATIONS

Spread spectrum techniques are widely used in military communicaton systems. In recent years there has been increased interest in code division multiple access (CDMA) in civilian applications due to the above reasons [12]. Spread spectrum has been applied to packet radio (which is a wireless extension of packet switching), to the Joint Tactical Information Distribution System (JTIDS) for jamming resistance, and to the Position Location Reporting System (PLRS) for ranging and data communications involving military vehicles [1].

Spread spectrum is attractive for mobile communication which offers one path toward relief in the crowded radio spectrum, by having on overlaid on the top of an existing band already "full" of mobile users employing conventional frequency modulation. Also another possibility is the creation of new bands, may be a 900 MHZ band, which would use SS exclusively to accommodate thousands of users. Generally, spread spectrum is used in satellite communication, computer communication network, packet radio and office environment.

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1.1 SPREAD SPECTRUM TECHNIQUES

There are three basic types of spread spectrum: direct sequence, frequency hopping, and time hopping. In addition, there are hybrids consisting of combinations of two or more of the above basic types.

1) Direct sequence (DS): One way of achieving spread spectrum operation consists of the use of direct sequence pseudonoise (PN) modulation. Assume that the data is represented as a sequence of binary digits. A bit of information (say 1) is encoded as a sequence of N binary digits, or "chips".

The same is done for information bit (0). It is the sequence of chips resulting from the concatenation of the code waveform corresponding to the bits in the data stream which then modulates a carrier and is transmitted. The receiver is equipped with matched filters that allow the detection of the presence of the code waveform used to represent the data bits. These filters perform the cross-correlation between the input signal and the waveform whose presence the filter is intended to detect. As the incoming signal is processed, whenever there is a match, the response of the filter will exhibit a peak ideally narrow in width and high in amplitude, corresponding to the main lobe of the autocorrelation of the signal to be detected [35].

These peaks allow the detection of the presence of the desired waveform, which are used for the acquisition of bit timing, and for the recovery of the transmitted data. In the

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absence of a match, the response is of much smaller amplitude. In DS-spread spectrum network, the bandwidth generally is much greater than information rate.

2) Frequency hopping (FH): As the name implies, frequency hopping is simply jumping to a number of different frequencies in an agreed sequence. Frequency hopping or FH CDMA systems use one hop per bit while fast frequency hopping or FFH uses multiple hops per bit, generally a fast hop is applied to defeat the smart jammers.

Slow frequency hopping systems or SFH uses multiple bits per hop. When slow frequency hop is employed, the carrier frequency remains constant for time periods far in excess of the propagation time. This usually allows many bits to be transmitted at each frequency, and the resulting transmitter and receiver equipment is simpler and less expensive than that for a faster frequency hop, but the drawback of this technique is that an enemy can implement smart jammers that could detect the antijam protection in many instances. In multiple access communication each user is given a different hopping pattern, all hopping are almost orthogonal [1,41].

3) Time hopping (TH): Time hopping is a form of pulse modulation using a code sequence to control the pulse. A data bit is transmitted in a designated time slot according to the code word. The difference between frequency hopping and time hopping is that in frequency hopping systems, the transmitted frequency is

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changed at each code chip, but a time-frequency hopping may change frequency only at one/zero transitions in the code sequence [11].

1.1.1 ADVANTAGES OF SPREAD SPECTRUM SYSTEMS

We note that the transmitted signal from spread spectrum systems has two main advantageous properties; **(1) low power spectral density** and **(2) wide bandwidth.** The spread spectrum signal has low power spectral density because the signal power is distributed over a wide bandwidth; the amount of energy in any hertz or kilohertz is very much smaller than for conventional narrow-band modulation technique. The processing gain is equal to the ratio of the system bandwidth to the data bandwidth of a transmission. The property of low power spectral density is useful in the following applications.

1) Multiple Access:

Suppose a Communication channel with fixed bandwidth is to be accessed by a number of users who are equipped with transmitters and receivers and who wish to Communicate with one another, then some strategies must be employed to prevent users from interferring with one another. Such strategies are called multiple access techniques. One method is to divide the channel bandwidth into a fixed number of frequency slot which provides access to a user. This technique is called frequency division multiple access (FDMA).

Another technique is to require users to transmit in disjoint

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time intervals in a coordinated manner. This technique is called time division multiple access (TDMA). However due to the bursty nature of TDMA, synchronization among many users is required; this adds to the complexity and cost of the system. In low traffic, many time slots in TDMA or frequency slots in FDMA remain effectively unused.

Another technique is to have all users employ the spread spectrum technique with bandwidth equal to the full bandwidth of the channel. Each user employs a different codeword of code sequence (code division multiple access). Users are unsynchronized and uncoordinated, and therefore no central controller is needed. CDMA allows each user to occupy the entire channel bandwidth rather than a portion of it as happens with FDMA technique.

2) Multipath Suppression:

Multipath interference is caused by the receiver receiving the transmitted signal from two or more paths with different distances, i.e. it receives various delayed versions of the signal. Depending on their frequency and relative path lengths, signals arriving by these paths may add destructively and produce deep nulls in the signal power available to a receiver. If a conventional narrow band data signal happens to fall in a deep null, it can suffer a loss that can exceed 25 dB [35]. To over come this loss either the transmitted power or the transmitted bandwidth can be increased.

The system reported here (CDMA) uses wide band approach,

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which requires far less transmitted power for a given operating rang. All the multipath signal have low power spectral density. By using correlation techniques at the receiver, it is possible to distinguish signals which arrive at different times via different paths and in this way substantially reduce the effects of multipath interference. If the main path signal is recognized, the other multipath signals behave just like additive uncorrelated wideband noise. The power spectral density implies that these multipath signals will not degrade the system performance.

3) Low interference to other systems

The low power spectral density spread spectrum signal behaves like wideband noises. In a digital communication, the performance (error probability) depends on the rates of the received power to the noise power spectral density. Therefore the performance of narrowband system is degraded by the additional power spectral density from spread spectrum. In order to minimize this in performance effect, the bandwidth of spread spectrum is chosen as large as possible. Also the low power spectral density per user of spread spectrum increases the possibility of overlay with certain existing systems.

4) Low detectability

It is sometimes required to transmit information through a communication channel without being detected by other users. The spread spectrum is useful in this application because the low

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power spectral density property makes it difficult to detect its presence of other noises [1].

The second property, namely the wide bandwidth of spread spectrum, which develops its wide bandwidth in its simplest form of direct sequence (DS) spread spectrum. In direct sequence spread spectrum we transmit each bit as a sequence of shorter bits, called chips, which constitute the spreading code. The code itself is generally chosen to have a random quality and imports a noise like appearance to the transmitted signal (thus the name pseudonoise). The wide bandwidth of spread spectrum leads to the following applications.

1) jamming resistance: A typical implementation of a direct sequence spread spectrum system: an NRE (non-return to zero) binary data signal of rate bits/sec. in which a "1" represents a mark and a "0" a space, is multiplied by a high bit-rate pseudorandom spreading sequence. With chip rate $1/T_c$, $T_c << T$, the bandwidth of the data signal prior to spreading is proportional to 1/T, (T=bit time), thus the DS modulation process has expanded the bandwidth by a factor of T/T_c . The benefits accompaying the increased complexity and bandwidth requirements of a DS system are resistance to narrow band, high powered "Jamming" signals, incresed privacy and security [41]. The key to these benefits is the demodulation process.

Consider a narrow band jamming signal not correlated with the DS spreading waveform. At the receiver, this signal is multiplied by the spreading waveform, which expands it to a bandwidth of at

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least B_{SS} (spread spectrum bandwidth). This can be seen by recalling that multiplication in the time domain is equivalent to convolution in frequency domain, and convolving a narrowband signal with a wide band signal results in a signal with a bandwidth greater than or equal to that of the original wideband signal. Most of the "spread" interference signal is then rejected by the integration and filtering process, which has a bandwidth sufficient to pass only the recovered data signal.

The effective power of the jamming signal is decreased by a factor of T/T_c. Thus, the effective signal to noise ratio (SNR) at the detector input is increased by $T/TC=(B_{SS})/(B_d)$, (B_d=data bandwidth). The factor $(B_{SS})/(B_d)$ is commonly known as the processing gain of DS system, assume for example, that processing gain equals 1000 (30 dB) and the output signal-to-noise power ratio must be 10:1 for adequate reception, thus signal at the processor output can be detected reliably even when the noise or interference at the input is up to 100 times the input signal power [41]. This is obviously a powerful advantages against interference.

If the jammer does not choose to spread its spectrum, but continues to concentrate its energy in the original bandwidth associated with the uncoded (or unspread) bit. Where the Jammer occupies only relatively a small portion of the total signal spectrum. However, it would be easy for the receiver to employ narrow-band interference elimination filter to eliminate the

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jamming signal. If the interference is more sophisticated than continuous noise transmissions (such as burst-noise or burst cw) then interleaving and forward error correction may be combined with the use of spread spectrum to minimize the effectiveness interference.

1.1.2 Practical Considerations:

A) Synchronization: In the design of a spread-spectrum system, usually the prime importance is synchronization (alignment) of code sequence at the receiver with that of the incoming signal, and reducing the time necessary for acquisition, the magnitude of this problem (a function of the timing offest) is primarily caused by clock inaccuracy at either receiver or transmitter and a changing path length [41].

In comparing the acquisition performance of frequency hop and direct sequence PN, the frequency hop technique has an inherent advantages over the direct sequence technique, as a matter of fact the frequency hop advantages is derived from the fact that the instantaneous bandwidth (the rate at which the pesudorandom variable changes) is significantly smaller for frequency hop than for direct sequence. Acquisition for frequency hop can be achieved in shorter period of time.

B) Tracking: The second part of the synchronization problem follows initial acquisition. Once a spread spectrum receiver has synchronized with a received signal it must continue to operate in such a way that it remains locked, with its code reference

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exactly tracking the coded incoming signal; that is, once the code sequences are matched in time, the receiver must cause its own code chip rate to match the incoming code chip rate as precisely as possible (usually so that the codes remain matched within a small fraction of a clock period).

Without some active method to force the receiver's code clock rate to track an incoming signal's code rate, the two will not maintain synchronization. The two most common techniques for doing this, are called "tau-dither" and "delay-lock". A third technique, is called "carrier lock". For frequency hopping, a method called split-bit tracking is also feasible [11].

C) Multiple access interference

It is not an easy task to design a set of codeword to be assigned to various users in an Asynchronous DS-CDMA. Because the multiplication of an exact replica of a code signal with the received signal at the receiver introduces interferences from other users that depend on the cross correlation of codewords, the system performance depends on the cross correlation of each pair of codewords.

The interference from other unwanted users will be called multiple access noise. The most common form of codewords used in DS-CDMA system are linear maximal sequences because they are easy to generate using shift register and proper feedback. Gold constructed a large set of codewords with uniformly low cross correlation known as gold codes. Other sets of codewords have been proposed for DS-CDMA, but this is another topic for

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research. Inspite of multiuser interference, the reason for adopting DS-CDMA system is its resistance to multipath interference and other interferences (jamming) and its superior system flexibility. This flexibility means that no central system controller and monitor are required, and also that no precise timing and frequency coordination are required. Discussion and brief comparison of Multiple Access techniques are given in the following section:

1.2 Multiple Access techniques

1.2.1 Fixed assignments and CDMA scheme

Multiple Access have traditionaly been channel-oriented. The transmission capacity is subdivided into seperate channels in time or frequency. Using fixed assignments can lead to poor channel utilization if individual traffic are low due to many time slots in TDMA or due to frequency slots in FDMA remain effectively unused. However in CDMA, the chip rate for each individual users is the same manner as the aggregated bit rate and each user occupies the complete available bandwidth. Therefore, channel resource utilization of CDMA is superior to the other two. Another important issue in comparing CDMA, FDMA and TDMA is the number of users served by each system.

This comparison depends on the practical assumptions such as guard band, and the type of modulation technique. Generally contention access (AlOHA, S-AlOHA, CSMA) among such users leads to more efficient utilization of the channel. A variety of

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digital radio systems, including packet radio, uses this approach. More discussions of demand assignment protocols and random access schemes will be discussed in the following section, see also table (1.1).

1.2.2 Demand assignments and CDMA scheme

In digital radio communication networks with a large number of stations, the demand assignment (DA) protocols or randam access protocols where the traffic requirements of each station have a high peak to average ratio. In TDMA/DA or FDMA/DA scheme, a time slot or frequency channel is assigned on demand from a pool of m available time slots or frequencies accordingly to a station belonging to a group of n stations. Typically n much greater than m, therefore fixed assignments TDMA or FDMA are inefficient with high traffic users.

Demand assignment requires special reservations protocol and in many cases a central controller and monitors are required. This may add to complexity, costs and vulnerability of the network. A random multi-access scheme like AlOHA, S-AlOHA and CSMA may not be suitable for many types of networks due to its low capacity and unstable effects. In CDMA, on the other hand, m out of N users may simultaneously access the shared channel at random, with no reservations or network control necessary. The number of simultaneous users m, however, is limited by acceptable level of mutual interference.

The mutual interference which has limiting effects on the

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number of simultaneous users is the main problem of CDMA . Therefore, only if a CDMA system to be designed for a multi-access communication network can meet the capacity requirements (i.e. provide for the required number of m simultaneous multiple access), it's advatages can be taken of its other desirable features. The performance of a multiple access protocol is strongly dependent on the traffic model and network loading. In general, some traffic characteristics do favor one class of protocols more than others. We list some of them in table (1.2).

1.3 MOTIVATION FOR THIS THESIS

The motivation for this research arises from the growing need for computer communication networks in military and civil applications: Spread spectrum techniques are widely used in military communicaton systems, because it can achieve reliable operation in the presence of interference or jamming . In recent years there has been an increased interest in code division multiple access (CDMA) in civilian applicatons in order to achieve security and noise rejections [12].

Another related problem is the need to solve the multiple access problem which exists in most of the computer communication networks (such as; CSMA/CD (ETHERENT), CSMA, ALOHA, SLOTTED ALOHA). If CDMA scheme can be employed on the top of CSMA/CD or CSMA or ALOHA or SLOTTED ALOHA, the performance of such networks can be improved. In CDMA networks, most previous analysis were

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based on the calculation of throughput using product form solution [8,10].

In this research we analyze the receiver-based code division multiple access network in terms of throughput, delay and stability. We present a two-dimensional continuous Markov chain model that will provide a detailed insight into the network operation. The analysis is given to the receiver-based code division multiple access packet network. Effect of Non-perfect codes is studied.

CDMA network with busy tone and code sensing is proposed and analyzed. Finally we discuss the Product Form solution providing the necessary and sufficient conditions for a protocol to have a product form solution. Such work will provide theortical grounds for future work in large size networks.

1.3.1 Previous work

A few number of papers have recently appeared in the literature on packet radio network dealing with the analysis of (CDMA) systems for packet radio environment, see [3,8,10]. The difficulty in the analysis has been mainly due to the fact that the proposed access protocol introduces overlapping of the signals in time and frequency domain, and introduces dependencies between the activity of different codes.

In [8], Boorstyn and Chen mong-song, developed and evaluated an approximation for the analysis of throughput in multihop packet radio networks, which uses CDMA protocol. They assume

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zero propagation delay (ZPD) and perfect capture. The approximation is validated by comparing it with the exact analysis for some small networks. The accuracy of the approximation is within five percent for mostly connected networks. They define network model in terms of its network topology and protocol; and they let v be a set of radios , i be a node and n_i denote the set of i's neighbors.

In general, path connecting nodes may have more than one link (hop). Protocol essentially specifies two procedures: transmission and reception. A node is idle if it is neither transmitting nor receiving, a node can initiate the transmission of a scheduled packet or start receiving a packet only if it is idle. At the end of an unsuccessful transmission, the packet scheduled for transmission, is assumed to follow an independent poisson process.

Although the approximation is quite satisfactory, the model has a draw back, namely the assumption that nodes always have the selective reception ability. This may be unreasonable in highly connected networks. In [3] Silvester and Sousa have classified spreading code protocols for spread spectrum packet radio networks as either common based code, receiver based code, transmitter based code or a hybrid of these. They presented hybrid spreading code protocol for a distributed network: a data packet is divided into minipackets with the leading minipacket containing destination and source addressing, and the rest

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containing the data. The address minipacket is transmitted using a common spreading code, where as the data is transmitted using a transmitter based code. Some throughput results for a slotted system with a slot size equal to the length of minipacket were presented.

The throughput of a synchronous "slotted transmitter-based code" system was studied by Raychauduri [6]. The system model described is as follows; user transmissions start at Common clock instances and are in the form of single L bit packets of duration T seconds. each subscriber is assigned a unique transmmision code in which all messages originated by him must be encoded. When an error situation occurs, the sender must reschedule the same packet for transmission after a random delay. He assumed that the fixed assigned error probability functions $P_B(m)$,$P_E(m)$, and $P_C(m)$ are available for any given set of code parameters, the composite arrivals in any given slot will have a steady state probability distribution $f_M(m)$, of the M attempted transmissions in a particular slot, some number S will be received correctly. Generlly, CDMA codes are sufficiently pseudo-random to permit the assumption that errors in different packets occur independently. He obtained the conditional distribution of the number of successfuly received packets and the steady state throughput (B) is the expected number of successful transmission per time slot. the drawback of his model is that, he did not consider the effects of transmission failures due to the inteded receiver

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being in the transmission mode and unable to receive, in addition he ignor the effects of multiuser interference. Also using transmitter based code, will make the receiver very complex and expensive.

Tobagi and Brazio [10] proposed throughput analysis for multihop radio network operating in a zero propagation delay enviroment, they used product form solution, their model is Markovian in nature and is an extension of that used by R. Boorstyn and A. Kershenbaum for CDMA. The model has a draw back, namely it can not obtain average network delay.

Musser and Daigle [18] discussed the throughput analysis of asynchronous CDMA protcol, they studied the system from the point of tagged arrival. Their approach to calculate the number of combinations of arrivals, given K packets in the system upon arrival of the tagged packet, using a recursive solution to determine the number of successful combination of n arrival. Their model is pure algebric, does not give physical insight to CDMA analysis. In addition they did not consider the effect of transmission failures due to the intended receiver being in the transmission mode and hence unable to receive.

Davis and Gronemeyer [14] analyzed a receiver-based code centralized system. The drawback to this scheme is that even after acquiring a packet (achieving synchronization and beginning to receive the data) a different terminal may transmit a packet to the same receiver which depending on relative delays, may cause the destruction of the packet being received.

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1.3.2 Contribution of this thesis

First, we will look at the asynchronous CDMA network. We have developed a two-dimensional Markov chain model that will enable us to obtain different performance parameters such as throughput, delay, channel capacity and channel backlog. Also, the model will allow us to give a meaningful comparison between ALOHA and CDMA network.

Secondly, we use the same two-dimensional model to study the effects of Non-perfect codes. The same performance parameters are obtained for varying code effects (namely, the code threshold).

Thirdly, we are proposing a new CDMA protocol that will enhance the capability of CDMA network. A busy tone is added to the user stations, also the capability of any station to listen before transmitting is added. We have looked at the asynchronous channel. The analysis of such model is complex and simplifying assumptions are needed (such as; zero propagation delay and perfect capture) to make the analysis tractable.

Finally, the thesis discusses the product form solution as another alternative mathematical tool for the analysis of CDMA packet network.

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Condition	Access scheme		
	CDMA	FDMA	TDMA
Requirement for maximun spectral efficiency.	Orthogonal code-words for all time shifts(can not be found).	Zero adjacent channel interference	Zero timing error(impossible for mobil users)
Practical requirement for good spectral efficiency	Quasi-orthogonal code words (resulting in added noise)	Frequency guard band	Time guard band
User data rate	Most efficient for users with same data rate or multiple of it	Users with different data rate requirement assigned different bandwidths	Users with different data rata requirement assigned different time slot lengths.
System requirement	Codeword assignment, no network synch.	Frequency slot assignment,no network synch.	Time slot assignment, need network timing.
Flexibility of adding new unscheduled users	Yes, with gracaful degradation	No	No
Transmitter power requirement	Average power	Average power	Peak power
Antijamming copability	Inherent antijamming capability	Vulnerable to selective jamming	Vulnerable to selective jamming.

Table (1.1) A Brief Comparison of Multiple Access Methods

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	Traffic model	Multiple access protocol favored
1	Nonbursty users	Fixed assignment channels (TDMA, FDMA)
2	Bursty users, short messages	Pure AloHA
3	Bursty users, long messages	Reservation protocols with contention
4	Bursty users	Reservation channel
5	Bursty users,long messages	Reservation protocols, with fixed TDMA
6	Bursty users, long messages	Carrier sense multiple access with collision detection CSMA/CD
7	Bursty users, long messages security and privacy	Code division multiple access scheme (CDMA)

Table (1.2) Selection of Multiple Access Protocol Based on Traffic Model

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CHAPTER 2

NETWORK MODEL AND MATHEMATICAL ANALYSIS

2.1 PERFORMANCE MEASURES

Modeling should be used when measurment is intractable. We are devising a model that captures the main factors determining system performance. The performance measures from the model can be used as estimates of performance of the actual system. However the sharing of resources inherently causes contention for resources; in a well designed system, the gains due to sharing more than make for the losses due to contention [28].

But the contention for resources is usually a very significant factor in performance and the most difficult performance factor to quantify. Relatively speaking, if there is no resource contention, then the performance evaluation is usually simple. In constructing a model, particularly in deciding which system characteristics to consider and which to ignore (it is usually impractical to consider all system characteristic) in determining performance. Our measures will be throughput which is the mean number of packets passing through successfully per unit of time. The end-to-end packet delay which starts when a packet enters the network and ends when it arrives at the destination station.

Loosely speaking, the broadcast channel is unstable for both the finite and infinite source models. A precise definition of stability can be considered only in the context of a model of the

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behavior of the broadcast channel. We define saturation as being the phenomenon whereby the number of blocked stations become arbitrarily large [4].

2.2 Spreading Code Protocols

A number of issues arises when considering spreading codes in a distributed spread spectrum packet network [3]. On the transmitter's choice of spreading code, the receiver is dependent on how the information coming out of each transmitter is coded. Each station may be assigned a unique transmitting code, or a unique receiving code, or a common code, or a hybrid of the above protocols.

A) Common code A single spreading code is used by all stations. Addressing information can be placed at the beginning of the packet. Since all transmissions are on the same spreading code, this approach is in a sense like ALOHA protocol if all the stations were synchronized and propagation delays were zero. The advantages of this approach are the transmitter and receiver will not be complex and can be used in a network with a small number of users.

B) Transmitter-based code A unique transmitter code is assigned to each station. The drawback of this scheme is how the receiver can anticipate a transmission addressed to itself, so that it can choose the appropriate despreading code?

C) Receiver-based Code. Each user assigned a separate code for reception which is the total packet encoded in the receiver's

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code. The station looks up the destination code and transmits on that code. On the other hand, the receiver monitors its code. The drawback to this scheme is that even after acquiring a packet, a different station may transmit a packet to the same receiver which, depending on relative delays, may cause the destruction of the packet being received.

D) Hybrid schemes. Various combinations of the above schemes are possible either fixed or dynamic. Examples of hybrid systems are common transmitter code (C-T) or Receiver- transmitter code (R-T) network model [3]. In C-T, the destination and source addresses are transmitted using the network code, and the data is transmitted using a transmitter-based code. In the receiving mode upon recognizing its address, the receiver notes the address of the source, which follows, and uses this address to select the corresponding despreading code. This protocol achieves some of the benefits in the use of a transmitter-based code which uses a network (contention) code for a small portion of the packet time; that is only to get the receiver's attention.

In the R-T protocol, the destination and source addresses are transmitted using the receiver code, and the data is transmitted using a transmitter code. In the receiving mode upon recognizing its address, the receiver notes the address of the source, which follows, and uses this address to select the corresponding despreading code.

In this dissertation we intend to analyze the receiver-based direct sequence code division multiple access packet network.

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In section (2.3) the transition rates are obtained. Throughput and delay analysis are given in section (2.4) and section (2.5). In section (2.4) and (2.8), the channel capacity and stability consideration are obtained. Section (2.9) addresses the difference between ALOHA and CDMA.

2.3 Two-dimensional Markov chain model

We define the system states by two vectors i and j; where $(0 \leq i \leq N/2)$, $(0 \leq j \leq N-2i)$ are mutually exclusive states where i represents the number of successfully communicating pair of stations in the network, j represents a number of collided single stations in the network and N represents the total number of users (stations) in the network.

The future behavior of the network (system) is dependent only on the current states of the system, i.e., it is independent of the previous states of the system. Also the time between corresponding entrances to and departures from a given state (the holding time) are independent and identically exponentional distributed with a given rate. Then the states for this sytem are Markovian. A Markov process is a set of Markov states and a set of transition probabilities.

Assumptions:

1) Users communicate equally likely with each other, i.e., uniform traffic matrix.
2) Messages are assumed to arrive according to a poisson process with rate λ packet/sec.

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3) The service times are taken to be exponential in distribution with mean 1/u .
4) For poisson arrivals process, the probability that more than one arrival occurs at the same time is zero.
5) The network consists of N mutually independent users who communicate with each other over a common broadcast channel, using receiver based codes.
6) A station may not transmit and receive simultaneously.
7) Acknowledgement has zero propagation delay (ZPD).
8) No priority is given to the users.
9) Each user has only a maximum of one packet in the buffer.
10) Users have perfect codes (zero cross correlation).

In the following chapter, we will address the case of Non-perfect codes.

In our model for the asynchronous spread spectrum network, we define the system states as follows:

1) A station is said to be in an idle state, if it is not transmitting or receiving packets from other stations.
2) A station is said to be in a success state, if it is transmitting successfully to an idle station. Note that i represents the number of successfully communicating pairs.
3) A station is said to be in collision state, if it is transmitting unsuccessfully to another station. Transmission is said to be unsuccessful in the following cases:

a) Transmission to a station that is already transmitting to another station.

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b) Transmission to a station with others transmitting to the same station.

C) When the number of successful transmitting-receiving pairs exceeds the channel threshold. We define channel threshold by the number of simultaneous communicating pairs that the system can support. The channel threshold results from the imperfect codes (non zero cross correlation between the codes) used in the code division multiple access schemes. If the number of successful transmitting pairs is less than the channel threshold, a newly transmitted packet from an idle user, say to another idle user, will succeed. On the other hand, if the number of successful transmitting pair equals the channel threshold, a newly transmitted packet, from an idle user to another idle user, will n't succeed due to the effect multiuser code interference, and the packet is said to be in collision.

As mentioned earlier, we are assuming perfect codes (zero cross correlation), i.e. the channel thresholds equals to N/2 . In the next section, we obtain the transition rates.

Two-dimensional Markov chain and transition rates

Figure (2.1) represents a packet flow in a random access CDMA network and Figure (2.2) represents the continuous time two dimensional Markov chain for CDMA network. Note that transitions from state (i-1,j) to state (i,j) occurs only when any one of the idle stations transmits successfully to another idle station.

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This occurs with transition rate of (1/N-1)(n-1) times n λ ; the total generated traffic by n idle users (n=N-2i-j), hence, the transition rate A from state (i-1,j) to state (i,j) is given by

$$A = \lambda\ [N-2(i-1)-j][(N-2(i-1)-j-1)/(N-1)] \quad \ldots\ldots(2.1)$$

Similarly, the transition rate from state (i,j) to state (i+1,j), D is given by

$$D = \lambda\ (N-2i-j)[(N-2i-j-1)/(N-1)] \quad \ldots\ldots(2.2)$$

The transition from state (i,j) to state (i,j+1) occurs when an idle unsuccessfully transmits. Unsuccessful transmission happens when the idle terminal transmits to any station of the communicating pair or to any of the colliding stations with probability (2i+j)/(N-1) . Hence the transition rate, B from state (i,j) to state (i,j+1), as in Fig. (2), is given by

$$B = \lambda\ [N-(2i+j)][(2i+j)/(N-1)] \quad \ldots\ldots(2.3)$$

Similarly,

$$G = \lambda\ [N-2i-(j-1)][(2i+j-1)/(N-1)] \quad \ldots\ldots(2.4)$$

The transition from state (i+1,j) to state (i,j) occurs by the departure of any of the successful communicating pairs with rate E is giving by

$$E = (i+1)u \quad \ldots\ldots(2.5)$$

Similarly, the transition rate from state (i,j) to state (i-1,j) , H is giving by

$$H = iu \quad \ldots\ldots(2.6)$$

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The transition from state (i,j+1) to state (i,j) occures by the departure of any of the unsuccessful communicating singles, see C in figure (2.2),

$$C = (j+1)u \qquad \text{.....(2.7)}$$

Similarly, the transition rate from state (i,j) to state (i,j-1) is giving by F,

$$F = ju \qquad \text{.....(2.8)}$$

Note that there is no transition from state (0,0) to state (0,1). At steady state, the rate of flow into any given state must equal the rate of flow out of the state, hence from figure (2.2), we derive the following equations:

At steady state
the rate of flow into the state = the rate of flow out of the state

$$\begin{aligned}
&\{ \tfrac{\lambda}{N-1}(N-2i-j)(2i+j) + \tfrac{\lambda}{N-1}(N-2i-j)(N-2i-j-1)+iu+ju\} p(i,j)= \\
&\{ \tfrac{\lambda}{N-1}[N-2(i-1)-j][2(i-1)+j]\} p(i-1,j) \\
&+\{ \tfrac{\lambda}{N-1}[N-2i-(j-1)]\,[2i+(j-1)]\ \} p(i,j-1) \\
&+\{(i+1)\,u\} p(i+1,j) \\
&+\{(j+1)\,u\} p(i,j+1) \qquad \text{..... (2.9)}
\end{aligned}$$

for $0 \le i \le N/2$ & $0 \le j \le N-2i$

$$\text{Also } \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} p(i,j) = 1 \qquad \text{..... (2.10)}$$

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2.4 Network throughput

The model that has been developed in this dissertation, gives insight into the behavior of the system and enables us in obtaining the throughput-delay equations as follows:

Average network throughput = S_N

$$S_N = \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\ p(i,j) \qquad \text{.....(2.11)}$$

Average throughput per pair = S

$$S = (2/N) \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\ p(i,j) \qquad \text{.....(2.12)}$$

The channel capacity = maximum attainable throughput

$$C = \text{Max} \{ \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\ p(i,j) \} \qquad \text{.....(2.13)}$$

2.5 Packet delay

The total average delay, incurred by a packet from the moment it is generated until it is successfully transmitted, is equal to the sum of the average waiting time in the buffer plus the average time from the first attempted transmission to the final successful one (average service time). We assumed here in this analysis that each user can have at most one packet in the buffer requiring transmission at any time, including any previously blocked packet. The averge channel backlog, K is given by

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$$K = \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} j\, p(i,j) \qquad \text{.....(2.14)}$$

From equations (2.12) and (2.14), and using Little's result [24], we obtain the average packet delay, D , as follows;

D = mean channel backlog / mean channel throughput

$$D = \frac{\sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} j\, p(i,j)}{(2/N) \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\, p(i,j)} \qquad \text{.....(2.15)}$$

2.7 Numerical results

The values of p(i,j) have been obtained by solving the set of linear equations , equation's (2.9) and (2.10) numerically. Then throughput and delay values are easily obtained from equation's (2.12) and (2.15), respectively. We have plot the curves [figures (2.3) through (2.5)] for N=8 . Figure (2.3) is the throughput versus channel traffic (S - λ), figure (2.4) is the average packet delay versus channel throughput (D - S), where figure (2.5) is the channel backlog versus throughput (K - S)

In figure (2.11), we plot the throughput per pair of station versus N for different values of N= 4, 8, 12 .

We notice that throughput per pair of stations is drop off for large N.

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2.8 STABILITY CONSIDERATIONS

Kleinrock and Lam [12] have discussed the stability problem of slotted ALOHA channel. Their results, based on simulation and fluid approximation, indicate that the channel becomes saturated if the set of terminals is very large, independently of the arrival rate of packets to the channel. In this section we shall present a stability problem based on our work for Asynchronous CDMA networks. Such stability of the propsed model will be discussed below.

The S - λ curve shows a negative slope. The model allows us to obtain the values p(i,j), the probability of having i communicating successfully pairs and j the single collided users, which helps in understanding the behavior of the system. These values are obtained in figures (2.6) through (2.10).

Note that for the same value of throughput, say s = 0.307 as given in Figure (2.3). There are two values of λ : one in the stable region λ_A = 400.0 packets/unit time, with its associated delay D_A = 2.3 packet time; the other in the unstable region λ_B = 2800.0 packets/unit time, with its associated delay D_B = 12.2 packet time. Also note that maximum throughput depends on N and λ . In such example, we have obtained p(i,j) for the two operating points of A & B. From these values, p(0,8) = the probability of all 8 users in collision is much higher in point B than in point A and that is expected since point B is an unstable point. On the other hand, p(4,0) = the probability of all 8

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users (4 pairs) in success is higher in point A than in point B which again is expected.

The S-D curve shows that there are two possible solutions for D; they correspond to a small delay = 2.3 packet time and a much larger delay = 12.2 packet time. We refer to point A as the stable operating point (for given offered traffic), since it yields the larger channel throughput and smaller delay and point B as unstable operating point, since as the offered traffic increases, the channel throughput decreases and the average packet delay increases very rapidly.

Note that in this case stable operating point, unstable operating point, exist in practical systems. An unstable channel may be accepted, if the average channel uptime is large and external control is available to bring the channel up whenever it goes down. External control must be applied at this point to restore proper channel operation. For controlling the channel, we should control either the new traffic or the previously collided traffic in order to achieve system stability .

The designer of a CDMA network is thus faced with the problem of deciding whether he/she wants a stable channel by using it for a small number of users (keep offered traffic below 1000 packets/unit time) and sacrifies channel throughput or uses the channel to support a large number of users if he/she willing to accept a certain level of channel reliability.

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2.9 Comparison between ALOHA AND CDMA network

ALOHA type network is based on the assumption that when a single packet is transmitted in a given time period, it is always received correctly, while if two or more transmissions occur, then all the packets are destroyed. But in code division multiple access systems, channel coding permits the simultaneous transmission of two or more users data. In ALOHA system either one packet is in success or all transmitted are in collision , but in CDMA the system may contain collided packets and successful packets at the same time.

With appropriate choice of coding techniques [6], there is the potential for improving on the capacity of CDMA. In addition, CDMA transmission can provide other benefits, such as greater immunity to interference and interception. We note that with spread spectrum the channel coding can support more than one simultaneous transmissions of users.

ALOHA throughput is given in [22] as the following :

$$S_{ALOHA} = Ge^{-2G} \qquad \text{.....(2.16)}$$

from equation (2.16), we find that at λ = 500 packets/unit time occurs the maximum throughput which is only 18 % of the channel capacity.

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In order to clarify the comparison between ALOHA network and CDMA network, the following discussion is given below.

For CDMA network, we defined S (throughput per pair) as the throughput per sub-channel of CDMA network. The total CDMA network throughput, S_N is given by

$$S_{CDMA} = S_N = (N/2)\ S \qquad \ldots\ldots(2.17)$$

as given in equation (2.11).

Hence in comparing CDMA network with ALOHA, we need to compare the ALOHA network throughput, S_{ALOHA} with the total CDMA network thgroughput, S_{CDMA} . For exampl; the maximum ALOHA throughput equals $S_{ALOHA} = 0.18$, while the maximum CDMA throughput equals (N/2)(S per pair) = (8/2)(0.37) = 1.48 .

So the CDMA network achieve higher throughput than ALOHA network. On the otherhand, due to the spreading nature of CDMA, the total user data rate $S_{CDMA\ user}$ is lower than the network throughput S_{CDMA} as follows;

$$S_{CDMA\ user} = \frac{S_{CDMA}}{PG}$$

$$S_{CDMA\ user} = \frac{(N/2)\ (S \text{ per pair})}{PG} \qquad \ldots\ldots(2.18)$$

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Where PG is the processing gain

For the ALOHA network, the user data rate = $S_{ALOHA\ user}$ equals the network throughput (no spreading).

$$S_{ALOHA\ user} = S_{ALOHA} \qquad \text{.....(2.19)}$$

Now if the comparison is done from the data user point of view, we should compare equation (2.18) with equation (2.19). Note that the comparison depends on {(N/2)/(PG)}, i.e. it depends on the number of user and the processing gain of the code used. For large number of users, CDMA is expected to achieve higher throughput and for small number of users, ALOHA will achieve higher throughput.

In summary, CDMA scheme improves upon the ALOHA throughput of 0.18 , but this is achieved at the expense of bandwidth. In order to compare CDMA system and ALOHA system, the throughput of a given system must be normalized to the operating bandwidth. Thus if we define "utilization" U as the ratio of throughput S to the bandwidth expansion (processing gain) PG which is the throughput per "unit" of bandwidth. Nominally, ALOHA has a bandwidth expansion PG of 1 , while CDMA systems of interest have PG much greater than 1 .

Curves of delay versus throughput and throughput versus channel traffic will provide a basis of comparison of unlike random access systems. A comparison of throughput (data rate) versus

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offered traffic for ALOHA nd CDMA is shown in figure (2.12). The figure shows that CDMA system achieve higher data rate for small processing gain. In addition, the channel degradation for CDMA scheme is more graceful since the throughput does not decrease as rapidly as in ALOHA when system is pushed behind capacity.

The only way to allow the fixed bandwidth network to be shared in a spread spectrum (CDMA) manner is to reduce the information rate while maintaining the raw bit rate of the original network for the pseudo-random spectral spreading sequence.

A throughput versus delay (CDMA system) shown in figure (2.13). The figure shows that CDMA system achieve lower delay for small processing gain.

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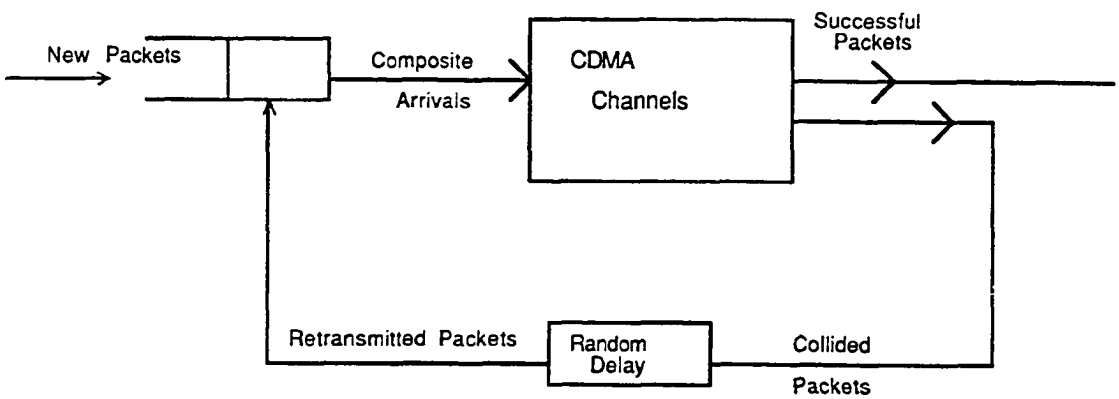

Fig (2.1) Packet flow in a random access CDMA network.

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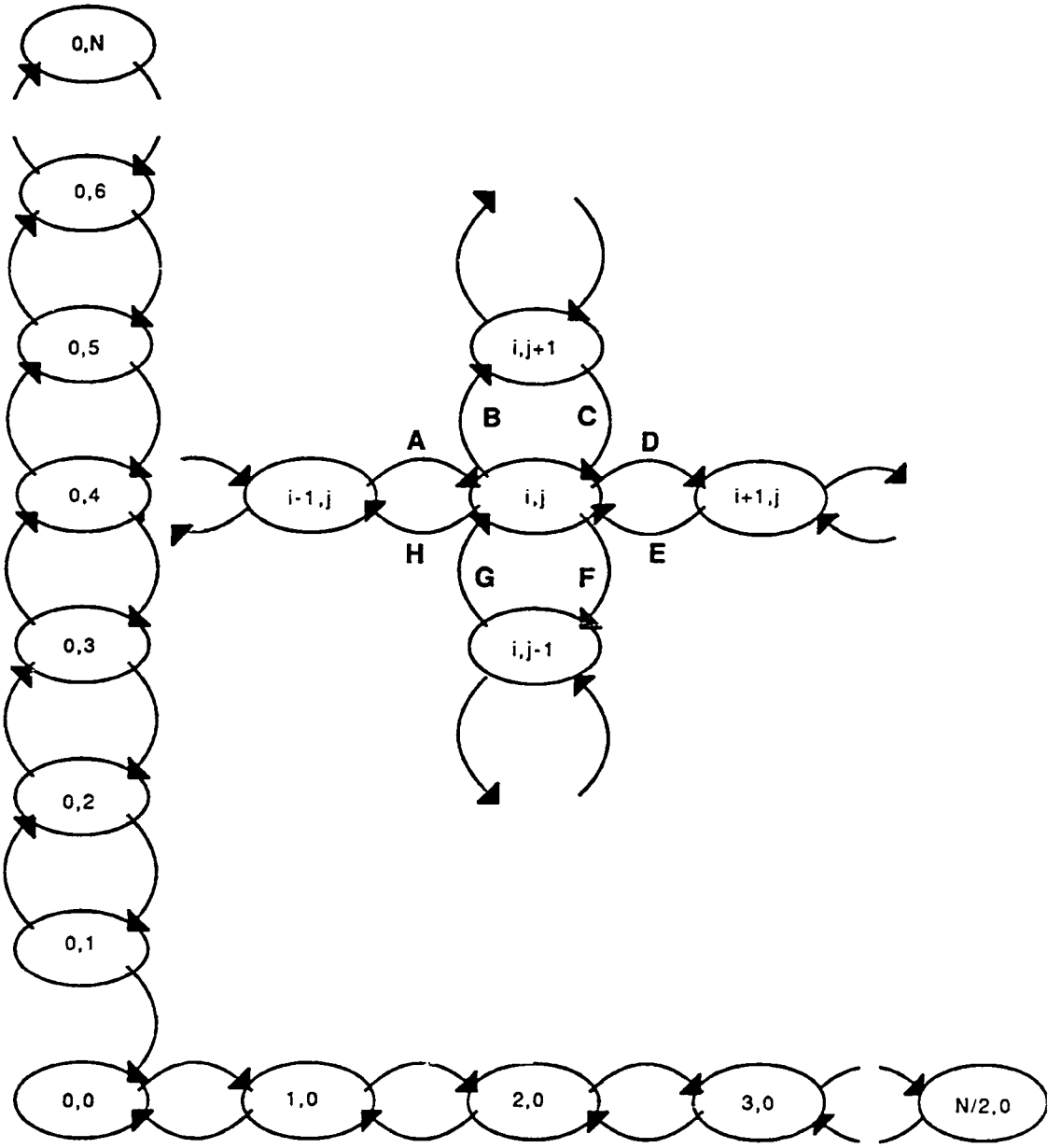

Fig (2.2) Steady State Transition Diagram

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FIG.(2.3)Throughput – Channel Input N = 8

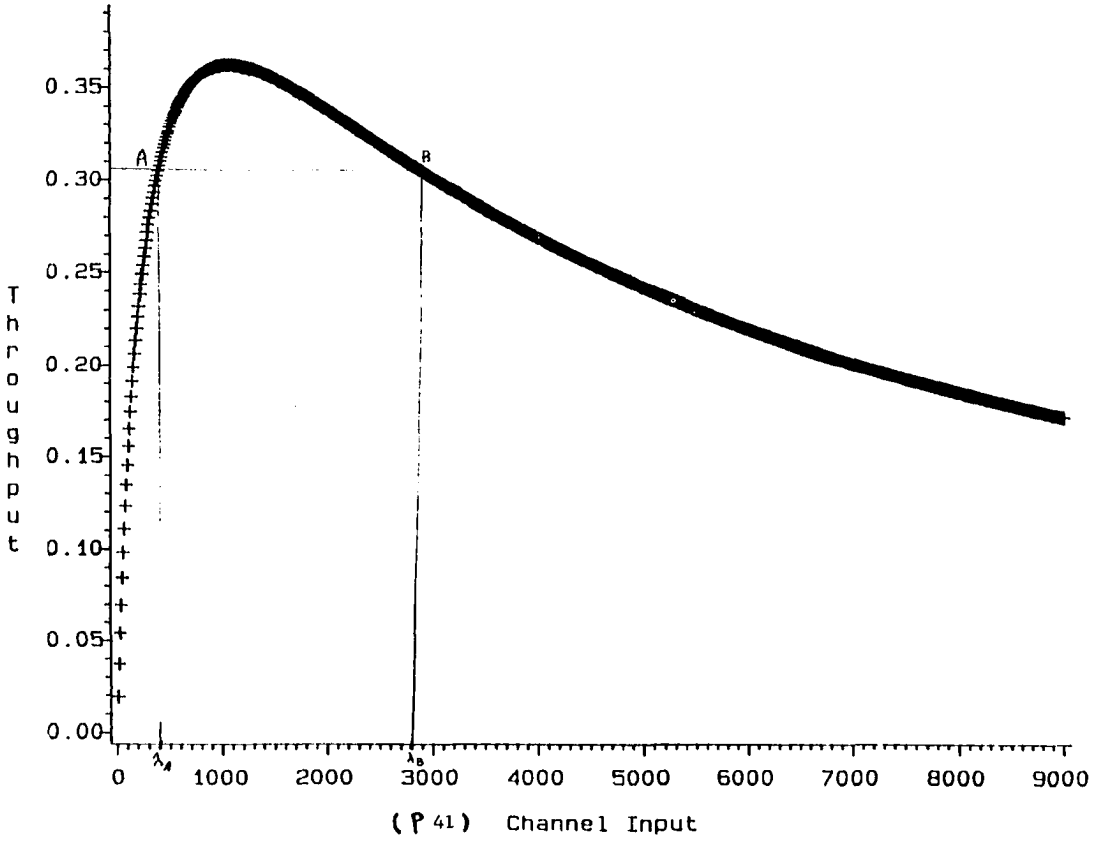

FIG.(2.4) Delay – Throughput N = 8

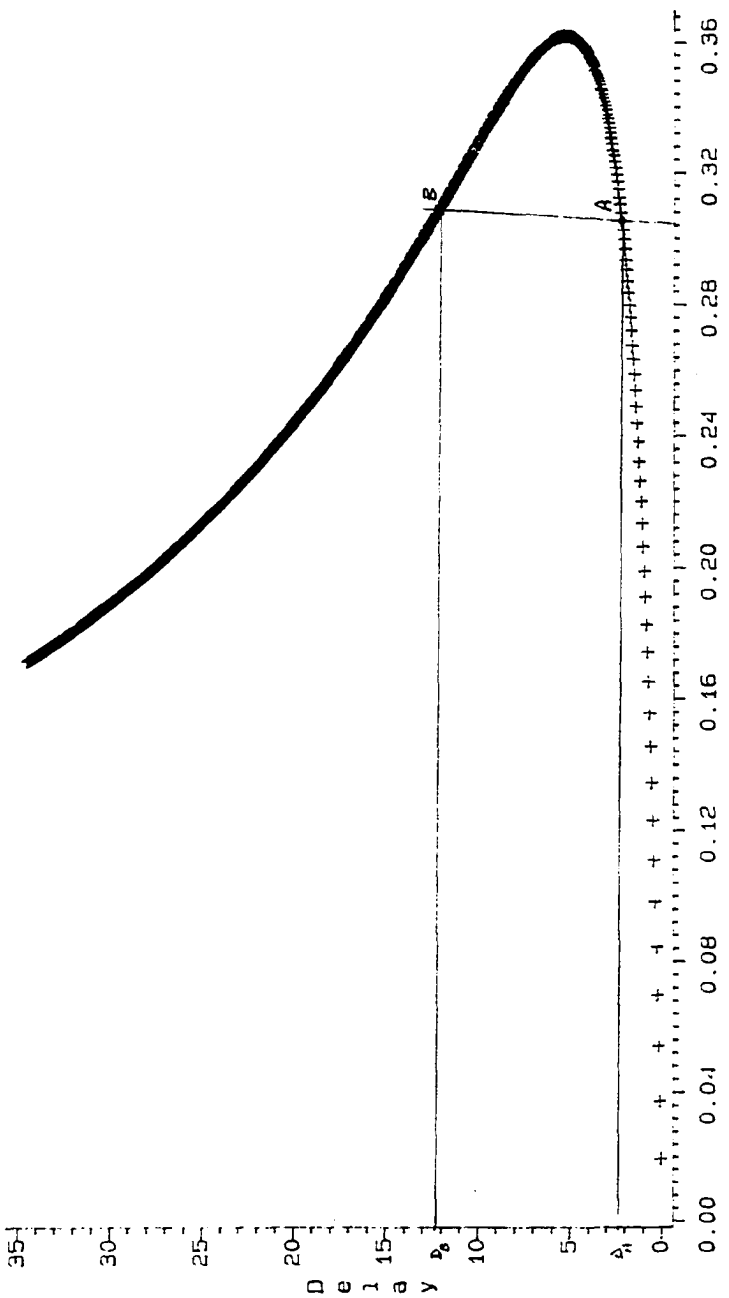

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FIG.(2.5)Channel Backlog -- Throughput N = 8

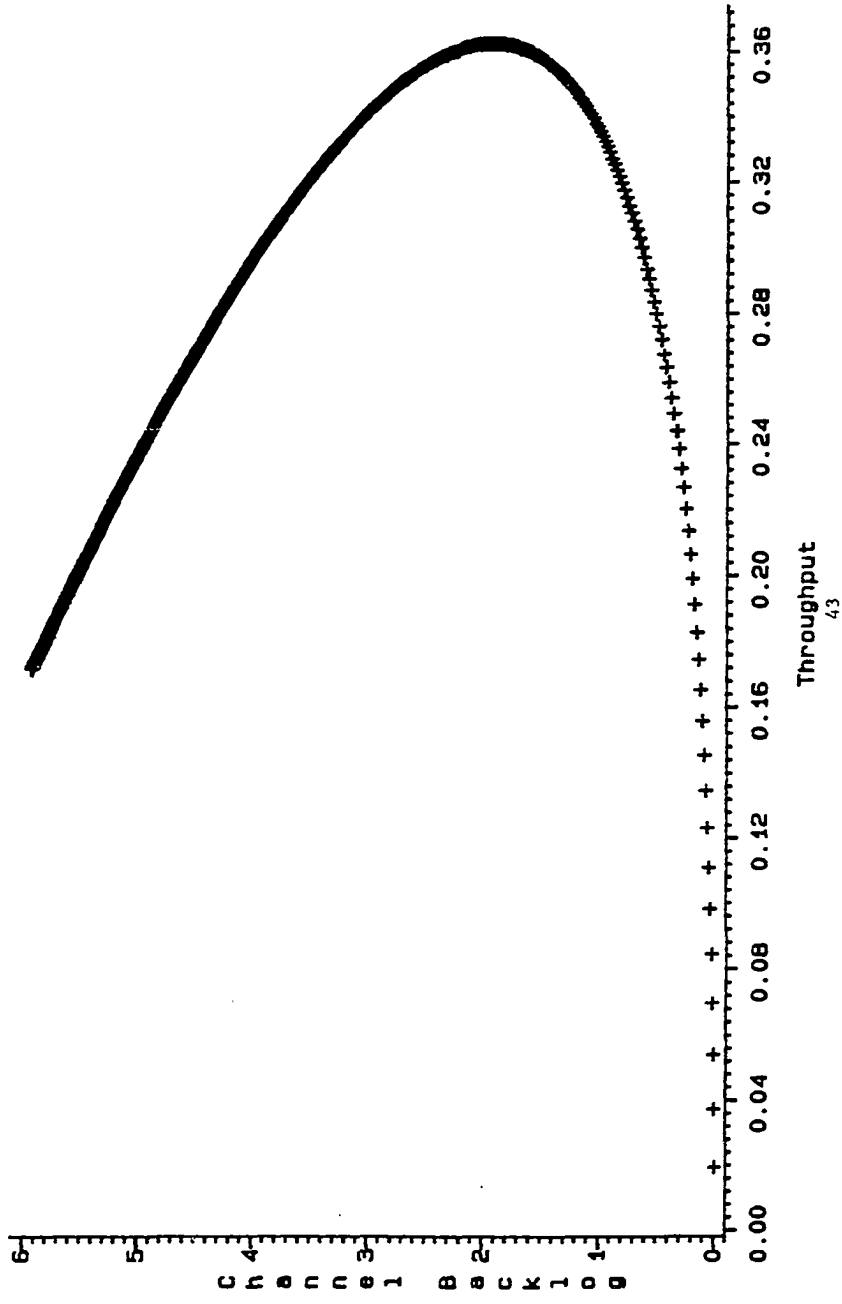

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FIG.(2.6) Probability – Channel Input

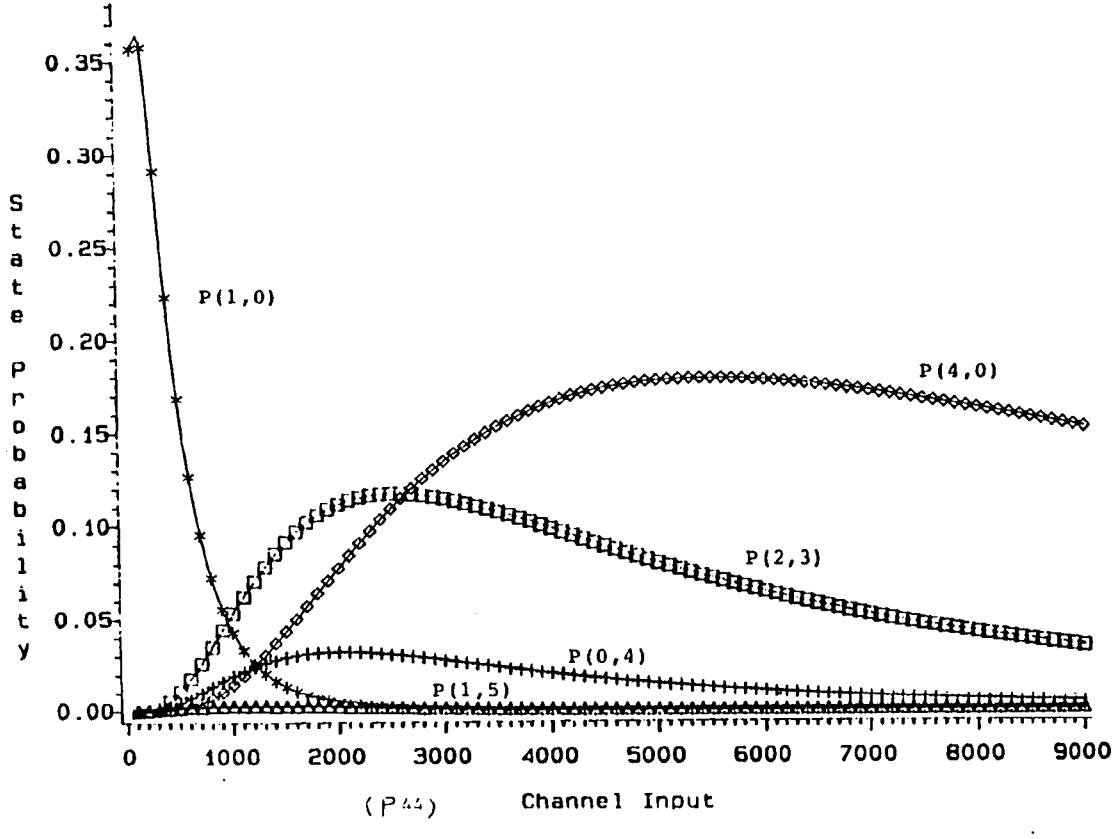

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FIG.(2.7) Probability – Channel Input

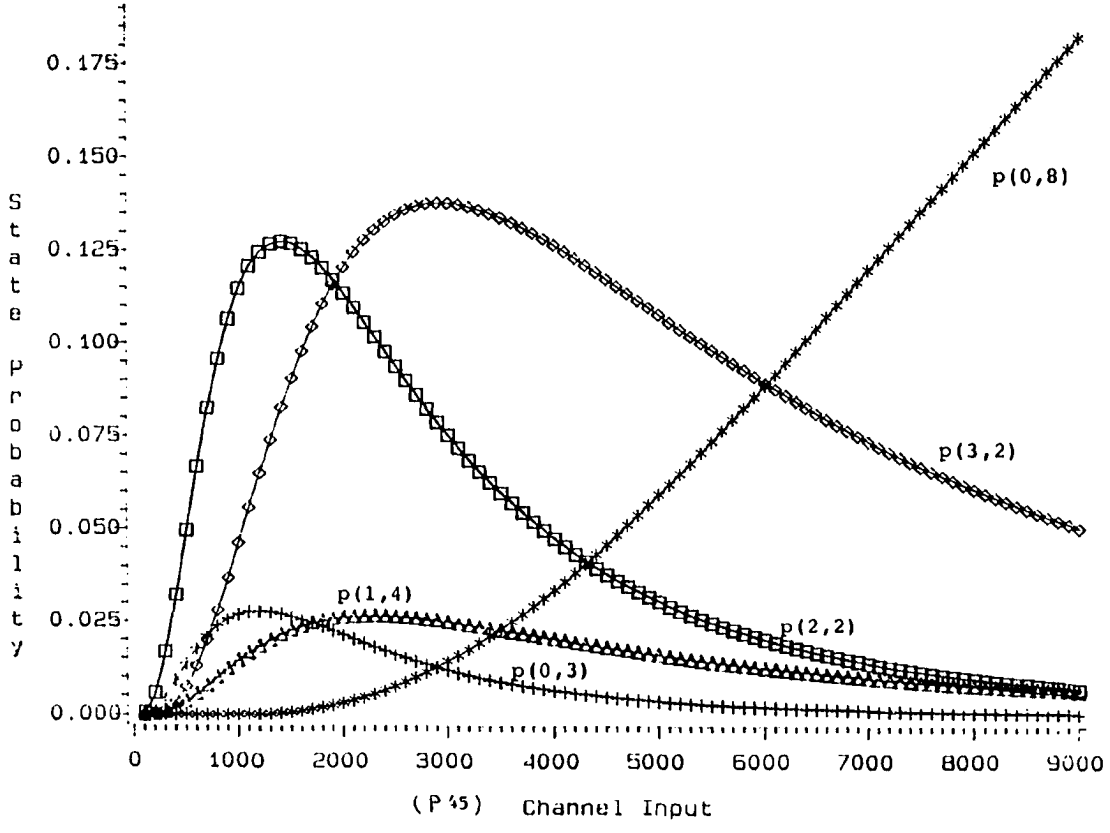

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FIG.(2.8) Probability – Channel Input

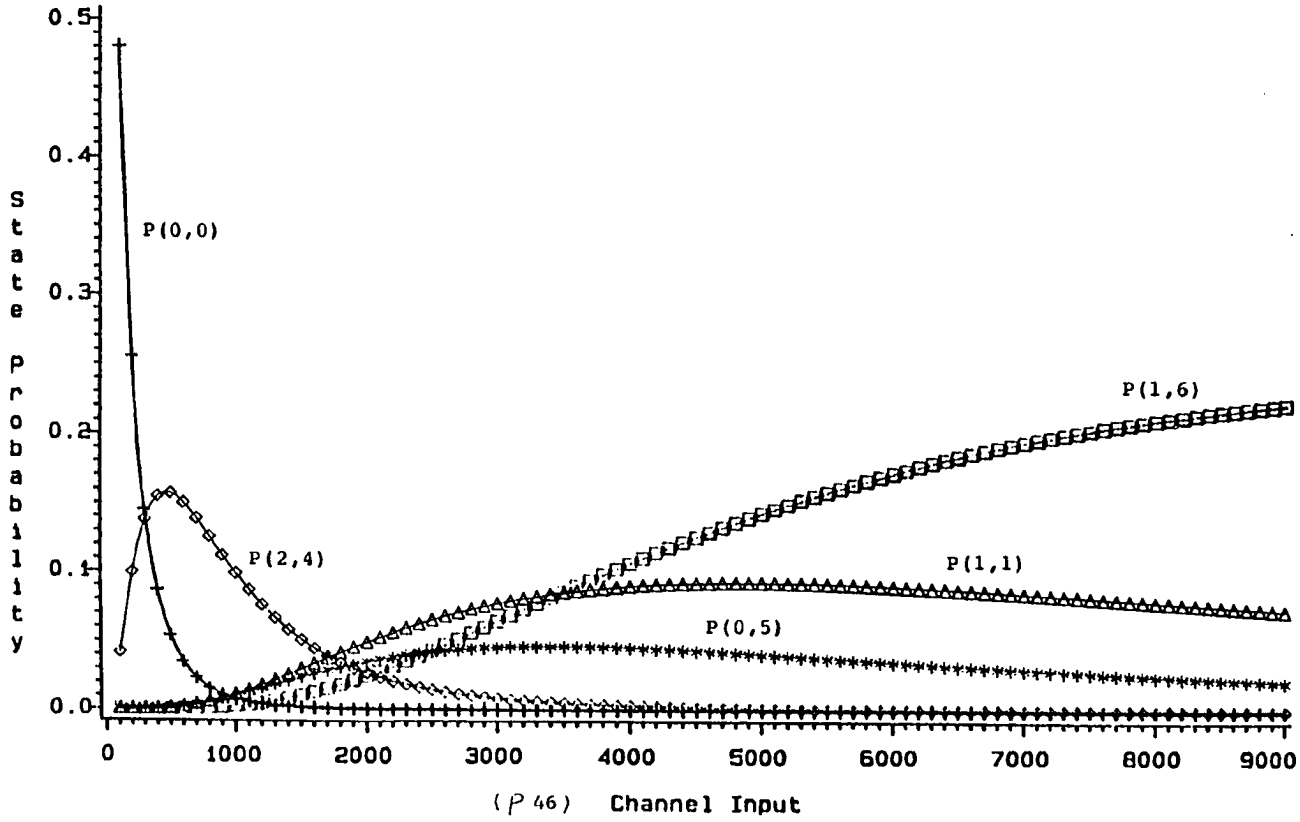

FIG.(2.9) Probability — Channel Input

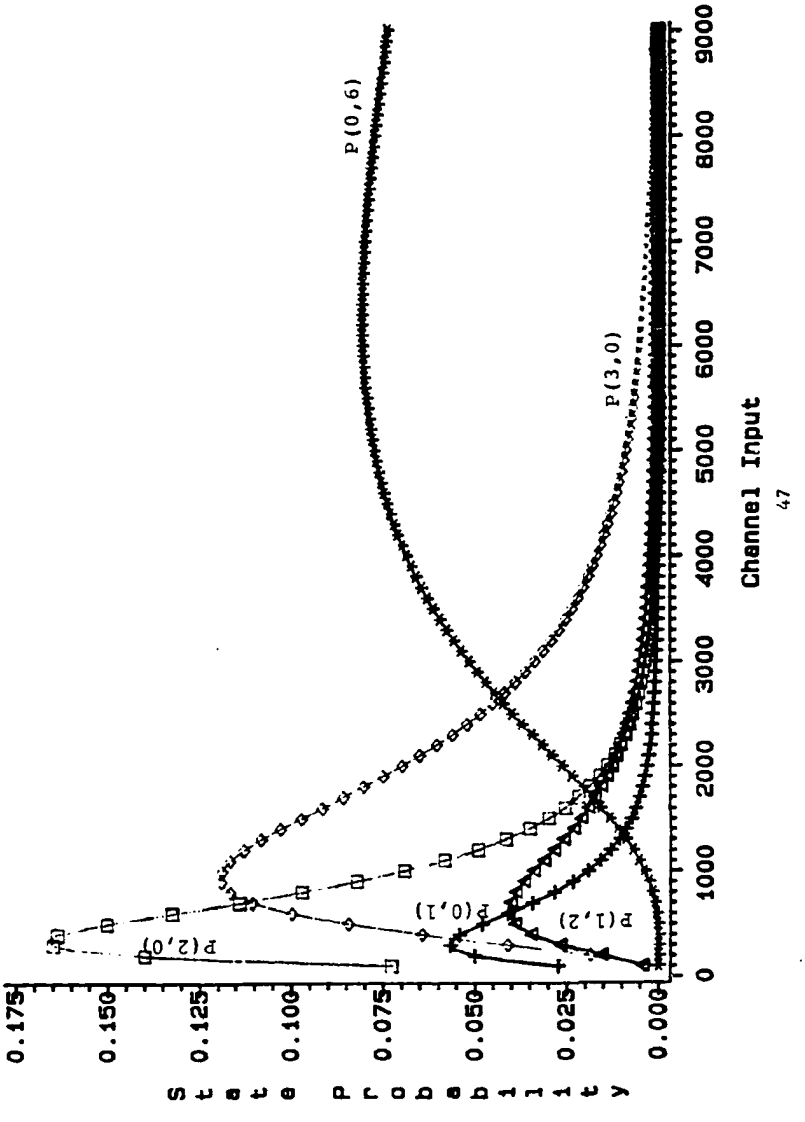

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FIG.(2.10) Probability -- Channel Input

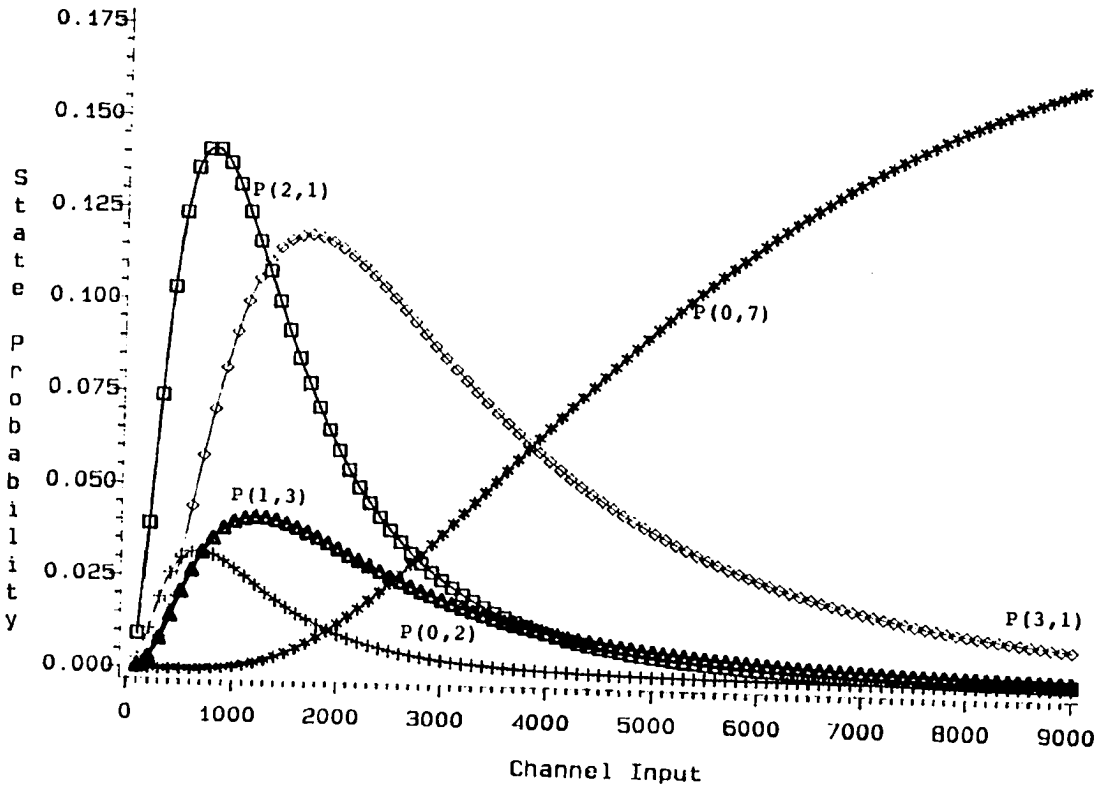

FIG.(2.11) ThroughPut – Number of Users

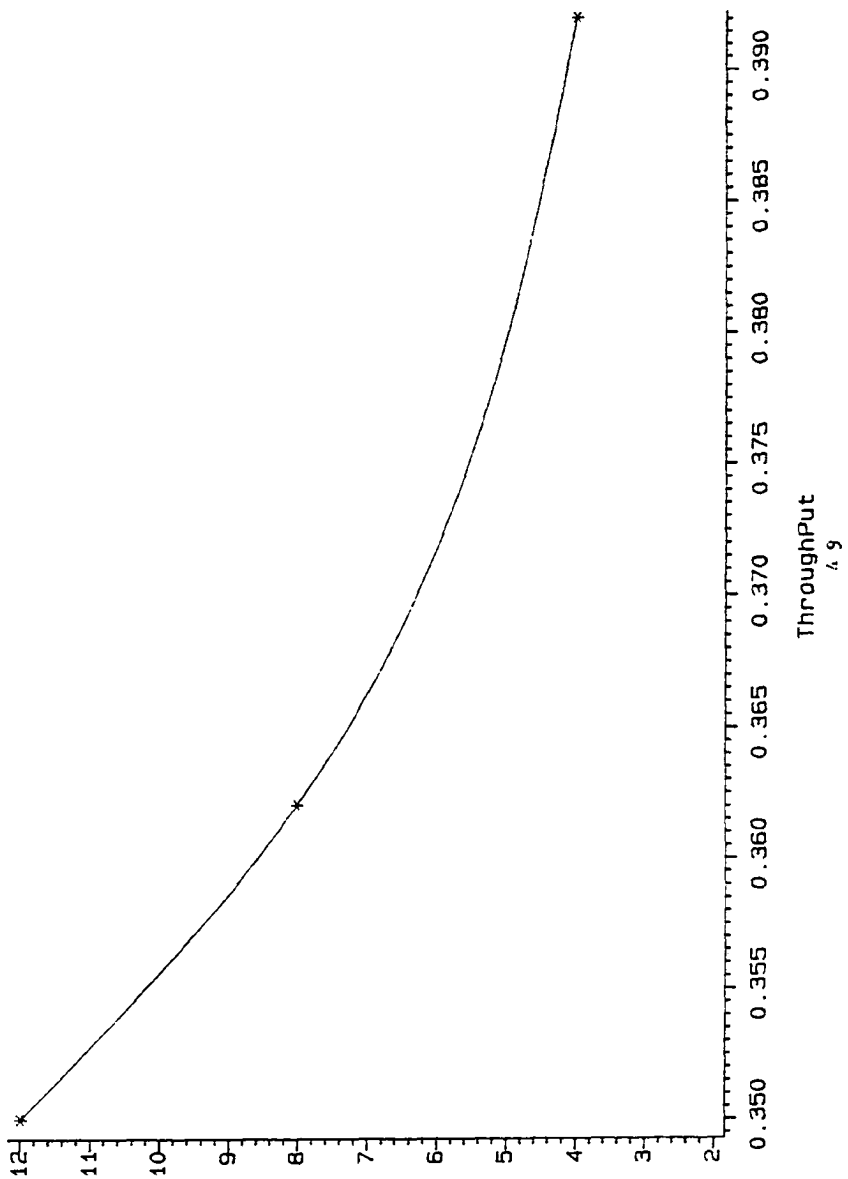

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FIG.(2.12) Throughput – Offered Traffic

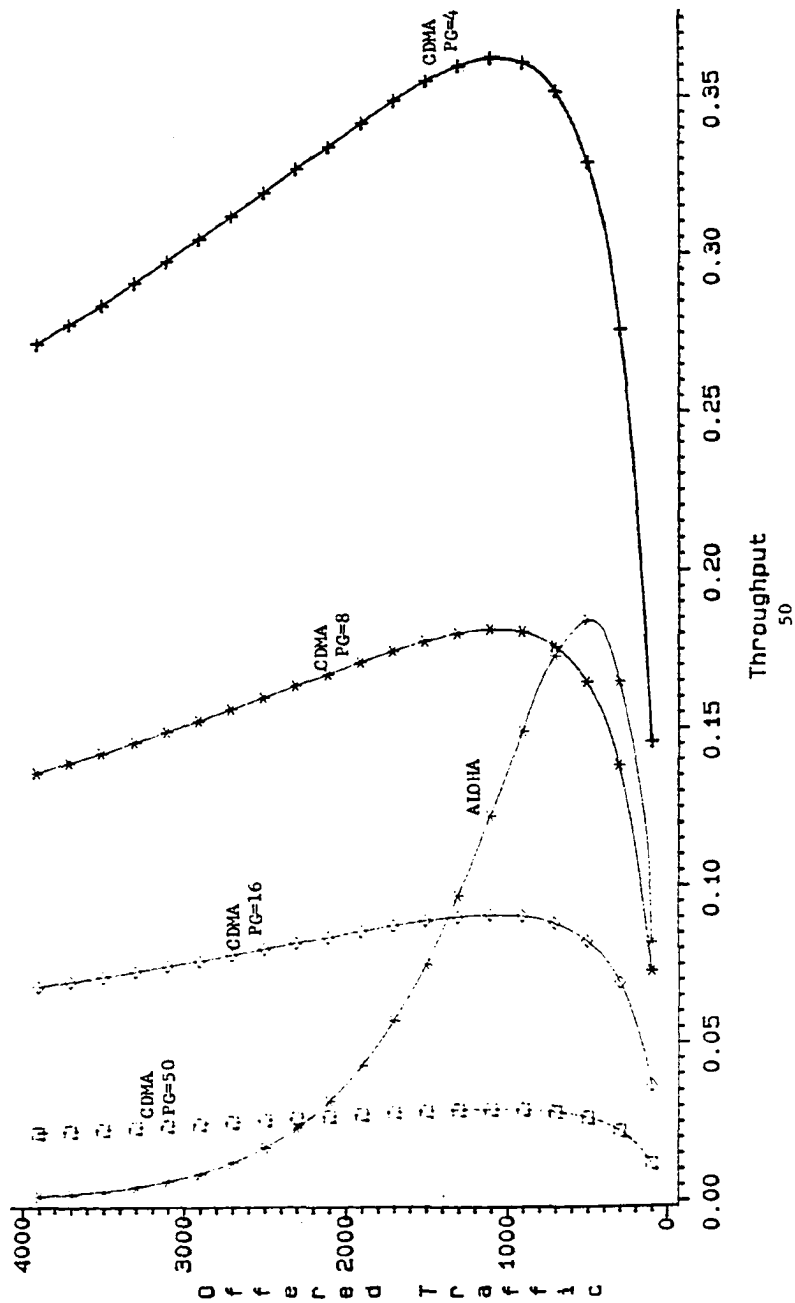

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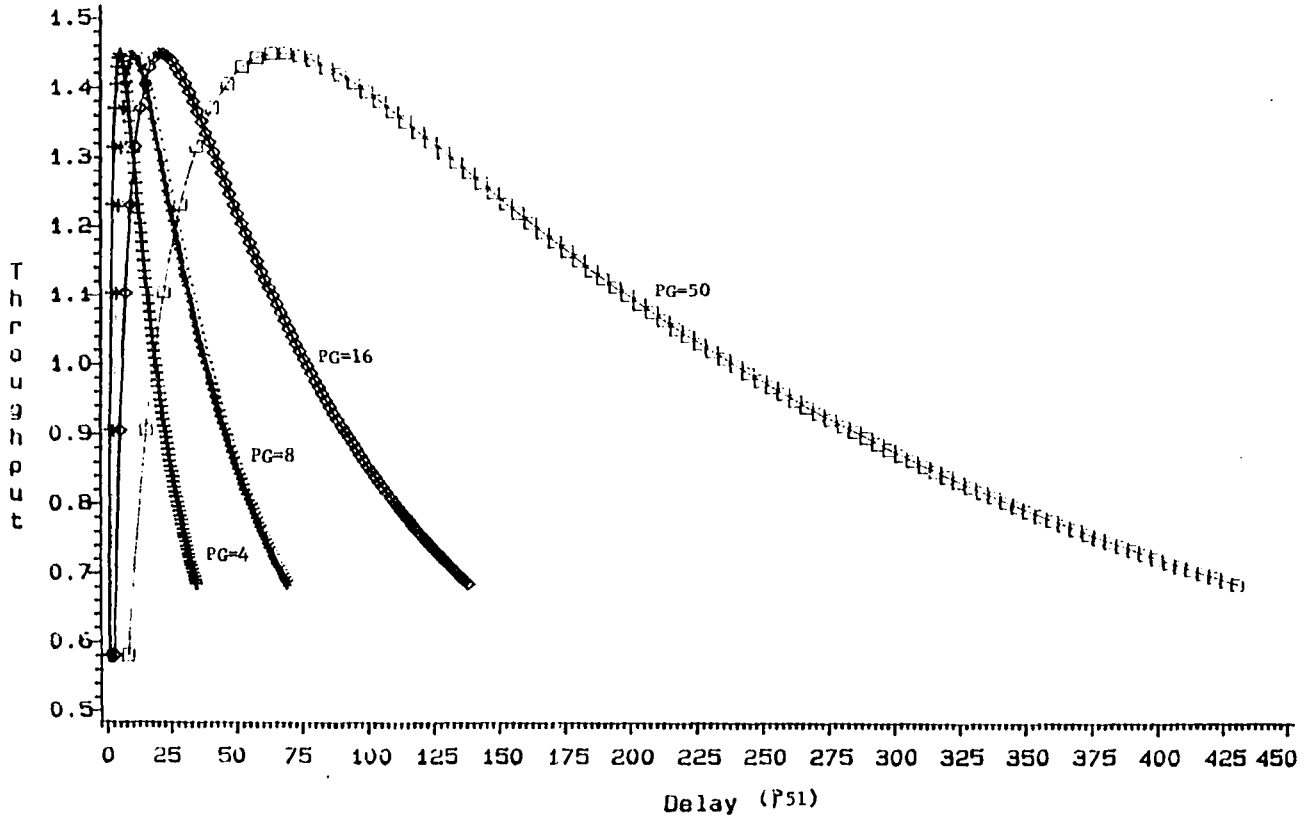
FIG.(2.13) THROUGHPUT – DELAY



CHAPTER 3

CASE OF NON-PERFECT CODES

3.1 Threshold effect

When users are allowed to transmit simultaneously in time and occupy the same RF bandwidth as well, some other means of separating the signals at the receiver must be available, and CDMA provides this necessary capability. In DS-CDMA, each user is given its own code, which is approximately orthogonal (i.e. has low cross correlation) with the codes of other users [1].

When codes are properly chosen for low cross correlation, minimum interference occurs between users. Receivers set to use different codes are reached only by transmitting that code. Thus more than one signal can be transmitted at the same frequency, and at the same time.

For asynchronous system, the number of users the system can accommodate is less than the processing gain [1]. One attractive feature of CDMA is that it does not require the network synchronization that TDMA requires. Another advantage of CDMA is that it is relatively easy to add additional users to the system. However, probably the dominant reason for considering CDMA is the need, in addition, for some type of external interference rejection capability such as multipath rejection or resistance to intentional jamming.

The interesting question here is the number of users

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supported by a CDMA network. This question has been subjected to various studies [1, 7, 22] . If the codes for different users are selected to be orthogonal (or approximately orthogonal), the users can share the common channel bandwidth without any sever mutual interference.

In our model presented in chapter 2, we have assumed that the user have perfect codes, for example, if all N/2 different code, then it is assumed that all N/2 transmissions will successed. Yet due to the Non-perfect nature of the codes, the number of success is normally less than N/2. This chapter considers such case of Non-perfect codes. The model developed in chapter 2, with some modifications, will allow us to study such case. Here, we define, α , as the upper limit of the number of successfully similtaneously transmitting pairs.

Note that in chapter 2 (case of perfect codes), α equals N/2, while in this chapter α is less than N/2.

3.2 Case of Non-perfect codes; Network model

The model here is an extension for the model developed in chapter 2. Assumptions (1) through (9) in section 2.3 are the same here. The definitions of the system states (idle, success, and collision) is the same. Again we define here the system state by (i,j); where ($0 \leq i \leq \alpha$), ($0 \leq j \leq N-2i$) and i represents the number of successfully communicating pair of stations in the network, j represents the number of collided single stations in

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the network and N represents the total number of users (stations) in the network.

The two dimensional Markov chain model and associated transition probabilities for the Non-perfect code will be identical to that of chapter 2, the difference lies in the range of different states. This is explained as follows;

From figure (3.1), D the transition rate from state (i,j) to state (i+1,j) is given by

$$D = \lambda n(n-1)/(N-1) \qquad i \leq \alpha$$

$$D = 0 \qquad i > \alpha \qquad \text{.....(3.1)}$$

Note that the number of successful pairs, i, can't exceed the threshold (case of Non-perfect codes).

Also, note that the value & the range of the transition probabilities(B, C, G, F) , as given in chapter 2, are the same, i.e.

$$A = \lambda [N-2(i-1)-j][(N-2(i-1)-j-1)/(N-1)] \qquad \text{.....(3.2)}$$

$$B = \lambda [N-(2i+j)][(2i+j)/(N-1)] \qquad \text{.....(3.3)}$$

$$C = (j+1)u \qquad \text{.....(3.4)}$$

$$D = \lambda [(N-2i-j][(N-2i-j-1)/(N-1)] \qquad \text{.....(3.5)}$$

$$E = (i+1)u \qquad \text{.....(3.6)}$$

$$F = ju \qquad \text{.....(3.7)}$$

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$$G = \lambda\,[N-2i-(j-1)]\,[(2i+j-1)/(N-1)] \qquad \ldots\ldots(3.8)$$

$$H = iu \qquad \ldots\ldots(3.9)$$

for $0 \le i \le \alpha$ & $0 \le j \le N-2i$

At steady state
the rate of flow into the state = the rate of flow out of the state

$$\{\tfrac{\lambda}{N-1}\ (N-2i-j)(2i+j) + \tfrac{\lambda}{N-1}\ (N-2i-j)(N-2i-j-1)+iu+ju\}\ p(i,j)=$$
$$\{\tfrac{\lambda}{N-1}\ [N-2(i-1)-j][2(i-1)+j]\}\ p(i-1,j)$$
$$+\{\tfrac{\lambda}{N-1}\ [N-2i-(j-1)]\ [2i+(j-1)]\ \}\ p(i,j-1)$$
$$+\{(i+1)\ u\}\ p(i+1,j)$$
$$+\{(j+1)\ u\}\ p(i,j+1) \qquad \ldots\ldots(3.10)$$

for $0 \le i \le \alpha$ & $0 \le j \le N-2i$

Also $\sum_{i=0}^{\alpha} \sum_{j=0}^{N-2i} p(i,j) = 1$ .....(3.11)

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Once we have obtained p(i,j), for all values of (i,j), using the above equations (3.10), (3.11), we can proceed to obtain the other network parameters such as throughput, delay, channel capacitiy and channel backlog as follows;

Network throughput = S_N

$$S_N = \sum_{i=0}^{\alpha} \sum_{j=0}^{N-2i} i\, p(i,j) \qquad \text{.....(3.12)}$$

and throughput per pair as the following:

$$S = (2/N) \sum_{i=0}^{\alpha} \sum_{j=0}^{N-2i} i\, p(i,j) \qquad \text{.....(3.13)}$$

Maximizing throughput S with respect to offered traffic, gives channel capacity (C).

$$C = \text{Max}\left[(2/N) \sum_{i=0}^{\alpha} \sum_{j=0}^{N-2i} i\, p(i,j) \right] \qquad \text{.....(3.14)}$$

It can be seen that there is more than a proportional increase in throughput as α increases. For a given N, the optimum number of successful pairs is simply $\alpha = N/2$. Also the channel backlog (K), and packet delay (D), are given as follows:

$$K = \sum_{i=0}^{\alpha} \sum_{j=0}^{N-2i} j\, p(i,j) \qquad \text{.....(3.15)}$$

$$D = \frac{\sum_{i=0}^{\alpha} \sum_{j=0}^{N-2i} j\, p(i,j)}{(2/N) \sum_{i=0}^{\alpha} \sum_{j=0}^{N-2i} i\, p(i,j)} \qquad \text{.....(3.16)}$$

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3.3 Numerical results

Figure (3.2) represents the throughput versus offered traffic for different value of threshold, α ; for example , when α=2, the maximum throughput is S = 0.28 and it occurs at an offered traffic of λ = 1000 packet/unit time. When α = 3 , the maximum throughput S = 0.36 and it occurs at an offered traffic of λ = 1000 packet/unit time. When α = 4 , the maximum throughput is S = 0.37 , and it occurs at an offered traffic of λ = 1000 packet/unit time. And as expected, for perfect codes (α = N/2 = 4), we obtain the maximum throughput of S = 0.37 .

Figure (3.3) represents the delay versus throughput for different value of threshold ; α. Notice that for higher values of α lower delay is obtained (in the stable region). For example; for a throughput, S = 0.28 ; when α = 2 , then D = 3.1 packet time . When α = 4 , then D = 1.6 packet time . Figure (3.4) represents the channel backlog versus offered traffic for different value of thresholds. Notice that for lower value of α ,higher channel backlog packets is obtained (in the stable region). For example; for a throughput, S = 0.28 ; when α = 2 , then K = 0.9 packet unit . When α = 4 , then channel backlog (K) = 0.42 packet unit.

This is expected, since Non-perfect codes will result in increased nonsuccessful transmission. Such results give great significance for the network designer, it shows the dependence

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between the code efficiency and the network throughput based on the type of code and signal to interference ratio; a threshold value, can be determined from [16,17]. Table (3.1) represents the throughput versus delay versus channel backlog for different values of threshold.

Also, we plot the throughput per user pair versus threshold in figure (3.5). For lower value of α, there is interaction between different pairs. Low throughput is obtained, as α increases, the throughput increases until $\alpha = N/2$.

3.4 The capture effect of spread spectrum receivers

One of the motivation for spread spectrum operation is the imposed self-interference behavior of the resulting system. The improvement centers mainly around the property known as capture, which consists of the ability for a receiver to successfully receive a packet despite the presence of other time overlapping transmissions. As general example, one way consider that correct reception is achieved if the number of bit errors in the received packet is below a certain value, whereby the rate at which bit errors can occur is a function of the number of currently overlapping transmission.

The transmission of packets being asynchronous, each packet transmission must be preceded by the transmission of a preamble which the receiver uses to acquire bit and packet synchronism [1]. Having successfully processed the preamble of an incoming packet, the receiver at a station will thus lock onto the data

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portion of the packet until its transmission is completed. Once a packet is locked onto by a receiver, it is important that future overlapping packets do not interfere with the completion of its successful reception. The effect of overlapping packets on the correct reception of preamble can be further reduced by the use of receiver based codes.

The network being modeled uses receiver based code, in this mode of operation each receiver is assigned a distinct code waveform, and transmitters must use the waveform assigned to the receiver they are trying to communicate with. The result is that a receiver will process the preamble of, and lock onto only those packets that are specifically destined to it. The destination receiver has a probability c_p of synchronizing to the packet header (capturing the packet), where c_p is a function of the capture time (T_c). In the analysis, the capture time is assumed equal to zero. Once capture occurs, the receiver never loses synchronization until the packet is completed.

In summery, we consider the possibility of correct reception of data carried by spread spectrum signals through nonslotted random access channel, this effect called capture, is shown to exist in the centeral receiver. Thus if the interval between the beginning moments of two packets transmissions is greater than the duration of the packet synchro-preamble (capture time) , the first packet received correctly; this the case of perfect capture, whereby correct reception is guranteed once the packet

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is locked onto. However, packets may not be captured, due to the destination receiver being busy (trasmitting or receiving).

Note also in slotted system when there are N greater than 1 incoming signals with the same PN code for a receiver, the receiver is equally likely to capture any one of these signals. So any contending signal has a probability of 1/N to be acquired. In that case we may lose the capture effect of CDMA scheme if the phase difference between the PN codes of the acquired signal and any incoming signal is within $\pm$ L chips, where L depends on the design of the acquisition circuit of the receiver and should be ideally be equal to one.

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TABLE (3.1) THRESHOLD EFFECT (α =4)

λ	S	K	D
100	0.14544988	0.09333283	0.64168376
300	0.27599561	0.48807573	1.76841831
500	0.32879972	0.91344523	2.77812004
700	0.35138810	1.30980206	3.72750759
900	0.36062694	1.66368294	4.61330700
1100	0.36211193	1.98323441	5.47685432
1300	0.35957873	2.27032089	6.31383514
1500	0.35464740	2.53008080	7.13407326
1700	0.34844255	2.76551437	7.93678665
1900	0.34144270	2.98059082	8.72940254
2100	0.33376360	3.17990112	9.52740479
2300	0.32666194	3.35821438	10.28039646
2500	0.31916416	3.52553082	11.04613590
2700	0.31180751	3.68027592	11.80303764
2900	0.30456781	3.82436562	12.55669594
3100	0.29755831	3.95843506	13.30305672
3300	0.29072821	4.08398247	14.04742336
3500	0.28386652	4.20360565	14.80838776
3700	0.27783203	4.31151295	15.51841545
3900	0.27168739	4.41548634	16.25207520
4100	0.26579344	4.51334953	16.98065186
4300	0.26009309	4.60598564	17.70898438
4500	0.25462782	4.69349003	18.43273926
4700	0.24934375	4.77659798	19.15667725
4900	0.24404776	4.85713291	19.90237427
5100	0.23942459	4.93001842	20.59111023
5300	0.23470473	5.00143719	21.30947876
5500	0.23017323	5.06939220	22.02424622
5700	0.22578812	5.13436985	22.73976135
5900	0.22157454	5.19634247	23.45188904
6100	0.21749425	5.25573063	24.16491699
6300	0.21338534	5.31393814	24.90299988
6500	0.20980752	5.36669159	25.57911682
6700	0.20613241	5.41898537	26.28884888
6900	0.20259166	5.46911430	26.99574280
7100	0.19915617	5.51737690	27.70376587
7300	0.19584310	5.56371593	28.40904236
7500	0.19262576	5.60840225	29.11552429
7700	0.18936956	5.65255928	29.84934998
7900	0.18653798	5.69259834	30.51708984
8100	0.18361175	5.73263645	31.22151184
8300	0.18078303	5.77122116	31.92346191
8500	0.17803073	5.80855560	32.62669373
8700	0.17536771	5.84458160	33.32757568
8900	0.17277443	5.87948227	34.02981567
9100	0.17013836	5.91418648	34.76103210
9300	0.16784728	5.94565868	35.42301941
9500	0.16546834	5.97733974	36.12376404
9700	0.16316152	6.00799847	36.82238770
9900	0.16091120	6.03777409	37.52238464

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α =3

λ	S	K	D
100	0.14529765	0.09333283	0.64235604
300	0.27523363	0.48807573	1.77331352
500	0.32720077	0.91344523	2.79169559
700	0.34938538	1.30980206	3.74887466
900	0.35807252	1.66368294	4.64621735
1100	0.35946977	1.98323441	5.51710987
1300	0.35699725	2.27032089	6.35949039
1500	0.35221148	2.53008080	7.18341351
1700	0.34619081	2.76551437	7.98841000
1900	0.33938873	2.98059082	8.78223228
2100	0.33208358	3.17990112	9.57560444
2300	0.32498372	3.35821438	10.33348465
2500	0.31765568	3.52553082	11.09859180
2700	0.31045222	3.68027592	11.85456371
2900	0.30335021	3.82436562	12.60709667
3100	0.29646289	3.95843506	13.35221004
3300	0.28974164	4.08398247	14.09525490
3500	0.28310752	4.20360565	14.84808826
3700	0.27702582	4.31151295	15.56357765
3900	0.27095687	4.41548634	16.29589844
4100	0.26512980	4.51334953	17.02316284
4300	0.25948894	4.60598564	17.75021362
4500	0.25407648	4.69349003	18.47273254
4700	0.24883950	4.77659798	19.19549561
4900	0.24368370	4.85713291	19.93211365
5100	0.23899937	4.93001842	20.62774658
5300	0.23431313	5.00143719	21.34509277
5500	0.22981179	5.06939220	22.05888367
5700	0.22545397	5.13436985	22.77346802
5900	0.22126484	5.19634247	23.48471069
6100	0.21720672	5.25573063	24.19689941
6300	0.21319366	5.31393814	24.92539978
6500	0.20955801	5.36669159	25.60957336
6700	0.20589936	5.41898537	26.31860352
6900	0.20237374	5.46911430	27.02481079
7100	0.19895196	5.51737690	27.73219299
7300	0.19565153	5.56371593	28.43685913
7500	0.19244564	5.60840225	29.14277649
7700	0.18926013	5.65255928	29.86660767
7900	0.18637800	5.69259834	30.54328918
8100	0.18346083	5.73263645	31.24719238
8300	0.18064034	5.77122116	31.94866943
8500	0.17789567	5.80855560	32.65145874
8700	0.17523968	5.84458160	33.35192871
8900	0.17265296	5.87948227	34.05375671
9100	0.17007172	5.91418648	34.77465820
9300	0.16773748	5.94565868	35.44621277
9500	0.16536379	5.97733974	36.14659119
9700	0.16306186	6.00799847	36.84489441
9900	0.16081607	6.03777409	37.54458618

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α =2

λ	S	K	D
100	0.14186203	0.09293711	0.65512317
300	0.24874282	0.47859991	1.92407513
500	0.27979326	0.88574862	3.16572475
700	0.28995895	1.26292229	4.35552025
900	0.29291499	1.60093975	5.46554375
1100	0.29307723	1.90919209	6.51429653
1300	0.29182696	2.18906879	7.50125599
1500	0.28970385	2.44503021	8.43975735
1700	0.28701854	2.67914581	9.33439922
1900	0.28388786	2.89477825	10.19690704
2100	0.28050387	3.09605408	11.03747368
2300	0.27678204	3.27677441	11.83882523
2500	0.27292001	3.44727993	12.63109970
2700	0.26895583	3.60548401	13.40548706
2900	0.26488674	3.75320339	14.16908741
3100	0.26079142	3.89090443	14.91960239
3300	0.25665593	4.02005863	15.66322041
3500	0.25255823	4.14338398	16.40565491
3700	0.24846554	4.25439644	17.12268066
3900	0.24439728	4.36158752	17.84629822
4100	0.24039710	4.46248817	18.56297302
4300	0.23643816	4.55800724	19.27778625
4500	0.23256266	4.64821529	19.98692322
4700	0.22874224	4.73387432	20.69522095
4900	0.22501063	4.81o98990	21.40782166
5100	0.22138238	4.89189148	22.09701538
5300	0.21779835	4.96541119	22.79820251
5500	0.21430945	5.03532505	23.49557495
5700	0.21088874	5.10214233	24.19351196
5900	0.20756245	5.16583061	24.88807678
6100	0.20430470	5.22682858	25.58349609
6300	0.20112765	5.28670597	26.28532410
6500	0.19807339	5.34068394	26.96315002
6700	0.19505239	5.39430141	27.65563965
6900	0.19211745	5.44566536	28.34548950
7100	0.18924654	5.49509048	29.03666687
7300	0.18645751	5.54251575	29.72534180
7500	0.18372977	5.58822632	30.41545105
7700	0.18106508	5.63348103	31.11300659
7900	0.17851818	5.67427254	31.78540039
8100	0.17599082	5.71516037	32.47418213
8300	0.17353427	5.75454330	33.16084290
8500	0.17113137	5.79263210	33.84902954
8700	0.16879487	5.82936668	34.53520203
8900	0.16650891	5.86493683	35.22294617
9100	0.16427028	5.90038967	35.91877747
9300	0.16213751	5.93233299	36.58827209
9500	0.16001379	5.96457863	37.27539063
9700	0.15794694	5.99576950	37.96064758
9900	0.15592349	6.02605057	38.64747620

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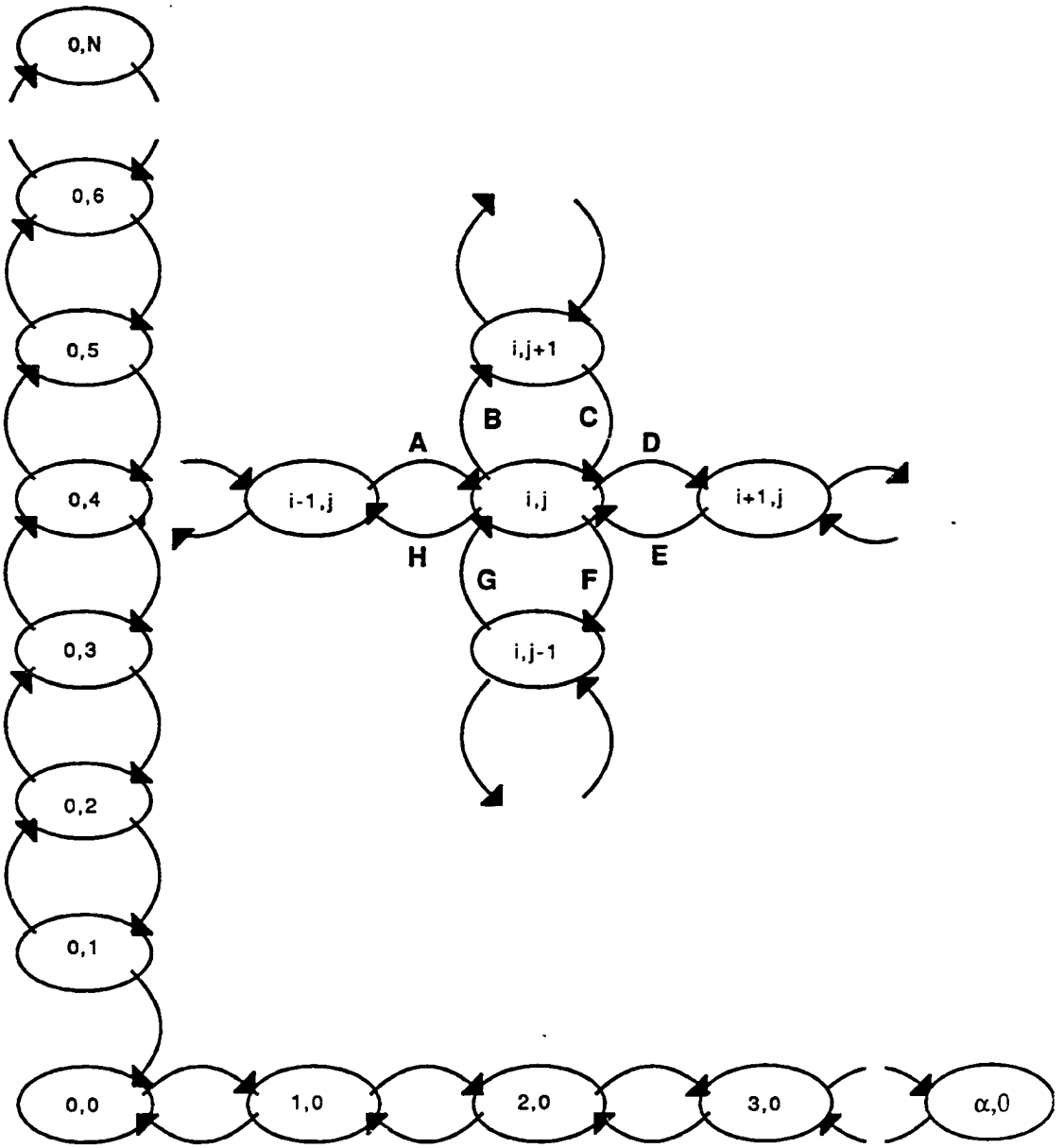

Fig (3.1) Steady State Transition Diagram

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FIG.(3.2) Throughput – Channel Input (N == 8)

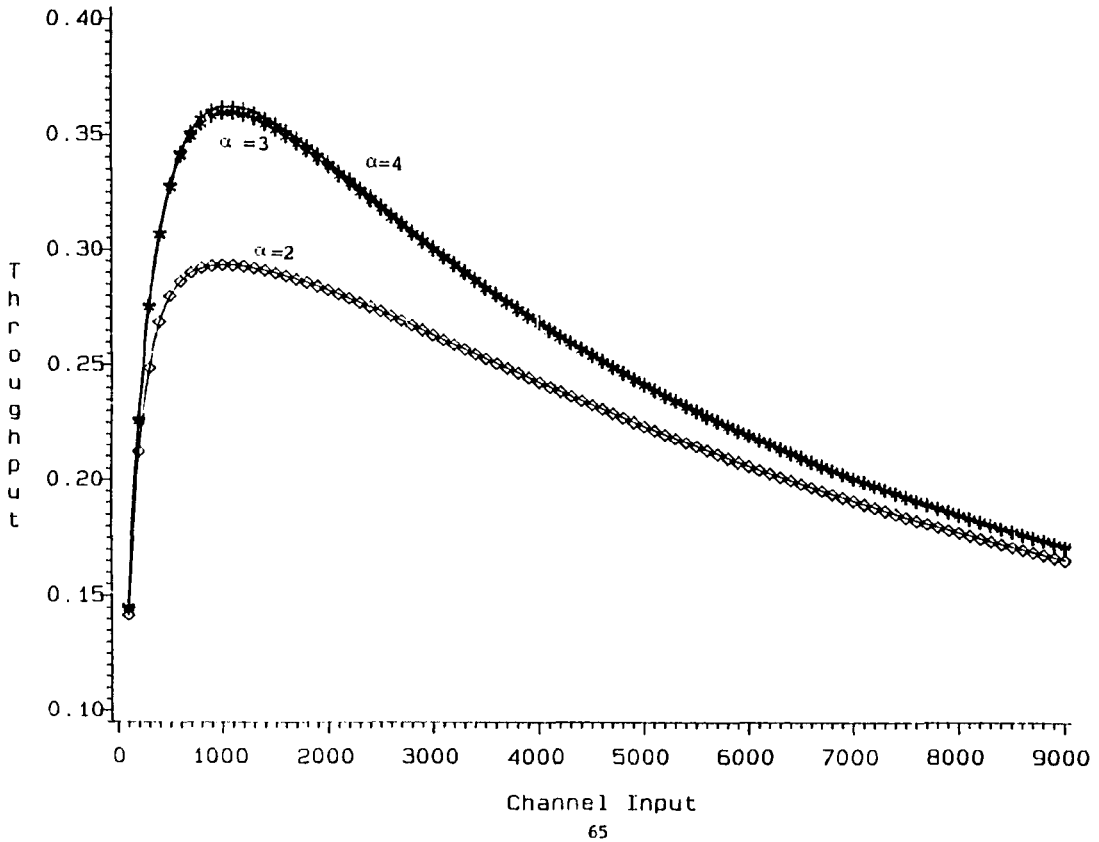

FIG.(3.3) Delay – Throughput (N = 8)

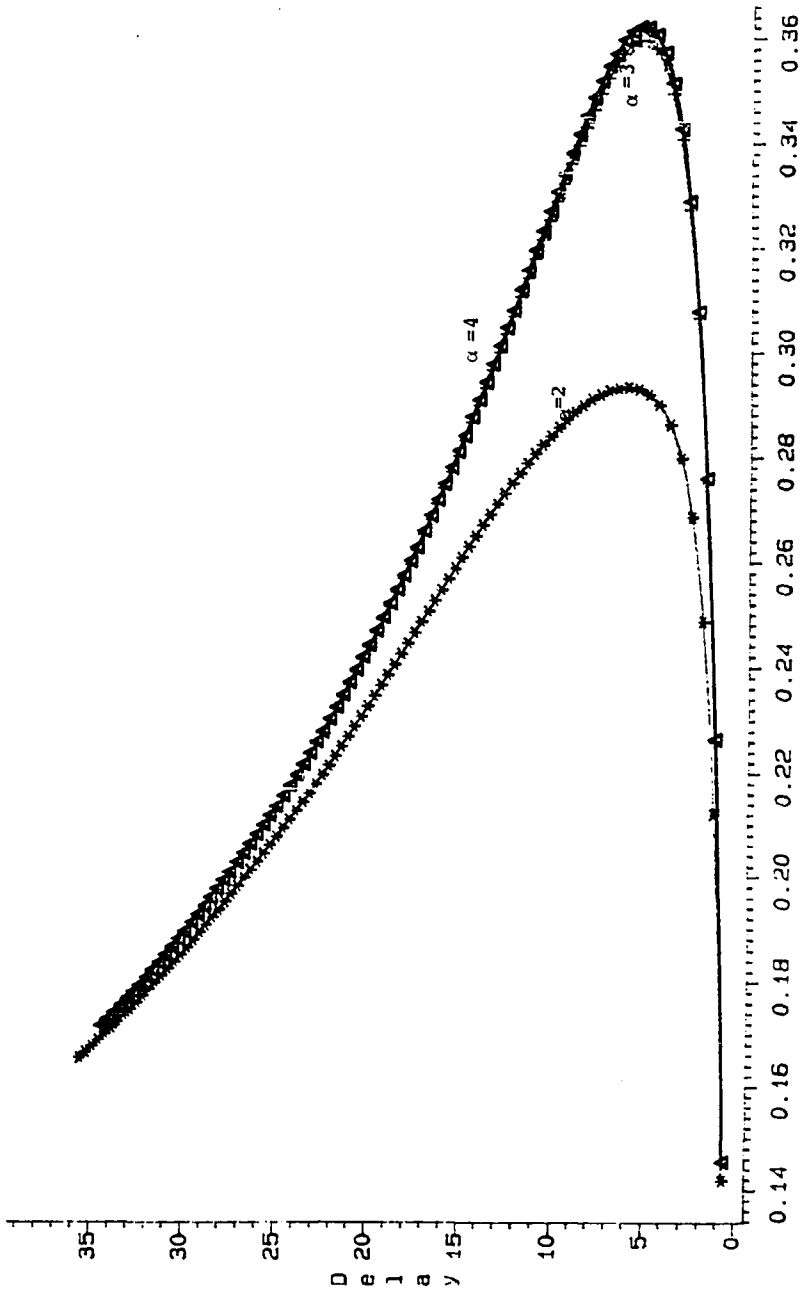

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FIG.(3.4) Channel Backlog – Throughput (N = 8)

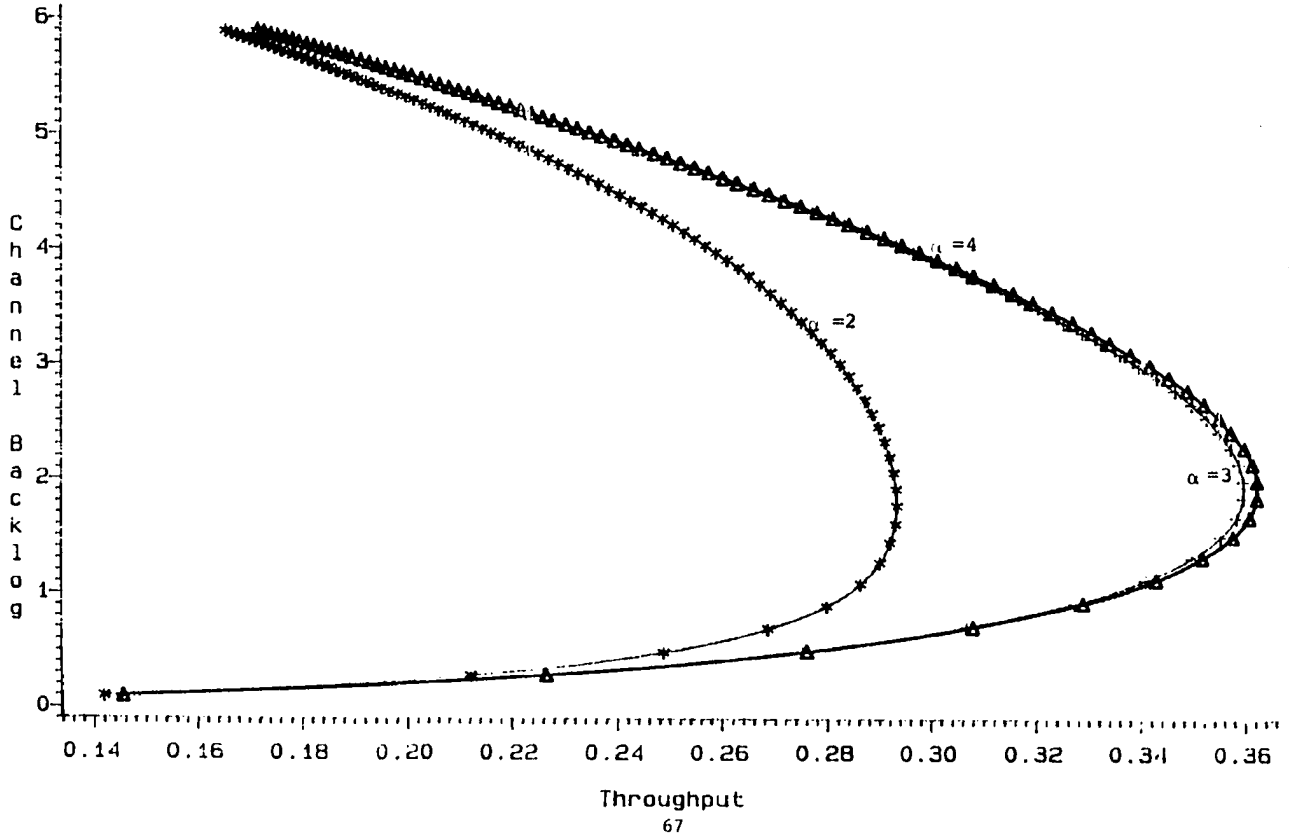

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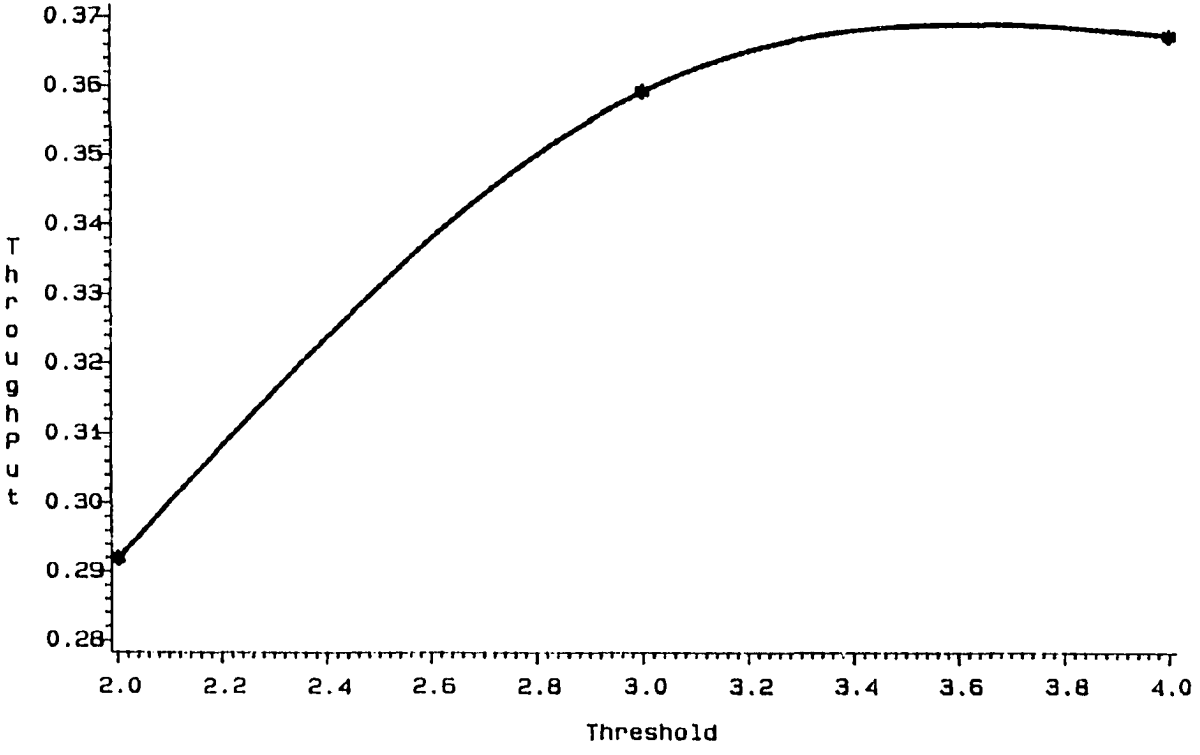
FIG.(3.5) ThroughPut – Threshold



CHAPTER 4

CDMA NETWORK WITH BUSY TONE AND CODE SENSING (CDMA/BT-CS)

4.1 INTRODUCTION

The previous models discussed in chapter 2 and 3 assumed a CDMA network. Due to the nature of the protocol, when a station generates packets, it is sent immediately over the channel. One or more station may collide and that leads to degradation in the channel performance. The modification to CDMA protocol presented in this chapter will avoid collision. As a result, we expect to achieve stability, higher throughput and lower delays.

Here, we intend to analyze the model presented here using Markov Chain models. Chapter 5 will address the product form solution as a powerful mathematical tool and will be used in analyzing the same model.

In this chapter, we introduce two capabilities to the user stations. The first is the ability of a transmitter to send a busy tone with his code on a seperate dedicated channel, referred to as a busy tone channel and thus eliminate contention on the main channel. Such a capability will prevent other users from transmitting to a station while it is transmitting.

The second is the ability of a station to listen on the intended receiver code to make sure that it is idle. We intend in this chapter to analyze the case of asynchronous channel.

In such case the analysis is more complex than the two

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previous models discussed in chapter 2 and chapter 3. As a result, we intend to make some simplifying assumption to make the analysis tractable.

4.2 Asynchronous CDMA network

All of the previous analysis in chapter 2 and chapter 3 used a network access protocol which is analogous to ALOHA. If a packet arrives at an idle station it is immediately transmitted. The network performance of ALOHA based systems can be improved by sensing the channel and blocking the transmission when the channel is busy.

In this section, we investigate the improvements that is gained by introducing a busy tone and code sensing access protocol. Analysis of such problem is complex, and our goal here is to obtain some performance results to help the designer of such a network. Hence, we have to make some simplifying assumptions such as zero propagation delay and perfect capture to make the analysis manageable.

4.2.1 Assumptions

There are several basic assumptions in our model, these are as follows:

1- The network consists of N mutually independent users, users communicate equally likely with each other.

2- Messages arrive according to a poisson process with rate λ packets/unit time.

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3- Each node (station) has a unique PN code for reception, and transmission will be encoded with the receiver's code.

4- The service times are taken to be exponential in distribution with rate 1/u.

5- Each user has only one packet in the buffer.

6- Zero propagation delay.

7- At any time, a node may either transmit or receive, but not both.

8- Perfect codes are used, i.e. channel threshold equals N/2. Also, if more than one station attempt transmitting to an idle station, only one packet will be captured by the receiving station.

9- Busy tone is encoded in the transmitter code, and is broadcast by the station while transmitting.

10-Any node ready for transmission senses both the receiver based code channel and the busy tone channel and blocks transmission if the destination is busy receiving or transmitting.

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4.2.2 Network model and mathematical analysis

In this model for asynchronous code sense multiple access/busy tone spread spectrum network, we define the system states as follows:

1) A station is said to be in the idle state, if it is not transmitting or receiving packets from other stations.
2) A pair of stations is said to be in the active state, if it is one transmitting successfully to an another idle station.

Note that i represents the number of successfully commmunicating pairs.

From the description of our model in sections (4.1, 4.2), we see that the sequence of events can be modeled using continuous time Markov Chain as shown in figure (4.1). Note that by introducing a channel code sense access protocol, stations are allowed to begin transmitting only if the destination node is free, and blocks transmission if the destination node is busy receiving.

In this case, with the assumption of ZPD, the collision resulting from more than one user transmitting to another station has been eliminated. Also the collision resulting from transmission to another station already in the transmit mode has been eliminated by introducing the busy tone signal.

In summery any idle station will avoid the loss of its transmitted packets to a station by monitoring the state of that particular station. When the busy tone signal is on, it indicates that the station is busy transmitting to another station. Also,

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by listening on the RBD code, the station can tell whether the intended receiver is busy or not.

Fig (4.1) represents the continuous time Markov chain. Note that the transition from state (i-1) to state (i) occurs only when any one of the ideal stations transmits successfully to another idle station. This occurs with transition rate of $n\lambda(n-1)/(N-1)$, i.e. the transition rate A is given by

$$A = \lambda [N-2(i-1)][N-2(i-1)-1]/(N-1) \qquad .....(4.1)$$

Similarly the transition from state (i) to state (i+1) occurs with transition rates as follows:

$$B = \lambda (N-2i)(N-2i-1)/(N-1) \qquad .....(4.2)$$

The transition from state (i+1) to state (i) occurs by the departure of any of the successful communicating pairs with rate

$$C = (i+1)u \qquad .....(4.3)$$

Similarly

$$D = iu \qquad .....(4.4)$$

At steady state, the rate of flow into any given state must equal the rate of flow out of the state, hence from figure (4.1), we have derived the following equations:

$$[iu+ \lambda \{(N-2i)(N-2i-1)/(N-1)\}]\ p(i) = \lambda \{[N-2(i-1)][N-2(i-1)-1]/(N-1)\}p(i-1)+(i+1)u\ p(i+1) \qquad .....(4.5)$$

$$\text{for } 0 \leq i \leq N/2$$

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We also know that

$$\sum_{i=0}^{N/2} p(i) = 1 \qquad \text{.....(4.6)}$$

4.2.3 Network throughput and channel capacity

The model developed in this section, gives insight into the behavior of the network and enables us in obtaining network throughput as follows:

The values of p(i) have been obtained by solving set of linear equations, at steady state the rate of flow into given state equals the rate of flow out of that state, as given below: The balance equation for state (0) is,

$$N \lambda p(0) = u p(1) \qquad \text{.....(4.7)}$$

So $$p(1) = (N \lambda / u) p(0) \qquad \text{.....(4.8)}$$

Similarly the equations for states i =1, 2 are,

$$[\lambda \{(N-2)(N-3)/(N-1)\}+u] p(1) = N \lambda p(0)+2u p(2) \text{.....(4.9)}$$

implies

$$p(2) = \lambda \{(N-2)(N-3)/(N-1)(2u)\} p(1) \qquad \text{.....(4.10)}$$

for state (2)

$$[\lambda \{N-4)(N-5)/(N-1)\}+2u] p(2) = \lambda \{(N-2)(N-3)/(N-1)\} p(1)$$

$$+3u p(3) \qquad \text{.....(4.11)}$$

implies

$$p(3) = \lambda \{(N-4)(N-5)/(N-1)(3u)\} p(2) \qquad \text{.....(4.12)}$$

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This derivation can be repeated for states 3, 4, ...,(N/2) to obtain closed form as follows.

$$p(i) = [\ \lambda\ \{(N-2(i-1))(N-2(i-1)-1)/(N-1)(iu)\}]\ p(i-1)\ ,$$
$$i = 1, 2, 3, \ldots\ldots, N/2 \qquad \ldots\ldots(4.13)$$

implies

$$p(i) = [\ \lambda^{i}\ (N!)/(\{u(N-1)\}^{i})(i!)\{(N-2i)!\}]p(0),$$
$$i = 0, 1, 2, \ldots\ldots, N/2 \qquad \ldots\ldots\ldots(4.14)$$

By solving equation (4.6) and equation (4.14) numerically, we can obtain the network throughput as follows:

$$\text{Network throughput} = \sum_{i=0}^{N/2} i\ p(i) \qquad \ldots\ldots(4.15)$$

$$\text{Throughput per user pair} = (2/N) \sum_{i=0}^{N/2} i\ p(i) \qquad \ldots\ldots(4.16)$$

$$\text{Channel capacity} = \text{Max}\ \{\ (2/N) \sum_{i=0}^{N/2} i\ p(i)\ \} \qquad \ldots\ldots(4.17)$$

4.2.4 Numerical results and conclusion

The properties of continuous time Markov chain model of CDMA with busy tone and code sensing network were investigated. The model allowed detailed analysis such as throughput and channel capacity. Closed form expressions for the performance of such network has been obtained.

In this section a model for asynchronous CDMA packet network was developed. It allowed efficient calculation of throughput and

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channel capacity. The results obtained are plotted in figure (4.2) and figure (4.3). Figure (4.2), shows throughput versus offered traffic for network with 8 users. Note that the throughput increases with the increase of offered traffic. In this case a maximum throughput of 1 can be achieved. Also, notice that the system is stable. This is true sense the code sensing eliminating the collision from the channel.

Figure (4.3) shows the comparison between the different CDMA models developed in section 2.3 and 4.2. The figure shows that, CDMA with busy tone and code sensing achieves stability and higher throughput than CDMA which is expected.

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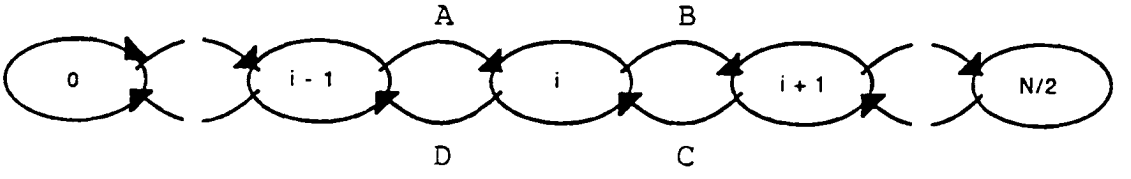

Fig (4.1) Steady State Transition Diagram

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FIG.(4.2) Throughput – Offered Traffic

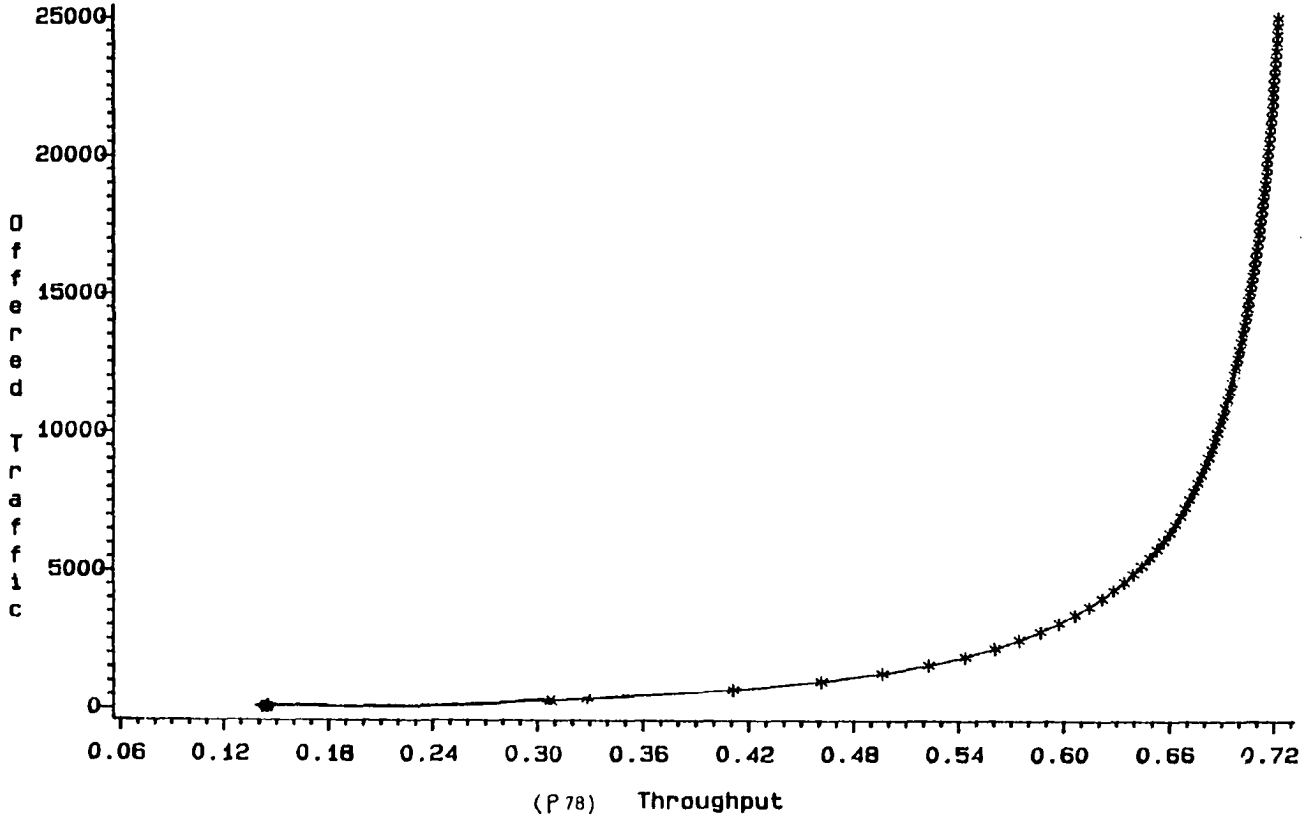

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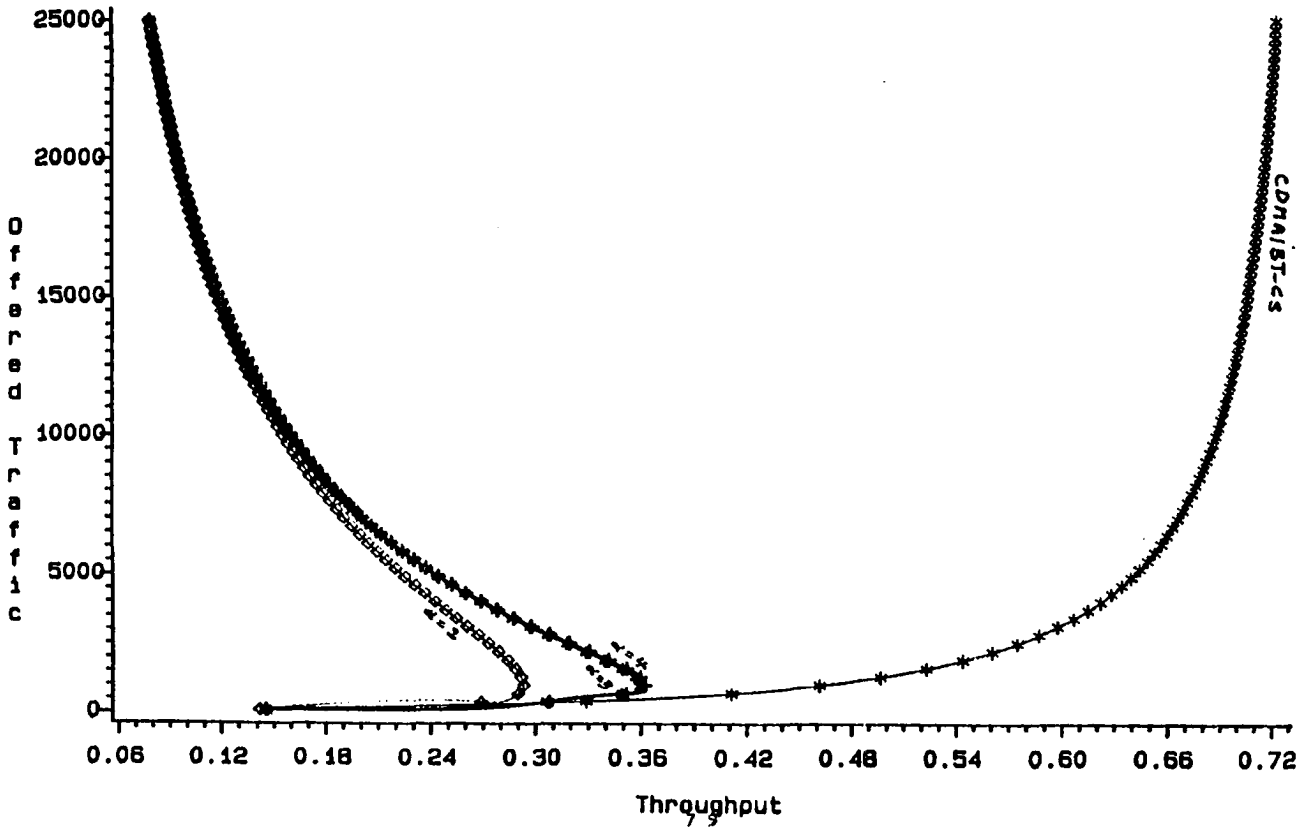
FIG.(4.3) Throughput – Offered Traffic



CHAPTER 5

THE PRODUCT FORM SOLUTION AND CONCLUSIONS

This chapter has two folds, first it analyzes the previous model discussed in chapter 4 using product form solution. The purpose here is to emphasize the importance of product form solution as opposed to Markov Chain approach. Secondly, section (5.2) discusses open problems and suggestions for research topics. Section (5.3) is the conclusion.

5.1 PRODUCT FORM SOLUTION

This study has two goals: the first is the development of topics surrounding reversibilty in time, a basic key to tractability. The second is the presentation of working tools needed to simplify the solution of finite Markov chains in discrete and continuous time. To demonstrate the capabilities of the product form solution, we apply it to the model developed in chapter 4.

The numerical methods (recursive, exact solution,...,etc.) are very general in the sense that they are used conceptually to very complex system models. These methods by themselves are of limited practical application. They are limited because they require solution of a set of linear equations and because that set may be enormous. In many cases, the queueing models generates a large number of set of equations. Thus we cannot hope to

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numerically solve the linear equations nor can we cope with performance measures which require numerical values for all of the state probabilities.

We must seek first algebraic simplication of the problem. Fortunately, a convent algebric simplification, the product form solution exists and it is expressed as follows:

$$P(s_1, s_2, \ldots, s_m) = P_1(s_1)P_2(s_2)\ldots P_m(s_m) \quad \ldots\ldots (5.1)$$

where $p(s_1, s_2, \ldots, s_m)$ is the probability of a network state in a network of m queueus. $p_m(s_m)$ is a factor reflecting the probability that queue m is in state s_m .

A solution with the form of equation (5.1) is called a product form solution. A stationary continuous time Markov chain x(t) possesses a product form solution for the steady state probability distribution if and only if it is reversible. Reversibility has a simple characterization in terms of ergodic chains in discrete or continuous time(kolmogorov's criterion) reversibility is equivalent of detail balance [40].

Characteristics of time reversible process

1- The time-reversible process is a broad and structurally simple class of processes which are tractable, i.e. which lead themselves to the kind of theoretical and numerical analysis required in applied problems.

2- Only for the time reversible class are ergodic probabilities available at once.

3-Every birth-death process is appropriate to the description of

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certain simple Networks; every ergodic birth-death process is reversible in time i.e. the system has detailed balance.

The necessary and sufficient conditions for existing reversibility are as follows;

A Markov chain is Reversible if $x(t_1)$, $x(t_2)$,...$x(t_n)$ has the same distribution as $x(T-t_1)$, $x(T-t_2)$,.. $x(T-t_n)$

Briefly, a Markov process is reversible if it evolves identically forward and backward in time. This property is equivalent to the statement that the steady state probabilities satisfy the "detailed balance" equations, which equate probability flows between any two communicating states. To illustrate the analysis, we consider the model presented in chapter 4 .

5.1.1 Analysis of CDMA/BT-CS using product form solution

Fortunately, we do not have to solve the global balance equations numerically for each local balance network separately to compute equilibrium state probabilities. When we are describing the state space of the network, we sould relate the network state space to the state space of each queue in isolation. We shall obtain network state probabilities from the state probabilities of each queue in isolation, since we can analyze a local balance queue in isolation very simply. From the local balance equations, the equilibrium state probabilities for each queue in isolation are readily obtainable. Computing network state probabilities is then conceptually straight forward.

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Let us first find out if the process in the model presented in chapter 4, is reversible ? . Accordingly, every state can be reached from the empty state in a nonzero period of time with nonzero probability. Similarly, the empty state can be reached from other state in a nonzero period of time with nonzero probability. It follows that all states communicate and the resulting Markov chain is reversible, i.e. we can apply PF solution. The solution given by equation (5.1) suggests a simpler approach to the analysis of computer networks by using local balance.

The local balance (detailed balance) is indeed very simple. It states that between any pair of states there should either be no transition at all or transition should be in both directions and the rates in both directions should be equal. From figure (4.1) we can derive the local balance equations as follows:

$$\lambda N p(0) = u p(1) \qquad \text{.....(5.2)}$$

$$\lambda [(N-2)(N-3)/(N-1)] p(1) = 2u p(2) \qquad \text{.....(5.3)}$$

$$\lambda [(N-2(i-1))(N-2(i-1)-1)/(N-1)] p(i-1) = iu p(i) \qquad \text{..(5.4)}$$

Similarly all state probabilities can be evaluated by forming a product of $\lambda/u(N-1)$ along any path from state (0) to a particular state.

proceeding in this manner , we can easily show that

$$p(i) = p(0) \{(N!)/(i!)((N-2i)!)\} \prod_{i=0}^{i} \lambda/u(N-1) \qquad \text{.....(5.5)}$$

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The probability of the idle state P(0), is evalulated by using the following equation:

$$\sum_{i=0}^{N/2} p(i) = 1 \qquad \text{.....(5.6)}$$

i.e. from equation (5.4) and equation (5.5), we have

$$p(0)\ [1+\ \sum_{i=1}^{N/2}(N!)/(i!)((N-2i)!)\ \pi^{i}\ \lambda/u(N-1)\ ] = 1 \quad \text{....(5.7)}$$

The values of p(i) have been obtained by simple substitution in solving set of local balance equation, so we can obtain the network parameters such as network throughput and throughput per pair and the channel capacity as given in equation (4.15) through (4.17).

The CDMA model developed in chapter 2 and product form solution

For models with product form solution we need not explicity solve for state probabilities to obtain the performance measures. However many interesting models will not have product form solutions.

For example, our model discussed in chapter 2 does not fall under the class of reversible processes that lead to simple product form evaluation. We can easily demonstrate this by showing that kolmogorov's criterion for reversibility is violated.

In this case, there exists valid recurrent state where the only activity in the network consists of a single node.

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transmitting unsuccessfuly while all other nodes feel free to transmit. From this state there is a direct transition to the idle state, the nodes complete its transmission but not vice versa (an unsuccessful transition can not be generated). For example consider the state (0,1) [figure (2.2)]. If the transmitter in state (0,1) finishes its transmission before any other event occurs, the system switches from state (0,1) to a state (0,0) in which all nodes are idle. However there is no legitimate transition from state (0,0) to state (0,1). Unilateral transitions of this kind indicate that reversibility does not hold, thus the tractable product form algorithm do not apply.

We conclude this section by noting that unfortunately, the product form formulation is not applicable to all access protocols. It is therefore of particular interest to identify rules that lead to applicability of product form. We have to determine the conditions on the access protocol, network topology and traffic requirments under which the resulting Markov chain is reversible. For examples the unslotted protocols CSMA with capture and BTMA have tactable product form (PF) steady state probabilities [8,10]. Protocols such as slotted ALOHA or CSMA without capture include more complex state space with unilateral transitions, thus their Markov modeling becomes very tedious and their analysis does not yield product form structure.

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SOME CONSIDERATIONS

We should state that even for a product form protocols, the computations are not trivial. Yet PF is a good tool to handle networks of arbitrary topology and non-trivial size. When a network does not have a product form solution and has too many states for numerical solution for the state probabilities, then alternative approximation and simulation are necessary.

A) APPROXIMATION: It is very attractive because they are usually computationally inexpensive. The most important approach to approximation is aggregation, and diffusion. In aggregation we replace a subnetwork by a single queue; the composite queue is intended to behave as the entire subnetwork in its interaction with the remaining queues of the network. The resulting network, i.e. the network with the composite queue, will have fewer states and may have few enough states to be solved numerically. The drawback of this technique is it may introduce an unknown amount of error and might be difficult to apply.

B) SIMULATION: the most popular approach to the solution of a computer system model is to simulate it, i.e. to use a program which behaves like the model and then observing the behavior of the program; the principle advantage of simulation is its great generality in most simulation models, is that of random variables characterized by probability distribution. These are used to represent service times, interarrival times and other system characteristics.

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5.2 OPEN PROBLEMS AND SUGGESTIONS FOR FUTURE RESEARCH

In order to fully characterize the performance of the proposed CDMA Network from a throughput-delay-stability standpoint, additional analysis is required. Below we identify some major points.

1-In the dissertation, we assumed each user has a buffer one packet length. Practically each buffer contains number of packets, to get the complete performance of total delay, we must take into consideration the effect of user buffer (for example, see [5]).

2- Because of the collision nature of the protocol, CDMA network is an unstable network. To achieve stability, techniques used in collision protocol such as ALOHA, CSMA, etc., can be adopted to control CDMA network.

3- Given the operation of CDMA, perfect capture can be assumed. This is the case since whenever a receiver locks on to a particular packet, then all future overlapping transmissions can be ignored. Clearly this requires that the preamble of the first packet, or a portion of it, be received free of collision. We assume perfect capture in the dissertation for tractable solution. Such calculation for the capture ratio and taking into consideration the collision effect on the preamble of the first packet is an open problem.

4- A network in which every node can communicate directly with all others is called a one hop network; otherwise intermediate relay (repeater) must be used, thus creating a multihop network.

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It is interesting here to model the system, we find that an idle node may receive a packet even if some of its neighbors are transmitting. This implies the use of orthogonal codes(CDMA) techniques. Transmission coded in this way provides receivers with the ability to receive one transmission and reject the others as noise. we note that this selective reception ability may be constrained by signal-to-noise ration (SNR) thresholds which place a limit on the number of simultaneous successful transmissions in a neighborhod. Extension of the model presented in this thesis to the multihop network presents a challenging problem.

5.3 CONCLUSIONS

Dissertation objective of this research has been to develop analytic models with which we can evaluate and optimize the performance of Asynchronous code division Multiple access (CDMA) Network; Our emphasis is on a large number of users. In this section the conclusion results of the analytical model are presented.

1) Two-dimensional Markov chain for Asynchronous CDMA Network has been developed, which describes the behavior of such Network, see section (2.3).

2) Numerical examples has been solved using Numerical analysis technique to numerically explore the Asynchronous CDMA Network behavior.

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3) IN section (2.3), we have calculated state occuption probabilities.

4) In section (2.4) we have derived an expressions which describes the throughput per user pair and the Network throughput as well and channel capacity.

Average Network throughput = S_N

$$S_N = \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\ p(i,j)$$

Average throughput per pair = S

$$S = (2/N) \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\ p(i,j)$$

The channel capacity = C

$$C = \text{Max} \left\{ \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\ p(i,j) \right\}$$

5) In section (2.5) we have derived an expression which describes the average packet delay.

Average packet delay = D

$$D = \frac{\sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} j\ p(i,j)}{(2/N) \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} i\ p(i,j)}$$

6) Throughput-delay tradeoffs has been calculated, as given in figure (2.4), the designer of CDMA Network can choose an

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7) In section (2.8) stability definition is given and discussion of the proposed model has been explored and the mean queue length has been calculated as the following.

Average channel backlog = K

$$K = \sum_{i=0}^{N/2} \sum_{j=0}^{N-2i} j \; p(i,j)$$

8) Threshold effect on network performance, steady state probabilities, throught, delay, channel capacity , all have been developed in chapter (3).

9) Capture effect in asynchronous and synchronous has been discussed in section (3.4).

10) Comparison between ALOHA and our model for asynchronous CDMA has been given in chapter (2.9).

11) CDMA network with busy tone and code sensing have been introduced in chapter 4. A model for Asynchronous CDMA have been developed which enables us to calculate network throughput and channel capacity. Comparsion between different models can be found in figure (4.3).

12) Product form solution has been introduced in chapter (5).

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REFERENCES

[1] Raymond L. Pickholtz, Donald L. Schilling and Laurance B. Milstein "Theory of spread spectrum communications-A tutorial" IEEE trans. on comm., vol. com - 30, may 1982.

[2] Leonard Kleinrock and Simon S. Lam, "Packet switching in a multiaccess broadcast channel: preformance evaluation," IEEE trans. on Comm. COM-23, No. 4, April 1975.

[3] Elvino S. Sousa and John A. Silvester, "A Spreading Code Protocol for a distributed spread spectrum packet radio network," GLOBCOM-84.

[4] Guy Faylolle and Erol Gelenbe "Stability and optimal control of packet switching Broadcast channel". IEEE Trans. Comput. c-22, 611-618

[5] Tarek N. Saadawi and Anthony Ephremides "Analysis, stability and optimization of slotted AlOHA with finite number of Buffered users". IEEE Trans. on automatic control, Jun 1981.

[6] D. Raychandhuri, "Performance analysis of random access packet switched code division multiple access system," IEEE trans. on Comm. COM-29, No. 6, June 1981.

[7] Jeffery M. Musser and John N. Daigle, "Throughput analysis of spread spectrum communications" IEEE trans. on comm, vol, com-30, no 5, May 1982.

[8] Mon-song chen and Robert Boorstyn "Throughput analysis of code division multiple Access (CDMA), GlOBCOM 1985.

[9] Leonard Kleinrock and Fouad Tobagi "packet switching in Rodio channels, part 1-Carrier sense Multiple-Access Modes and their throughput-delay characteristics" IEEE trans. on comm. vol. Com-23, no. 12, December 1975.

[10] Jose M. Brazio and Fouad A. Tobagi "Throughput analysis of spread spectrum multihop packet radio networks". ICC 1985.

[11] Robert C. Dixon "Spread Spectrum System" second edition, John Wiley-Interscience, 1984.

[12] Michael J. Marcus "Recent U.S. Regulatory decisions on civil uses of spread spectrum". Milcom 1985.

[13] Szu-lin Su and Victor O.K. Li "Performance Analysis of a slotted code division multiple Access Network." ICC 1984.

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[14] Donald H. Davis and Steven A. Gronemeyer "Performance of Slotted AlOHA Random Access with delay capture and Randomized time of arrival" IEEE trans, on Comm, vol Com 28 No. 5, 1980.

[15] Ahmed K. Elhakeem, H.M. Hafez and Samy A. Mohamoud, "Spread Spectrum access to mixed voice-data local area networks," Journal on Selected Areas in Communication, vol. com-1, No. 6, December 1983.

[16] Michael B. Pursley "Performance Evaluation for Phase coded Spread Spectrum Multiple-Access Communication Part 1: system Analysis "IEEE trans, on Comm.vol Com-25 No. 8, August 1977.

[17] Michael B. Pursley and Dilip V. Sarvate "Performance Evalution for phase coded spread spectrum multiple-access Communication-part II: code sequence analysis" IEEE trans. on comm, vol. com-25, No.8, August 1977.

[18] Gordon S.G. Beveridge and Robert S. Schechter "Optimization theory and practice" McGrow-Hall, 1970.

[19] Andrew J. Viterbi "Convolution codes and their performance in communcation systems" IEEE trans on comm. Technology, vol, com 19 No. october 1971.

[20] Kung Yao "Error probability of Asynchronous Spread Spectrum Multiple Access Communication Systems". IEEE trans on comm. vol 2 comm. No.8, August, 1977.

[21] Adam Livne "Design Consderations for code division Multiple Access in voice/data Radio Network" Milcom 1984.

[22] Leonard Kleinrock and simon lam "packet switching in a multi access Broadcost channel performance Evaluation" IEEE, Trans. on comm. August 1978.

[23] John A. Silvester and Leonard Kleinrock "On the capacity of single-hop slotted AlOHA Networks for varies traffic Matrices and transmission strategies" IEEE trans. on comm, vol. Com 31, No. 8, August 1983.

[24] Aydano B. carleial and Martin E. Hellman "Bistable Behavior of AlOHA-Type systems. IEEE trans on Comm, vol. Com23, No.4, April 1975

[25] Ivan Lee and John Silvester "An Iterative scheme for performance modeling of slotted AlOHA packet Radio Network", INFOCOM 1982.

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[26] David J. Goodman and Adel A.M. Saleh "Local AlOHA Radio Communication with capture and packet Buffers" ICC 1985.

[27] Robert T. Chen "Block coding Techniques for Reliable data transmission" IEEE trans on Comm. Tech, vol. com-19, No. 5, October 1971.

[28] Kleinrock "Queueing systems vol,1, 11, John wiley 1975.

[29] A. J. Viterbi,"When Not to spread Spectrum-a Sequal", IEEE Communications magzine, vol.23, No.4, April 1985.

[30] Kenji yamada, Kazuhiro Daikoka and Hidenori Usui " Performance of portable Radio Telephone using spread spectrum" IEEE trans on comm. vol. com-32. No.7, July 1984.

[31] Joseph Y.N. Hui "Throughput Analysis for code division multiple accessing of the Spread Spectrum Channel" IEEE Journal on Selected Areas in Communications, vol. SAC-2, No.4, July 1984.

[32] J. R. Lee, S. M. Ryu, C. U. Un and W. D. Cho "A local area Network Based on the Code division Multiple Access Method" GlOBCOM 1984.

[33] Charles L. Weber, Gaylord K. Huth and Bartus H. Batson "Performance consideration of code division multiple access systems" IEEE trans. on comm. vol. VT-30, No.1, Feberuary 1981.

[34] N. Hamamoto, T. Nishigaki, R. Suzuki, I. Nishiyama "Experimantal Results and applications of Quadri-Phase Spread Specturm Systems for Satellite Communications" GLOBCOM 1984.

[35] M. Kavehard and P. J. Mclane "Performance of direct sequence spread spectrum for indoor wireless digital communication" Comm. ACM, 1984.

[36] Jay E. Padgett "Analysis of spread specturm modulation for coordless Telephones" INFOCOM 1985.

[37] Paul F. Sass "Why is The Army Interested in Spread Spectrum" IEEE Comm. magazine, vol. 21, No. 4, July 1983.

[38] Wendell E. Grove "Brief Numerical Methods" prentice-Hall 1966.

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[39] D. Raychaudhuri and stephen S. Rappaport "Orthogonal and Quasi-orthogonal Tree codes with applications to muliple access" IEEE trans. on comm. vol. com- 27, No. 2, February 1979.

[40] F. Kelly "Reversibility and stochastic networks, Wiley, New York, 1979.

[41] Charless E. Cook and Howard S. Marsh "Introducation to spread spectrum" IEEE Communication Magazine, March 1983.

[42] S. Ross " Applied probability models with optimization applications" Holden-day, s. Franciso, 1970.

[43] M.K. Simon, J.K. omura, R.A. Scholtz, B.k. leviff" spread spectrum communications" vol 1, 2, 3, computer science press, 1985.

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